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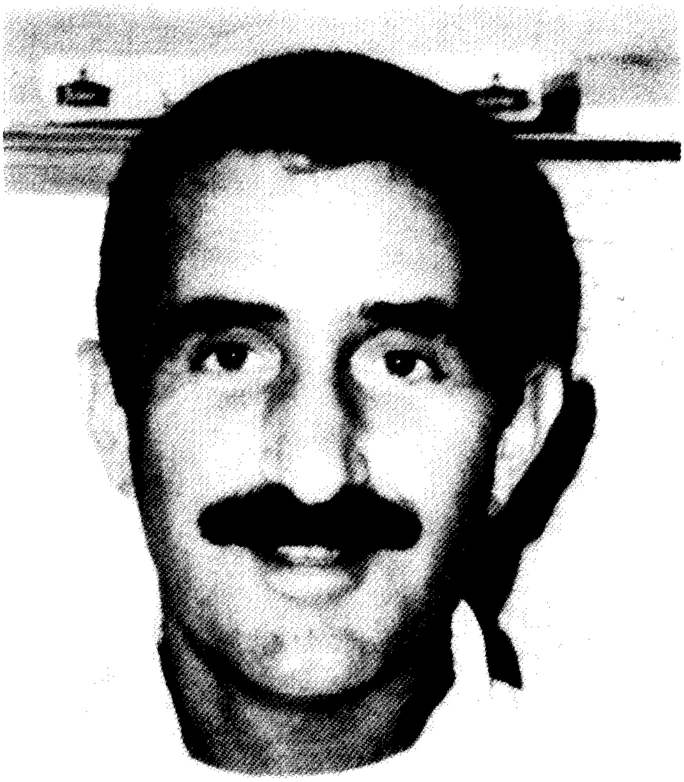
IN MEMORIAM



Alan Rittenberg, longtime member of the Particle Data Group, died January 3, 1989 following a long illness.

Alan was born December 27, 1938 in Nashville, Tennessee. He received a B.S. in Physics from Yale University in 1960 and a Ph.D. from the University of California at Berkeley in 1969. His graduate research work was done in particle physics in the Alvarez Group at Lawrence Berkeley Laboratory. He participated in the discovery of the η' meson and in several other experiments.

After receiving his Ph.D., Alan joined the Particle Data Group at LBL, while continuing to work on several bubble chamber experiments. He served as group leader from 1974 to 1976 and for nearly two decades was responsible for the organization, editing, and production aspects of the *Review of Particle Properties* and other Particle Data Group publications. His attention to detail and constant striving for excellence played a major role in the accuracy and integrity of these publications. The entire particle physics community has benefited. We miss him greatly.

INTRODUCTION

I. OVERVIEW

This review is an updating through December 1989 of the Review of Particle Properties, a compilation of experimental results on the properties of particles studied in elementary particle physics. These properties include masses, widths or lifetimes, branching ratios, and so on. Where feasible, we suggest a "best" value of each property, based on what in our judgment are the best available data.

We also give an extensive summary of searches for hypothesized particles. Results of searches usually take the form of limits on masses under specified assumptions. Since such limits are often complex functions of mass and may be model-dependent, our summary cannot provide the detailed information given in the original papers.

Our compilation is presented in two sections, the "Summary Tables of Particle Properties" and the "Full Listings." The Summary Tables give our best values of the properties of those particles that we consider to be well established. We try to be conservative in judging whether or not a particle is well established. The Summary Tables also give a condensed version of search limits for hypothesized particles, and a summary of experimental tests of conservation laws.

All data used for the best values in the Summary Tables are given in the Full Listings, with references and occasional comments. Other measurements considered recent enough or important enough to mention, but which for some reason are not used to get the best values, appear separately just beneath the data we do use for the Summary Tables. The Full Listings also give information on unconfirmed particles and on particle searches, as well as short "mini-reviews" about subjects of particular interest.

The Full Listings were once an archive of all published data on particle properties. This is no longer possible because of the growth of information. We refer interested readers to earlier editions for references to data now considered to be obsolete [Particle Data Group (1988)].

In previous editions, we organized the Summary Tables and Full Listings into three categories:

Stable Particles
Mesons
Baryons

With this edition, we adopt a new organization into five categories:

Gauge and Higgs Bosons
Leptons
Mesons
Baryons
Searches for Other Particles

The last category is for searches for particles that do not belong to the previous four groups.

In addition to the compilations of measurements and best values, we give a long section of "Miscellaneous Tables, Figures, and Formulae," a quick reference for the practicing particle physicist.

In Sec. II of this Introduction, we list the main areas of responsibility of the various authors, and also list our large number of consultants on various special topics. In Sec. III, we summarize the naming scheme for hadrons, first introduced in our 1986 edition [Particle Data Group (1986)]. In Sec. IV, we discuss our procedures for selecting measurements of particle properties and for obtaining best values of the properties from the measurements.

The accuracy and usefulness of this compilation depends in large part on interaction between the users and the authors and consultants. We appreciate comments, criticisms, and suggestions for improvements of any kind. Please send them to the appropriate author, according to the list of responsibilities in Sec. II below, or to

Particle Data Group, MS 50-308
Lawrence Berkeley Laboratory
Berkeley, CA 94720, USA

Or send them via computer mail to

LBL::PDG on HEPNET,
PDG@LBL on BITNET, or
PDG@LBL.GOV on INTERNET

A pocket-sized Particle Properties Data Booklet is available. This contains the complete Summary Tables of Particle Properties and the most frequently used parts of the Miscellaneous Section, but not the Full Listings. For North and South America, Australia, and the Far East, write to

Technical Information Department
Lawrence Berkeley Laboratory
Berkeley, CA 94720, USA

For all other areas, write to

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Consultants

Of great importance to this Review is our world-wide network of consultants, experts in particular topics. We mention the following people with thanks:

- D. Anderson (Fermilab)
- V.I. Balbekov (Serpukhov)
- A. Baldini (CERN)
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- R.D. Tripp (LBL)
- P. Trower (Virginia Polytechnic Inst.)
- E. Wang (LBL)
- R. Wigmans (NIKHEF, Amsterdam)
- H. Wahl (CERN)
- L. Wolfenstein (Carnegie-Mellon University)

In addition, the Berkeley Particle Data Group has benefited from the advice of the PDG Advisory Committee, which meets annually. The members of the 1989 committee were J. Dorfan (SLAC), Chair, M. Della Negra (CERN), J. Donoghue (University of Massachusetts), E. Eichten (Fermilab), and B. Taylor (National Institute of Standards and Technology). The members of the 1988 committee were S. Ellis (University of Washington), Chair, J. Dairiki (LBL), M. Della Negra (CERN), J. Donoghue (University of Massachusetts), and J. Dorfan (SLAC).

III. THE NAMING SCHEME FOR HADRONS

A. Introduction

We introduced in the 1986 edition [Particle Data Group (1986)] a new naming scheme for the hadrons. Here we summarize the rules and rationale for the scheme.

The virtues sought after were as follows. The symbols were to be as few and as simple as possible, with those already in common use retained where possible; the symbols were to convey unambiguously the important quantum numbers of the particles they name; and the quark model was to guide the whole scheme, without limiting it. Some compromise between simplicity and long-established usage was unavoidable.

Changes from older terminology affected mainly the heavier mesons made of u, d, and s quarks. Otherwise, the only important change was that the $F^{\pm}$ became the $D_s^{\pm}$. None of the lightest pseudoscalar or vector mesons changed names, nor did the $c\bar{c}$ or $b\bar{b}$ mesons (we do, however, now use χ_c for the $c\bar{c}$ χ states), nor did any of the established baryons. The Summary Tables give both the new and old names whenever a change has occurred.

We follow custom and use spectroscopic names such as $\Upsilon(1S)$ as the primary name for most of those ψ, Υ, and χ states whose spectroscopic identity is known. We continue to use the form $\Upsilon(9460)$ as an alternate, and as the primary name when the spectroscopic identity is not known.

B. "Neutral-flavor" mesons ($S = C = B = T = 0$)

Table I shows the naming scheme for mesons having the strangeness and all heavy-flavor quantum numbers equal to zero. The naming scheme is designed for all mesons, whether ordinary or exotic. First, we assigned names to those states with quantum numbers compatible with being $q\overline{q}$ states. The rows of the Table give the possible $q\overline{q}$ content. The columns give the possible parity/charge-conjugation states, $PC = -+$, $+-$, $--$, and $++$; these combinations correspond one-to-one with the angular-momentum state $^{2S+1}L_J$ of the $q\overline{q}$ system being $^1(L\text{ even})_J$, $^1(L\text{ odd})_J$, $^3(L\text{ even})_J$, or $^3(L\text{ odd})_J$.[§]

The entries in the Table give the particle symbol. The spin J is to be added to the symbol as a subscript except for pseudoscalar and vector mesons, and the mass is added in parentheses for any meson that decays strongly. However, for the lowest mass meson resonances, we sometimes shorten names by writing ρ for $\rho(770)$, etc.

Table I. Symbols for mesons with the strangeness and all heavy-flavor quantum numbers equal to zero.

$J^{PC} =$	0^{-+}, 2^{-+}, …	1^{+-}, 3^{+-}, …	1^{--}, 2^{--}, …	0^{++}, 1^{++}, …
$q\overline{q}$ content $^{2S+1}L_J=$	$^1(L\text{even})_J$	$^1(L\text{odd})_J$	$^3(L\text{even})_J$	$^3(L\text{odd})_J$
$u\overline{d}, u\overline{u} - d\overline{d}, d\overline{u}\ (I = 1)$	π	b	ρ	a
$\left.\begin{array}{l} d\overline{d} + u\overline{u} \\ \text{and/or } s\overline{s} \end{array}\right\}(I = 0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\overline{c}$	η_c	h_c	$\psi^\dagger$	χ_c
$b\overline{b}$	η_b	h_b	Υ	χ_b
$t\overline{t}$	η_t	h_t	θ	χ_t

[†] The J/ψ remains the J/ψ.

Experimental determination of the mass, quark content (where relevant), and quantum numbers I, J, P, and C (or G) of a meson thus fixes its symbol. Conversely, these properties may be inferred unambiguously from the symbol.

If the main symbol cannot be assigned because the quantum numbers are unknown, X is used. Sometimes it is not known whether a meson is mainly the isospin-0 mix of $u\overline{u}$ and $d\overline{d}$ or is mainly $s\overline{s}$; a prime (or symbol ϕ) may be used to distinguish two such mixing states.

Names have been assigned for the anticipated $t\overline{t}$ mesons.

Gluonium states or other mesons that are not $q\overline{q}$ states are, if the quantum numbers are *not* exotic, to be named just as the $q\overline{q}$ mesons are named. Such non-$q\overline{q}$ states will probably be difficult to distinguish from $q\overline{q}$ states and will likely mix with them; that is, our scheme makes no attempt to distinguish the "mostly gluonium" or "mostly $q\overline{q}$" nature of a particle.

An "exotic" meson with quantum numbers that a $q\overline{q}$ system cannot have, namely $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$, will use the same symbol as would an ordinary meson that has all the same quantum numbers as the exotic meson except for the C parity. Then a caret or "hat" is added to the symbol. For example, an isospin-1 0^{--} meson would be a $\widehat{\pi}$, an isospin-0 1^{-+} meson would be an $\widehat{\omega}$.

The results of all this were as follows. None of the lowest mass pseudoscalar or vector mesons (π, η, and η'; ρ, ω, and ϕ) changed names, nor did any of the $c\overline{c}$ or $b\overline{b}$ mesons (except for χ becoming χ_c). Established mesons whose names changed slightly are:

Old name	New name	Old name	New name
$H(1170)$	$h_1(1170)$	$A_2(1320)$	$a_2(1320)$
$B(1235)$	$b_1(1235)$	$f'(1525)$	$f_2'(1525)$
$A_1(1260)$	$a_1(1260)$	$\omega(1670)$	$\omega_3(1670)$
$f(1270)$	$f_2(1270)$		

Established mesons whose names changed completely are:

Old name	New name	Old name	New name
$S(975)$	$f_0(975)$	$A_3(1670)$	$\pi_2(1670)$
$\delta(980)$	$a_0(980)$	$g(1690)$	$\rho_3(1690)$
$D(1285)$	$f_1(1285)$	$\theta(1720)$	$f_2(1720)$
$\epsilon(1400)$	$f_0(1400)$	$X(1850)$	$\phi(1850)$
$E(1420)$	$f_1(1420)$	$h(2030)$	$f_4(2050)$
$\iota(1440)$	$\eta(1440)$		

Note that the $S(975)$, $D(1285)$, $\epsilon(1300)$, $E(1420)$, $\theta(1690)$, and $h(2030)$ all became f mesons; the new scheme reveals that all have $PC = ++$ and are $^3(L\text{ odd})_J$ states.

C. Mesons with nonzero S, C, B, and/or T

Since the strangeness or a heavy flavor is nonzero, none of the mesons here are eigenstates of charge conjugation, and in each of them one of the quarks must be heavier than the other. The rules are:

(1) The main symbol is an upper-case Roman letter indicating the heavier quark as follows:[‡]

$$s \to \overline{K} \qquad c \to D \qquad b \to \overline{B} \qquad t \to T\,.$$

(2) If the lighter quark is not a u or a d quark, its identity is given by a subscript.

(3) If the spin-parity is in the "normal" series, $J^P = 0^+, 1^-, 2^+, \cdots$, a superscript "*" is added.

(4) The spin is added as a subscript unless the meson is a pseudoscalar or a vector.

Thus the pseudoscalar and vector K, K^*, D, D^*, and B mesons did not change names. Established mesons whose names did change were:

Old name	New name	Old name	New name
$Q_1(1270)$	$K_1(1270)$	$L(1770)$	$K_2(1770)$
$Q_2(1400)$	$K_1(1400)$	$K^*(1780)$	$K_3^*(1780)$
$\kappa(1430)$	$K_0^*(1430)$	$K^*(2045)$	$K_4^*(2045)$
$K^*(1440)$	$K_2^*(1440)$	F	D_s

Most notably, the F (the $c\overline{s}$ state) changed to a D_s. However, with the prospect of B_s, B_c, T_s, and similar mesons, there was no consistent and simple alternative. The rules can lead to cumbersome symbols, such as a D_{s2}^*, but such particles are unlikely to be often seen.

D. Baryons

No change has been made to the symbols N, Δ, Λ, Σ, Ξ, and Ω used for 25 years for the baryons made of light quarks (u, d, and s quarks). They tell the isospin and quark content and the same information is conveyed by the symbols used for the baryons containing one or more heavy quarks (c, b, and t quarks). The following system was invented earlier and independently by Hendry and Lichtenberg (1978) and by Samios (1980). The rules are:

(1) Baryons with *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).

(2) Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a heavy quark (not an s quark) its identity is given by a subscript. This nomenclature was already used for the $\Lambda_c(2285)$, $\Sigma_c(2455)$, and $\Lambda_b(5500)$.

(3) Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, etc.

(4) Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.

In short, the total number of u and d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, etc.

IV. PROCEDURES

A. Selection and treatment of data

The Full Listings contain a complete record of all *relevant* data known to us. As a general rule, we do not include results from preprints or conference reports. There are a few exceptions to this exclusion, decided on a case-by-case basis after consultation with the experimenters.

As mentioned earlier, we no longer maintain an archival record of data of historical importance only. We do, however, quote the references of discoveries, even when the data are no longer useful.

If data are included in the Full Listings but not used in calculating or estimating the value given in the Summary Tables, they are listed in a separate section immediately following the data that *are* used. We give explanatory comments in many such cases. Amongst the reasons a measurement might be excluded are the following:

- It is superseded by or included in later results.
- No error is given.
- It is from a preprint or conference report.
- It involves some assumptions we question.
- It has a poor signal-to-noise ratio, low statistical significance, or is otherwise of much poorer quality than other data available.
- It is clearly inconsistent with other results that appear to be more reliable (see discussion in Sec. IV.D below).
- It is not independent of other results.
- It is not the best limit (see below).

In some cases, *none* of the measurements is entirely reliable and no average is calculated. For example, the masses of many of the baryon resonances, obtained from partial-wave analyses, are quoted as a range thought to probably include the true value, rather than as an average with error. This is discussed in the Baryon Full Listings.

For upper limits, we normally quote in the Summary Tables the strongest limit. We do not average or combine upper limits except in a very few cases where they may be re-expressed as measured numbers with Gaussian errors.

As is customary, we assume that antiparticles are the result of operating with CPT on particles, so both share the same spins, masses, and mean lives. The Tests of Conservation Laws Table, following the Summary Tables, lists tests of CPT and other conservation laws.

We use the following indicators in the Full Listings to tell how we get values from the tabulated measurements:

- OUR AVERAGE—From a weighted average of the selected data.
- OUR FIT—From a constrained or overdetermined multiparameter fit of selected data.
- OUR EVALUATION—Not from a direct measurement, but evaluated from measurements of other quantities.
- OUR ESTIMATE—Based on the observed range of the data. Not from a formal statistical procedure.
- OUR LIMIT—For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

B. Criteria for new states

An experimentalist who sees indications of a particle will of course want to know what has been seen in that region in the past. Hence we include in the Full Listings all reported states that, in our opinion, have sufficient statistical merit and that have not been disproved by more reliable data.

We are much more conservative about promoting a particle to the Summary Tables. We include only those reported states that we feel are well established. This judgment is, of course, somewhat subjective; therefore no precise criteria can be defined. For more detailed discussions, see the mini-reviews in the Full Listings. Here we attempt to specify some guidelines.

(a) When energy-independent partial-wave analyses are available (mostly for πN resonances), approximate Breit-Wigner behavior of the amplitude appears to be the most satisfactory test for a resonance. We can check that the Argand plot follows roughly a counterclockwise circle, and that the "speed" of the amplitude also shows a maximum near the resonance energy; further, there should be data well above the resonance, showing that the speed again decreases.

(b) When there are insufficient data to perform energy-independent analyses, one often resorts to energy-dependent partial-wave analyses. In this case, Breit-Wigner behavior is an input. We usually require that resonance solutions be found by several different analyses, preferably in different channels ($\overline{K}N \to \overline{K}N$, $\Sigma\pi$, etc.), before putting the resonance in the Summary Tables.

(c) Particles stable under strong decay, most meson resonances, Ξ resonances, and some other high-mass baryon resonances fall into a category for which no partial-wave analyses exist. In general, we accept such states if they are experimentally reliable, are of high statistical significance, or are observed in several different production processes.

C. Averages and Fits

We divide this discussion on obtaining averages and errors into three sections:

1. Treatment of errors;
2. Unconstrained averaging;
3. Constrained fits.

1. Treatment of errors

In what follows, the "error" δx means that the range $x \pm \delta x$ is intended to be a 68.3% confidence interval about the central value x. We treat this error as if it were Gaussian. Thus, when the error *is* Gaussian, δx is the usual one standard deviation (1σ). Many experimenters now give statistical and systematic errors separately. In such cases, we usually quote both errors, with the statistical error first. For averages and fits, we then add the the two errors in quadrature and use this combined error for δx.

When experimenters quote asymmetric errors $(\delta x)^+$

and $(\delta x)^-$ for a measurement x, the error that we use for that measurement in making an average or a fit with other measurements is a continuous function of these three quantities. When the resultant average or fit $\overline{x}$ is less than $x - (\delta x)^-$, we use $(\delta x)^-$; when it is greater than $x + (\delta x)^+$, we use $(\delta x)^+$. In between, the error that is used is a linear function of x. Since the errors that are used are functions of the result, we iterate to get the final result. Asymmetric output errors are determined from the input errors assuming a linear relation between the input and output quantities.

In fitting or averaging, we do not usually include correlations between different measurements, but we try to select data in such a way as to reduce correlations. When a group improves statistical or systematic errors by further data-taking or analysis, we use only the improved result. The earlier result is either put into the list of measurements that are not used in averages or fits or is omitted entirely.

Correlated errors are, however, treated explicitly when there are a number of results of the form $A_i \pm \sigma_i \pm \Delta$ that have identical systematic errors Δ. In this case, one can first average the $A_i \pm \sigma_i$ and then combine the resulting statistical error with Δ. One obtains, however, the same result by a second procedure, averaging $A_i \pm (\sigma_i^2 + \Delta_i^2)^{1/2}$, where $\Delta_i = \sigma_i \Delta [\sum (1/\sigma_j^2)]^{1/2}$. The second procedure has the advantage that, with the modified systematic errors Δ_i, each measurement may be treated as independent and averaged in the usual way with other data. Therefore, when appropriate, we adopt this procedure, tabulate Δ_i rather than Δ for the systematic error, and include a footnote that this has been done.

2. Unconstrained averaging

To average data, we use a standard weighted least-squares procedure with the addition of a "scale factor" applied to the errors. It is worth noting, however, that a 2σ error might well be somewhat larger than twice a 1σ error, owing to the non-Gaussian character of some sets of real measurements. This is a persistent problem in averaging mildly discrepant measurements.

We begin by assuming that measurements of a given quantity are uncorrelated, and calculate a weighted average and error as

$$\overline{x} \pm \delta\overline{x} = \left(\sum_i w_i\, x_i\right) \Big/ \sum_i w_i \pm \left(\sum_i w_i\right)^{-1/2} ,$$

with

$$w_i = 1/(\delta x_i)^2 , \tag{1}$$

where x_i and δx_i are the value and error reported by the ith experiment, and the sums run over N experiments. We also calculate $\chi^2 = \sum w_i (\overline{x} - x_i)^2$ and compare it with its expectation value, which is $N - 1$ if the measurements obey a Gaussian distribution.

If $\chi^2/(N-1)$ is less than or equal to 1, and there are no known problems with the data, we accept the above results.

If $\chi^2/(N-1)$ is very large, we may choose not to average the data at all. Alternatively, we may quote the calculated average, but then give an educated guess as to the error, a conservative estimate designed to take into account known problems with the data.

Finally, if $\chi^2/(N-1)$ is greater than 1, but not greatly so, we still average the data, but then also do the following:

(a) We try to take account of $\chi^2/(N-1)$ being greater than 1 by scaling up our quoted error of $\delta\overline{x}$ in Eq. (1) by a scale factor S defined as

$$S = \left[\chi^2/(N-1)\right]^{1/2} . \tag{2}$$

Our reasoning is as follows. The large value of the χ^2 is likely to be due to underestimation of errors in at least one of the experiments. Since we do not know which of the errors are underestimated, we assume that they are all underestimated by the same factor S. If we scale up all input errors by this factor, the χ^2 becomes $N - 1$, and of course the output error $\delta\overline{x}$ scales up by the same factor.

When combining data with widely varying errors, we modify this procedure slightly. We evaluate S by using only the experiments with errors that are not much greater than those of the more precise experiments, i.e., only those experiments with errors less than a "ceiling" δ_0, arbitrarily chosen to be

$$\delta_0 = 3N^{1/2}\, \delta\overline{x} .$$

Here $\delta\overline{x}$ is the unscaled error of the mean of all the experiments. This is done because although the low-precision experiments have little influence on the value $\overline{x}$ and $\delta\overline{x}$, they can make significant contributions to the χ^2, and the contribution of the high-precision experiments tends to be obscured by them. Note that if each experiment had the same error δx_i, then $\delta\overline{x}$ would be $\delta x_i/N^{1/2}$, so each individual experiment would be well under the ceiling.

This scaling approach has the property that if there are two values with comparable errors separated by much more than their stated errors (with or without a number of other experiments of lower accuracy), the error on the mean value $\delta\,\overline{x}$ is increased so that it is approximately half the interval between the two discrepant values.

We emphasize that our scaling procedures for *errors* in no way affect central values. In addition, to recover the unscaled error $\delta\overline{x}$, simply divide the quoted error by S.

(b) If, after removing experiments with errors larger than δ_0, the number M remaining is at least three, and $\chi^2/(M-1)$ is greater than 1.25, then we plot in the Full Listings an ideogram to display the pattern of the data. We do not extract numbers from these ideograms; they are intended simply as visual aids. Sometimes only one or two data points lie apart from the main body; other times the data split into two or more groups. The reader can use this information in deciding upon an alternative average. Figure 1 shows such an ideogram.

Each measurement appearing in an ideogram is represented by a Gaussian with a central value x_i, error δx_i, and area proportional to $1/\delta x_i$. The choice of $1/\delta x_i$ for the areas is somewhat arbitrary. With this choice, the center of gravity of the ideogram corresponds to an average that uses weights equal to $1/\delta x_i$ rather than the $(1/\delta x_i)^2$ used in the weighted averages. This may be appropriate for the case in which some experiments have seriously underestimated their systematic errors. However, since for this choice of area the height of the Gaussian for each measurement is proportional to $(1/\delta\, x_i)^2$, the peak position of the ideogram will often favor the high-precision measurements at least as much as does the least-squares average. The 1986 edition [Particle Data Group (1986)] contains a detailed discussion of the

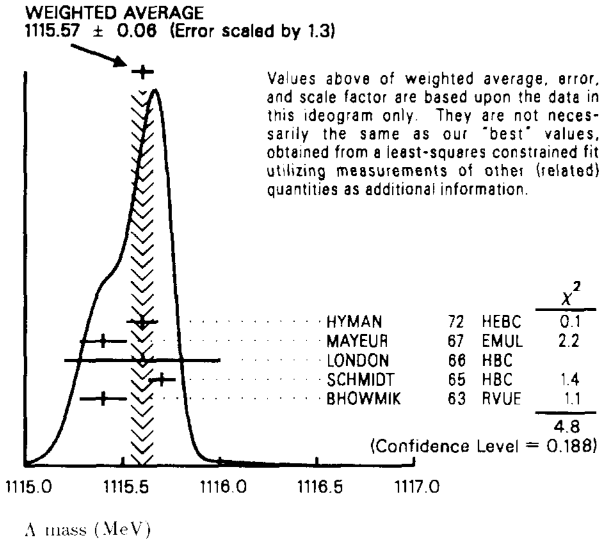

Fig. 1. Ideogram of measurements of the Λ mass. The "data point" at the top shows the position of the weighted average, while the width of the error bar (and the shaded pattern beneath it) shows the error in the average after scaling by the factor S. Only those experiments indicated by + error flags were precise enough to be accepted in the calculation of S; the column on the far right gives the χ^2 contribution of each of these experiments. Less precise experiments would be included in the calculation of the weighted average, but not of S; they would have ⊥ error flags.

motivation behind the use of ideograms.

3. Constrained fits

Except for trivial cases, all branching ratios and rate measurements are analyzed by making a simultaneous least-squares fit to all the data and extracting the partial decay fractions P_i, the partial widths Γ_i, the full width Γ, and the associated error matrix.

Assume, for example, that a state has m partial decay fractions P_i, where $\sum P_i = 1$. These have been measured in N_r different ratios R_r, where, e.g., $R_1 = P_1/P_2$, $R_2 = P_1/P_3$, etc. [We can handle any ratio R of the form $\sum \alpha_i P_i / \sum \beta_i P_i$, where α_i and β_i are constants, usually 1 or 0. The forms $R = P_iP_j$ and $R = (P_iP_j)^{1/2}$ are also allowed.] Further assume that *each* ratio R has been measured by N_k experiments (we designate each experiment with a subscript k, e.g., R_{1k}). We then find the best values of the fractions P_i by minimizing the χ^2 as a function of the $m-1$ independent parameters:

$$\chi^2 = \sum_{r=1}^{N_r}\left[\sum_{k=1}^{N_k}\left(\frac{R_{rk}-R_r}{\delta R_{rk}}\right)^2\right] , \tag{3}$$

where the R_{rk} are the measured values and R_r are the fitted values of the branching ratios.

In addition to the fitted values $\overline{P}_i$, we calculate an error matrix $\langle \delta\overline{P}_i\, \delta\overline{P}_j \rangle$. We tabulate the diagonal elements of $\delta\overline{P}_i = \langle \delta\overline{P}_i\, \delta\overline{P}_i \rangle^{1/2}$ (except that some errors are scaled as discussed below). In the Full Listings we give the complete correlation matrix; we also calculate the fitted value of each ratio, for comparison with the input data, and list it above the relevant input, along with a simple unconstrained average of the same input.

Three comments on the example above:

(1) There was no connection assumed between measurements of the full width and the branching ratios. But often we also have information on partial widths Γ_i as well as the total width Γ. In this case we must introduce Γ as a parameter in the fit, along with the P_i, and we give correlation matrices for the widths in the Full Listings.

(2) We do *not* allow for correlations between input data. We *do* try to pick those ratios and widths that are as independent and as close to the original data as possible. When one experiment measures all the branching fractions and constrains their sum to be one, we leave one of them (usually the least well-determined one) out of the fit to make the set of input data more nearly independent.

(3) We calculate scale factors for both the R_r and P_i when the measurements for any R give a larger-than-expected contribution to the χ^2. According to Eq. (3), the double sum for χ^2 is first summed over experiments $k = 1$ to N_k, leaving a single sum over ratios $\chi^2 = \sum \chi_r^2$. One is tempted to define a scale factor for the ratio r as $S_r^2 = \chi_r^2 / \langle \chi_r^2 \rangle$. However, since $\langle \chi_r^2 \rangle$ is not a fixed quantity (it is somewhere between N_k and N_{k-1}), we do not know how to evaluate this expression. Instead we define

$$S_r^2 = \frac{1}{N_k}\sum_{k=1}^{N_k}\left[\frac{\left(R_{rk}-\overline{R}_r\right)^2}{(\delta R_{rk})^2-(\delta\overline{R}_r)^2}\right] , \tag{4}$$

where $\delta\overline{R}_r$ is the fitted error for ratio r. With this definition the expected value of S_r^2 is one.

The fit is redone using errors for the branching ratios that are scaled by the maximum of S_r and one, from which new and often larger errors $\delta\overline{P}_i'$ are obtained. The scale factors we finally list in such cases are defined by $S_i = \delta\overline{P}_i' / \delta\overline{P}_i$. However, in line with our policy of not letting S affect the central values, we give the values of $\overline{P}_i$ obtained from the original (unscaled) fit.

There is one special case in which the errors that are obtained by the preceding procedure may be changed. When a fitted branching ratio (or rate) $\overline{P}_i$ turns out to be less than three standard deviations $(\delta\overline{P}_i')$ from zero, a new smaller error $(\delta\overline{P}_i'')^-$ is calculated on the low side by requiring the area under the Gaussian between $\overline{P}_i - (\delta\overline{P}_i'')^-$ and $\overline{P}_i$ to be 68.3% of the area between zero and $\overline{P}_i$. A similar correction is done for branching fractions that are within three standard deviations of one. This keeps the quoted errors from overlapping the boundary of the physical region.

D. Discussion

The problem of averaging data containing discrepant values is nicely discussed by Taylor (1982). He considers a number of algorithms that attempt to incorporate inconsistent data into a meaningful average. Problems occur because it is difficult to develop a procedure that handles simultaneously in a reasonable way two basic types of situations: (a) data that lie apart from the main body of the data are incorrect (contain unreported errors); and (b) the opposite (the main body of the data is systematically wrong). Unfortunately, as Taylor shows, case (b) is not infrequent. His conclusion is that the choice of procedure is less significant than the initial choice of data to include or exclude.

We place much emphasis on this choice of data to include or exclude. Unfortunately, the volume of data precludes spending as much time on the problem as we would like. We address this problem by soliciting the help of many outside experts (consultants). In the final analysis, however, it is often impossible to determine which of a set of discrepant measurements are correct. Our scale-factor technique is an attempt to address this ignorance by increasing the error above that suggested by least-squares analysis. In effect, we are saying that present experiments do not allow a precise determination of this constant because of unresolvable discrepancies, and one must await further measurements. The reader is warned of this situation by the size of the scale factor, and can then go back to the literature (via the Full Listings) and redo the average as desired.

Our situation with regard to discrepant data is easier to handle than most of the cases Taylor considers, such as estimates of the fundamental constants like $\hbar$, etc. Most of the errors in his case are dominated by systematic effects. In particle properties data, statistical errors are often at least as large as systematic errors, and statistical errors are usually easier to estimate. A notable exception occurs in partial-wave analyses, where different techniques applied to the same data yield different results. In this case, as stated earlier, we often do not make an average but just quote a range of values.

A brief history of early Particle Data Group averages is given in Rosenfeld (1975). Updated versions of some of Rosenfeld's figures are shown in Fig. 2. The least-squares error is shown by the thick portion of the error bars; the full error bar shows the scale factor extension.

Some cases of rather wild fluctuation are shown. This usually represents the introduction of significant new data or the discarding of some older data. Older data are sometimes discarded in favor of newer data if it is felt that the newer data had smaller systematic errors, had more checks on systematic errors, made corrections unknown at the time of the older experiments, or simply had much smaller total errors. Sometimes near the time at which a large jump takes place, the scale factor becomes large, reflecting the uncertainty introduced by the new and inconsistent data. By and large, a full scan of our history plots shows a rather dull progression toward greater precision at a central value completely consistent with the first data point shown.

We conclude that the reliability of the combination of experimental data and Particle Data Group averaging procedures is usually good, but it is important to realize that fluctuations outside of the quoted errors can and do occur, perhaps with more frequency than would be expected for truly Gaussian errors.

ACKNOWLEDGMENTS

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FOOTNOTES

[‡] Two different conventions exist in the literature for the sign of the flavor of b quarks. We have adopted the convention that *the sign of the flavor of a quark is the same as the sign of its charge.* Thus the strangeness of the s quark is negative, the charm of the c quark is positive, and the bottom of the b quark is negative. In addition, I_3 of the u and d quarks is positive and negative, respectively. The effect of this convention is as follows: Any *flavor* carried by a *charged* meson has the *same* sign as its *charge*. Thus the K^+, D^+, and B^+ have positive strangeness, charm, and bottom, respectively, and all have positive I_3. The D_s^+ has positive charm *and* strangeness. Furthermore, the $\Delta(\text{flavor}) = \Delta Q$ rule, which is best known for the kaons, applies to every flavor.

[§] The relations between the quantum numbers are $P = (-1)^{L+1}, C = (-1)^{L+S}, G = (-1)^{L+S+I}$, where, of course, the C quantum number (charge conjugation) is only relevant to neutral mesons.

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B.N. Taylor, "Numerical Comparisons of Several Algorithms for Treating Inconsistent Data in a Least-Squares Adjustment of the Fundamental Constants," U.S. National Bureau of Standards NBSIR 81-2426 (1982).

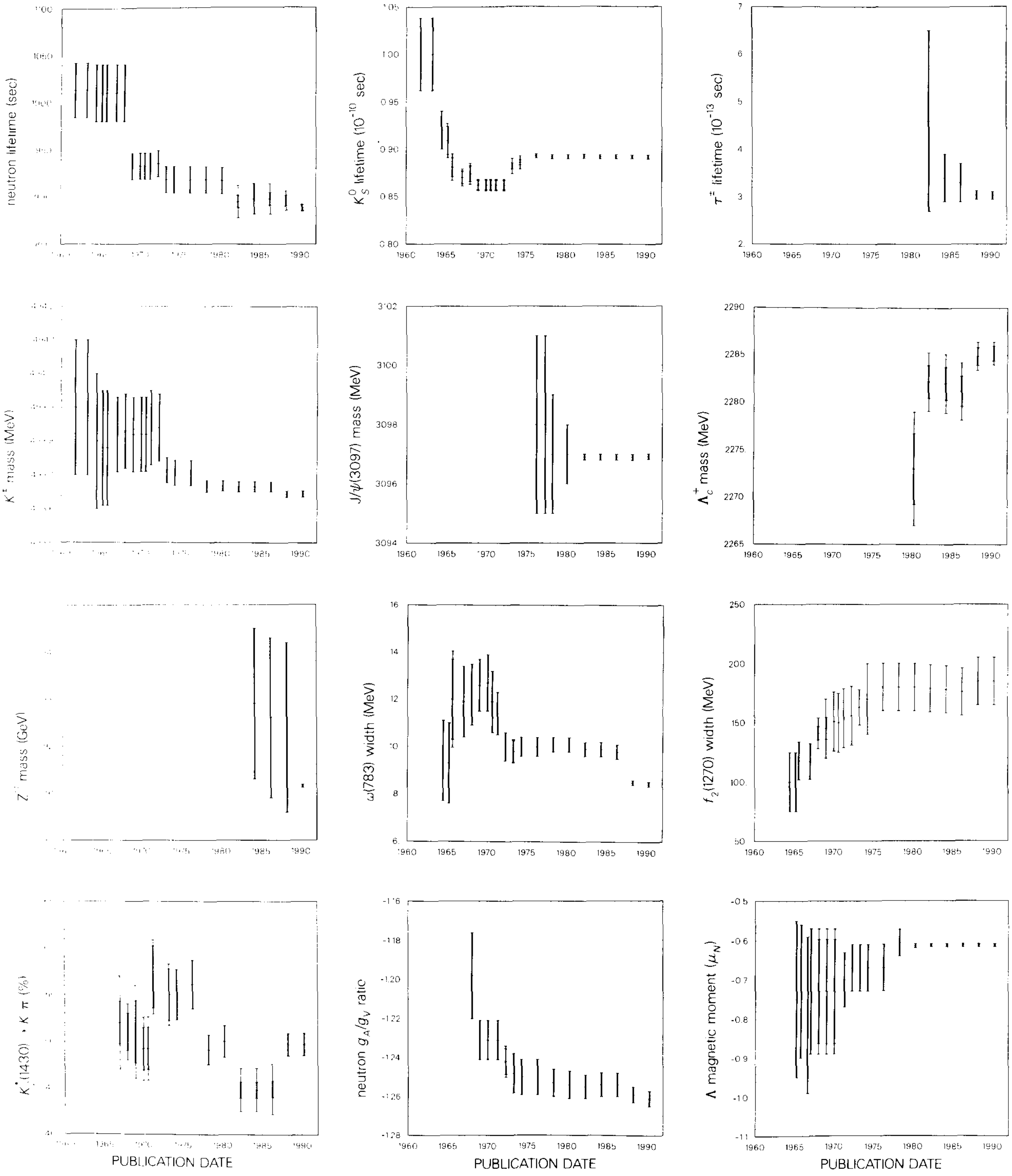

Fig. 2. Historical perspective of a few quantities tabulated in the Review of Particle Properties. The abcissa specifies the date of publication of the Review. Data measured by a variety of different techniques are included. The general reliability of the averages is good; very few are presently more than two standard deviations from their first tabulated values. A full error bar indicates the quoted error; a thick-lined portion indicates the same, but without the "scale factor" (see Sec. IV.C above). Errors with no thick-lined portion are uncertain and represent a best educated guess.

ACCESSING AND USING PARTICLE PHYSICS DATABASES*

Several publicly accessible computer databases exist which contain particle physics information. Some of these allow the user to locate papers of interest, while others contain actual numerical data. The following tells what is available and how to get started using these databases.

The SLAC Particle Physics Databases

The databases of interest at SLAC are:

1. HEP, a guide to particle physics journal articles, preprints, reports, theses, conference papers, etc., indexed by the standard bibliographic quantities as well as by citations and topics. HEP is a joint project of the SLAC and DESY libraries and in April 1990 contained more than 200,000 records.
2. CONF, giving past and future conferences of interest to particle physicists.
3. HEPNAMES, giving electronic-mail addresses of many people working in high-energy physics.
4. INST, giving addresses (including phone and fax numbers) of high-energy physics institutions.
5. DATAGUIDE, an adjunct to HEP, which indexes papers containing experimental data by accelerator, detector, beam momentum, reactions, and particles studied.
6. PARTICLES (formerly RPP), giving the Full Listings from this Review of Particle Properties, indexed by particle and particle property.
7. REACTIONS, giving numerical data (e.g., cross sections, polarizations, etc.) on reactions.
8. EXPERIMENTS, a guide to current and past particle physics experiments, indexed similarly to the HEP and DATAGUIDE databases.

Anyone with a SLAC computing account can access these databases online. If you do not have an account and cannot find anyone who does (at major laboratories, ask at the library), contact SLAC directly. More information on the databases can be found in "A User's Guide to Particle Physics Computer-Searchable Databases on the SLAC-SPIRES System," LBL-19173, available from: Particle Data Group, Lawrence Berkeley Laboratory, Bldg. 50–Rm. 308, Berkeley, CA 94720, USA. A new edition of the "Search Guide to HEP" is available from: Library, SLAC, P.O. Box 4349, Stanford, CA 94309, USA. Or contact Louise Addis at SLAC (ADDIS@SLACVM, tel. 415-926-2411).

QSPIRES Access to SLAC/SPIRES

People without a SLAC computing account can use QSPIRES (see 'NOTE' below) to access the databases at SLAC either interactively via BITNET using the '**tell**' command ('**send**', '**bsend**', or a similar command on some systems) or using electronic mail. Here is an interactive search on HEP; the query is refined as QSPIRES sends responses to your screen:

```
tell QSPIRES@SLACVM FIND TITLE HADRON
(response)
tell QSPIRES@SLACVM AND PION
(response)
tell QSPIRES@SLACVM AND DATE 1988
```

To receive the search result on your screen (≤ 10 records):

```
tell QSPIRES@SLACVM OUTPUT (TYPE
```

Otherwise to receive the search result as a file (via electronic mail):

```
tell QSPIRES@SLACVM OUTPUT PRINT BRIEF
```

You may combine search criteria in a single command (FIND TITLE HADRON AND PION AND DATE 1988), but the command 'OUTPUT PRINT BRIEF' must be separate. Also note that a QSPIRES search defaults to the HEP database. To search another database, like CONF:

```
   tell QSPIRES@SLACVM FIND PLACE VIENNA (IN CONF
   tell QSPIRES@SLACVM OUTPUT PRINT BRIEF
or tell QSPIRES@SLACVM OUTPUT (TYPE
```

Or to access the electronic version of the Review of Particle Properties (results always being returned as mail):

```
tell QSPIRES@SLACVM
    EXPLAIN PARTICLES (IN PARTICLES
tell QSPIRES@SLACVM
    FIND PP ETA MODES (IN PARTICLES
```

For the HEPNAMES and INST databases, you may use the special short-cut searches:

```
tell QSPIRES@SLACVM WHOIS ARMSTRONG,B
tell QSPIRES@SLACVM WHEREIS FERMILAB
```

If your system does not support interactive BITNET communication or is not on the BITNET network, send electronic mail to:

QSPIRES AT SLACVM (for BITNET)
LBL::"QSPIRES@SLACVM.BITNET" (for DECNET)
ST%"QSPIRES@SLACVM.BITNET"(for LBL/DECNET)
QSPIRES%SLACVM.BITNET@LBL.GOV (for Internet)

as in the examples above. You **must** remove the '**tell** QSPIRES@SLACVM' from all messages:

```
FIND PLACE VIENNA (IN CONF
```

Each mail message must contain **only one line**, and the mail 'subject line' must be blank. QSPIRES will send its responses as mail. For other networks, contact your local system manager.

For more information, you can send electronic mail to HEPNAMES@SLACVM and request material on the QSPIRES commands. You can get the 'HELP' file by mailing the command 'HELP' to QSPIRES@SLACVM.

- NOTE: Use of QSPIRES is free. Anyone may use the special short-cut searches for the HEPNAMES and INST databases. Other use of QSPIRES requires that your specific computer node be registered with SLAC; an individual account is **not** required. Send mail to QSPI@SLACVM.BITNET for questions about node registration.

SPIRES HEP Databases at other Institutions

SLAC/DESY HEP and several of the other databases mentioned above are available on SPIRES at DESY, KEK, and Kyoto University, RIFP. Clone copies of HEP are kept current by nightly updates.

Contacts at these institutions are:
DESY—Hartmut Preissner (L00HTP@DHHDESY3);
KEK—Y. Miura (MIURA@JPNKEKVM);
Kyoto University, RIFP—K. Aoki (AOKI@JPNRIFP).

Kyoto also operates a 'remote SPIRES' for Japan.

The CERN Preprint Database

CERN has a database of high-energy preprints, PREP, similar to the SLAC/DESY HEP database. (CERN proposes adding journal articles making their database comparable in scope to HEP.) For information on QALICE, a QSPIRES-like facility for accessing this database, contact Maja Gracco, MGR@CERNVM.BITNET.

The PREP database will also run on an IBM PC (or compatible) using Micro CDS/ISIS, an information storage and retrieval system developed by UNESCO. The system is call MicroPREP and is intended for use in countries without direct access to BITNET or other electronic mail capabilities. For further information, contact Alec Hester, CERN Scientific Information Service, CH-1211 Geneva 23, Switzerland.

The Durham-RAL Particle Physics Databases

These databases contain compilations of experimental particle physics data (e.g., reaction cross sections, polarizations, etc.) and may be searched interactively using VM/CMS on both the Rutherford Appleton Laboratory (RAL) and CERN central computers. The topics include:

(1) two-body (and quasi-two-body) reactions;
(2) hadron and photon one- and two-particle inclusive distributions;
(3) lepton-produced inclusive data (i.e., deep inelastic scattering, structure functions, etc.);
(4) data from e^+e^- annihilations.

A subset of the SLAC/DESY HEP literature-searching guide (from 1980 onwards) is linked to the reaction data to inform users when new data is available. Also available are the EXPERIMENTS and PARTICLES databases from the SLAC system. (See above.)

The databases run under the Berkeley Database Management System and are menu-driven with full on-line help information for easy use. They can be accessed by anyone having network access to the RAL or CERN computers. For PSS access to RAL, the relevant address is 23422351919169, then .2) — a guest account, PDG (password HEPDATA), is available at RAL for those without a CMS account. An EXEC file, HEPDATA, resident on the user-disk (UDISK), gives interactive access to the databases. The data are retrieved using simple keyword-based searches, and resulting data records can be listed on the terminal, sent to a printer, or transferred to the user's own machine as desired.

To insure that the databases are current, experimentalists are urged to send their data to the compilers as soon as they are available.

For more information or a user guide (1988 edition), contact Mike Whalley at Durham University, South Rd., Durham City DH1 3LE, England (MRW@UKACRL or MRW@CERNVM) or Dick Roberts at Rutherford Appleton Lab, Chilton, Didcot, Oxon. OX11 0QX, England (RGR@UKACRL). At CERN, user guides may be obtained from Alec Hester of the CERN library (HES@CERNVM).

The Serpukhov Particle Physics Databases

Many of the databases referred to above are available at Serpukhov, Inst. for High Energy Physics, 142 284 Protvino, Moscow region, USSR. Contact V.V. Ezhela for more information. Copies of the Serpukhov databases also reside on CERNVM.

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* Revised May 1990.

PHYSICAL CONSTANTS

Revised 1989 by B.N. Taylor. Based mainly on the "1986 Adjustment of the Fundamental Physical Constants" by E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the uncertainties in parts per million (ppm) are given in the last column. The uncertainties of the values from a least-squares adjustment are in general correlated, and the laws of error propagation must be used in calculating additional quantities; the full variance matrix is given in the cited paper. The set of constants resulting from the 1986 adjustment has been recommended for international use by CODATA (Committee on Data for Science and Technology), and is the most up-to-date, generally accepted set available.

Quantity	Symbol, equation	Value	Uncert. (ppm)
speed of light	c	299 792 458 m s^{-1}	(exact)*
Planck constant	h	6.626 075 5(40)$\times10^{-34}$ J s	0.60
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 572 66(63)$\times10^{-34}$ J s	0.60
		= 6.582 122 0(20)$\times10^{-22}$ MeV s	0.30
electron charge magnitude	e	1.602 177 33(49)$\times10^{-19}$ C = 4.803 206 8(15)$\times10^{-10}$ esu	0.30, 0.03
conversion constant	$\hbar c$	197.327 053(59) MeV fm	0.30
conversion constant	$(\hbar c)^2$	0.389 379 66(23) GeV^2 mbarn	0.59
electron mass	m_e	0.510 999 06(15) MeV/c^2 = 9.109 389 7(54)$\times10^{-31}$ kg	0.30, 0.59
proton mass	m_p	938.272 31(28) MeV/c^2 = 1.672 623 1(10)$\times10^{-27}$ kg	0.30, 0.59
		= 1.007 276 470(12) u = 1836.152 701(37) m_e	0.012, 0.020
deuteron mass	m_d	1875.613 39(57) MeV/c^2	0.30
unified atomic mass unit (u)	(mass C^{12} atom)/12 = (1 g)/N_A	931.494 32(28) MeV/c^2 = 1.660 540 2(10)$\times10^{-27}$ kg	0.30, 0.59
permittivity of free space	$\left.\begin{matrix}\epsilon_0\\ \mu_0\end{matrix}\right\} \epsilon_0\mu_0 = 1/c^2$	8.854 187 817 ... $\times10^{-12}$ F m^{-1}	(exact)
permeability of free space		$4\pi\times10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times10^{-7}$ N A^{-2}	(exact)
fine structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	1/137.035 989 5(61)†	0.045
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 92(38)$\times10^{-15}$ m	0.13
electron Compton wavelength	$\lambdabar_e = \hbar/m_e c = r_e\alpha^{-1}$	3.861 593 23(35)$\times10^{-13}$ m	0.089
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	0.529 177 249(24)$\times10^{-10}$ m	0.045
wavelength of 1 eV/c particle	hc/e	1.239 842 44(37)$\times10^{-6}$ m	0.30
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	13.605 698 1(40) eV§	0.30
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 246 16(18) barn	0.27
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 382 63(52)$\times10^{-11}$ MeV T^{-1}	0.089
nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 66(28)$\times10^{-14}$ MeV T^{-1}	0.089
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	1.758 819 62(53)$\times10^{11}$ rad s^{-1} T^{-1}	0.30
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	9.578 830 9(29)$\times10^{7}$ rad s^{-1} T^{-1}	0.30
gravitational constant	G_N	6.672 59(85)$\times10^{-11}$ m^3 kg^{-1} s^{-2}	128
		= 6.707 11(86)$\times10^{-39}$ $\hbar c$ $(\text{GeV}/c^2)^{-2}$	128
standard grav. accel., sea level	g	9.806 65 m s^{-2}	(exact)
Avogadro number	N_A	6.022 136 7(36)$\times10^{23}$ mol^{-1}	0.59
Boltzmann constant	k	1.380 658(12)$\times10^{-23}$ J K^{-1}§	8.5
		= 8.617 385(73)$\times10^{-5}$ eV K^{-1}§	8.4
Wien displacement law constant	$b = \lambda_{\max}T$	2.897 756(24)$\times10^{-3}$ m K§	8.4
molar volume, ideal gas at STP	$N_A k$(273.15 K)/(1 atmosphere)	22.414 10(19)$\times10^{-3}$ m^3 mol^{-1}§	8.4
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	5.670 51(19)$\times10^{-8}$ W m^{-2} K^{-4}§	34
Fermi coupling constant	$G_F/(\hbar c)^3$	1.166 37(2)$\times10^{-5}$ GeV^{-2}	17
weak mixing angle	$\sin^2\theta_W$	0.2259±0.0046	
$W^\pm$ boson mass	m_W	80.6±0.4 GeV/c^2	
Z^0 boson mass	m_Z	91.161±0.031 GeV/c^2	

π = 3.141 592 653 589 793 238 $\qquad e$ = 2.718 281 828 459 045 235 $\qquad \gamma$ = 0.577 215 664 901 532 861

1 in ≡ 0.0254 m

1 barn ≡ 10^{-28} m^2

1 eV = 1.602 177 33(49) $\times10^{-19}$ J

1 gauss (G) ≡ 10^{-4} tesla (T)

1 Å ≡ 10^{-10} m

1 dyne ≡ 10^{-5} newton (N)

1 eV/c^2 = 1.782 662 70(54) $\times10^{-36}$ kg

0° C ≡ 273.15 K

1 fm ≡ 10^{-15} m

1 erg ≡ 10^{-7} joule (J)

2.997 924 58 $\times10^{9}$ esu = 1 coulomb (C)

1 atmosphere ≡ 760 torr ≡ 1.013 25 $\times10^{5}$ N/m^2

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* The speed of light is now *defined* to be 299 792 458 m/s. For a discussion, see B.W. Petley, Nature **303**, 373 (1983).

† At $Q^2 = m_e^2$. At Q^2 of order m_W^2 the value is approximately 1/128.

§ Since the 1986 adjustment, new experiments have yielded improved values of the Rydberg constant for R_∞, and also for the gas constant R and hence for quantities derived from it such as the Boltzmann constant k. The new results are R_∞ = 10 973 731.571(4) m^{-1}, k = 1.380 651 3(25) $\times10^{-23}$ J K^{-1} (1.8 ppm) = 8.617 344(15) $\times10^{-5}$ eV K^{-1} (1.7 ppm), b = 2.897 769 4(49) $\times10^{-3}$ m K (1.7 ppm), $N_A k$ = 22.413 992(38) $\times10^{-3}$ m^3 mol^{-1} (1.7 ppm), and σ = 5.670 399(38) $\times10^{-8}$ W m^{-2} K^{-4} (6.8 ppm).

ASTROPHYSICAL CONSTANTS*

Quantity	Symbol, equation	Value
Newtonian gravitational constant	G_N	$6.672\,59(85) \times 10^{-11}$ m^3 kg^{-1} s^{-1}
astronomical unit	AU	$1.495\,978\,706\,6(2) \times 10^{11}$ m
Planck mass	$\sqrt{\hbar c/G_N}$	$1.221\,047(79) \times 10^{19}$ GeV/c^2 $= 2.176\,71(14) \times 10^{-8}$ kg
tropical year (1900)[†]	yr	31 556 925.974 7 s
mean sidereal day		$23^{\rm h}\,56^{\rm m}\,04\overset{\rm s}{.}090\,53$
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,6 \times 10^{16}$ m
light year	ly	$0.306\,6$ pc $= 0.946 \times 10^{16}$ m
solar mass	$M_\odot$	$1.988\,92(25) \times 10^{30}$ kg
Schwarzschild radius of the sun	$2G_N M_\odot/c^2$	2.953 250 074 km
solar luminosity	$L_\odot$	$3.826(8) \times 10^{26}$ J s^{-1}
solar equatorial radius	$R_\odot$	$6.959\,9(7) \times 10^8$ m

Quantity	Symbol	Value
earth equatorial radius	$p_\oplus$	$6.38\,140 \times 10^6$ m
$v_\odot$ around center of galaxy		220 (20) km s^{-1}
solar radius in galaxy		8.5 kpc
local density of matter	$\rho_{\rm local}$	0.3 GeV cm^{-3} $\approx 3 \times 10^4\ \rho_c$
Hubble parameter[‡]	H_0	100 h_0 km s^{-1} Mpc^{-1} $h_0 \times (0.977\,81 \times 10^{10}\,{\rm yr})^{-1}$
normalized Hubble parameter[‡]	h_0	$0.4 < h_0 < 1$
critical density of the universe[‡]	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,273 \times 10^{11}\ h_0^2\ M_\odot$Mpc^{-3} $= 1.878\,82(24) \times 10^{-29}\ h_0^2$ g cm^{-3}
density parameter of the universe[‡]	$\Omega_0 \equiv \rho_0/\rho_c$	$0.05 < \Omega_0 < 4$
cosmological constant	Λ	$\lvert\Lambda\rvert < 3 \times 10^{-52}$ m^{-2}
age of the universe[‡]	t_0	$1.5(5) \times 10^{10}$ yr

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[*] Compiled with the help of K.A. Olive, J. Primack, S. Rudaz, and E. M. Standish, Jr. Some values are taken from C.W. Allen, *Astrophysical Quantities* (Athlone Press, London, 1973) and *The Astronomical Almanac for the year 1990* (U.S. Government Printing Office, Washington, and Her Majesty's Stationery Office, London).

[†] Equinox to equinox; defining constant. The 1990 value is about 0.7 s less.

[‡] Subscript 0 indicates present-day values.

BIG-BANG COSMOLOGY*

All observational evidence to date indicates that our universe is very nearly homogeneous and isotropic. The most general space-time interval with these properties is the Friedmann-Robertson-Walker metric (with $c = 1$):

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right] \ ,$$

where $\kappa = +1,\ -1$, or 0 corresponds to closed, open, or spatially flat geometries; $R(t)$ is a scale factor for distances in comoving coordinates. Einstein's equations lead to the Friedmann equation

$$H^2 \equiv \left(\frac{\dot R}{R}\right)^2 = \frac{8\pi\, G_N\, \rho}{3} - \frac{\kappa}{R^2} + \frac{\Lambda}{3} \ ,$$

as well as to

$$\frac{\ddot R}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}\,(\rho + 3p) \ ,$$

where $H(t)$ is the Hubble parameter, ρ is the total mass-energy density, p is the isotropic pressure, and Λ is the cosmological constant. (For limits on Λ, see the Table of Astrophysical Constants; we will assume here $\Lambda = 0$.) The Friedmann equation serves to define the density parameter Ω_0 (subscript 0 indicates present-day values):

$$\kappa/R_0^2 = H_0^2(\Omega_0 - 1) \ , \qquad \Omega_0 = \rho_0/\rho_c \ ;$$

and the critical density is defined as

$$\rho_c \equiv \frac{3H_0^2}{8\pi\, G_N} = 1.88 \times 10^{-26}\, h_0^2 \ {\rm kg\ m}^{-3} \ ,$$

with

$$H_0 = 100 h_0 \ {\rm km\ s}^{-1}\ {\rm Mpc}^{-1} \ .$$

Observational bounds give $0.4 < h_0 < 1$. The three possible values of κ, $+1$, -1, and 0, correspond to $\Omega_0 > 1$, < 1, and $= 1$, i.e., to closed, open, and flat (critical) universes. The value of Ω_0 is inferred from velocity measurements on scales greater than 100 kpc, which are all consistent with $0.1 \lesssim \Omega_0 \lesssim 0.4$. Conservative bounds are $0.05 \le \Omega_0 \le 4$. The portion of Ω in luminous matter is much smaller, $0.005 \le \Omega_{\rm lum} \le 0.02$. The excess of Ω_0 over $\Omega_{\rm lum}$ leads to the inference that most of the matter in the universe is nonluminous "dark" matter.

Energy conservation implies that $\dot\rho = -3(\dot R/R)\,(\rho + p)$, so that for a matter-dominated ($p = 0$) universe $\rho \propto R^{-3}$, while for a radiation-dominated ($p = 1/3\rho$) universe $\rho \propto R^{-4}$. Thus the less singular curvature term κ/R^2 in the Friedmann equation can be neglected at early times when R is small. Energy conservation also implies that the universe expands adiabatically, $R^3 s$ = constant, where the entropy density $s = (\rho + p)/T$ and T is temperature. The energy density of radiation can be expressed as

$$\rho_r = \frac{\pi^2 k^4}{30}\, N(T) T^4 \ ,$$

with $\hbar = 1$, where $N(T)$ counts the effectively massless degrees of freedom of bosons and fermions:

$$N(T) = \sum_B g_B + \frac{7}{8}\sum_F g_F \ .$$

For example, for $m_\mu > kT > m_e$, $N(T) = g_\gamma + 7/8\,(g_e + 3g_\nu) = 2 + 7/8\,[4 + 3(2)] = 43/4$. For $m_\pi > kT > m_\mu$, $N(T) = 57/4$.

In the early universe when $\rho \sim \rho_r$, then $\dot R \sim 1/R$, so that $R \propto t^{1/2}$ and $Ht \to 1/2$; the time-temperature relation then follows:

$$t = 2.4\,[N(T)]^{-1/2}\left(\frac{1\ {\rm MeV}}{kT}\right)^2 \ {\rm s} \ .$$

Today, the energy density in photons is $\rho_\gamma = (\pi^2 k^4/15)T_0^4$, where the present temperature of the microwave background is $T_0 = 2.73 \pm 0.05$K, and the number density of photons n_γ is $400\,(T_0/2.7\ {\rm K})^3$ cm^{-3}. For nonrelativistic matter (such as baryons) today, the energy density is $\rho_B = m_B n_B$ with $n_B \propto R^{-3}$, so that for most of the history of the universe n_B/s is constant. Today, the entropy density is related to the photon density by $s \approx 7n_\gamma$. Big Bang nucleosynthesis calculations limit $\eta = n_B/n_\gamma$ to $3\times10^{-10} \le \eta \le 10^{-9}$. The parameter η is also related to the portion of Ω in baryons

$$\Omega_B = 3.6 \times 10^7 \eta\, h_0^{-2}\, (T_0/2.7\ {\rm K})^3 \ ,$$

so that $0.01 < \Omega_b\, h_0^2 < 0.04$ and hence the universe cannot be closed by baryons.

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[*] Written December 1985 by K.A. Olive and S. Rudaz.

DARK MATTER*

There is increasing evidence for the existence of large quantities of dark matter in the Universe. The most direct piece of evidence comes from the astronomical observation of the motion of visible matter (stars and regions of neutral hydrogen gas) in galaxies. The observed velocities due to rotational motion in spiral galaxies are measured to be largely independent of the distance to the center of these galaxies. In the absence of any unseen component, we would expect that the velocity falls off with increasing distance, $v^2 \approx G_N\, M_{\rm vis}/r$. In contrast, a flat rotation curve implies a total mass $M_{\rm tot} \approx G_N^{-1}\, v_{\rm obs}^2 r$ [$\approx 10^{11} M_\odot\ (v_{\rm obs}/200\ {\rm km\ s}^{-1})^2\ (r/10\ {\rm kpc})$] in excess of the visible mass $M_{\rm vis}$. It can be inferred from these observations that there exists a dark matter component distributed in a (roughly) spherical halo about the galaxy. The dynamics of groups of galaxies and clusters, as well as the presence of very hot gas in elliptical galaxies require large quantities of unseen matter as well. In addition, theories of cosmological inflation predict that the density parameter of the Universe $\Omega_{\rm tot} = 1$, whereas standard Big Bang nucleosynthesis requires $\Omega_{\rm baryon} \leq 0.1$, implying the existence of nonbaryonic dark matter. Less direct evidence comes from our theoretical understanding of the growth of density perturbations as seeds for galaxy formation. Without the presence of dark matter, it is very difficult to reconcile the existence of galaxies (and quasars) at high redshifts with limits on the anisotropy of the microwave background radiation. Perturbations in baryons can grow only after the time of recombination, i.e. when the baryons decouple from the microwave background. When $\Omega_{\rm tot} = 1$ due to dark matter, matter domination occurs much earlier and dark matter perturbations grow for a longer period thus avoiding a conflict with limits on the anisotropy of the microwave background.

In our own galaxy, the distribution of the visible matter and its observed circular motion determine the local (solar neighborhood) dark matter density $\rho^{\rm DM} \approx 0.3\ {\rm GeV\ cm}^{-3}$. Regardless of the nature of the dark matter, it must behave as a collisionless gas, with a broad velocity distribution (typically assumed to be Maxwellian); $\langle v \rangle \approx \Delta v \approx 300\ {\rm km\ s}^{-1}$ in our galaxy.

We do not know the identity of the dark matter nor whether there is more than one type of dark matter. Baryons are difficult to conceal and in the standard Big Bang model cannot make up all of the dark matter if $\Omega_{\rm tot} = 1$. It is also theoretically unlikely and is not at present observationally motivated that galactic halos could be made of very dim objects. There are several theoretical elementary particle candidates that could explain the existence of dark matter, of which the most commonly discussed are: a neutrino (if massive), a neutralino (from supersymmetry), and the axion (from the strong *CP* problem).

Regardless of the exact identity of the dark matter, its kinetic energy at the time when dark-matter domination begins determines the subsequent evolution of the density perturbations that seed galactic and large structures. If the dark matter is relativistic (hot dark matter, HDM) only the largest (supercluster) structures survive and they must fragment to form galactic structure, whereas if it is nonrelativistic (cold dark matter, CDM), structure on all scales is preserved. The large-scale distribution of matter in N-body simulations of a HDM-dominated universe is not compatible with observations (unless there are point-like density perturbations), whereas a flat CDM-dominated universe requires that the visible matter be predominantly concentrated in the denser regions of the DM distribution (biased galaxy formation).

For a cold dark matter particle species with equal particle (X) and antiparticle ($\overline{X}$) densities (except for the axions), its cosmological density at present is

$$\Omega_X\, h^2 \approx 1.6 \times 10^{-10}\, N_F^{1/2}\, (T_X/T_\gamma)^3$$
$$\times \left(a + \frac{1}{12} b\, \langle v^2 \rangle_f \right)^{-1} \langle v^2 \rangle_f^{-1} \tag{1}$$

with a, b determined from the (velocity averaged) annihilation cross section, expanded in powers of momentum, $\langle v\, \sigma_{X\overline{X}} \rangle = a + \frac{1}{6} b\, \langle v^2 \rangle_f$, at freezeout temperature T_f ($\langle v^2 \rangle_f = 6T_f/M_X$) at which the X's drop from thermal equilibrium (typically $T_f \approx \frac{1}{20} M_X$). In Eq. (1), N_F is the total number of relativistic degrees of freedom at T_f and (T_X/T_γ) is the ratio of the temperatures of X's and photons at T_f. In the halo of our galaxy $\langle v^2 \rangle \sim 10^{-6}$, thus $\langle v\, \sigma_{X\overline{X}} \rangle_{\rm halo}$ and Ω_X are closely related.

Several proposals or experiments exist to detect cold dark matter candidates. In the case of heavy ($M \geq 1$ GeV) particles, elastic scattering from nuclei would produce nuclear recoils with energies of $\gtrsim 1$ keV, and several techniques have been proposed to detect these recoils. The expected collision rate for a target nucleus mass m_N is:

$$R = 4.3\ {\rm kg}^{-1}\ {\rm day}^{-1} \left(\frac{{\rm GeV}^2}{m_N\, m_x} \right) \left(\frac{\sigma_{\rm el}}{10^{-38}\ {\rm cm}^2} \right)$$
$$\times \left(\frac{\rho^{\rm DM}}{0.3\ {\rm GeV\ cm}^{-3}} \right) \left(\frac{\langle |v_E| \rangle}{300\ {\rm km\ s}^{-1}} \right) , \tag{2}$$

where $\langle |v_E| \rangle$ is the average velocity at which they strike the detector. Since crossing symmetry relates $\sigma_{\rm el}$ to $\sigma_{X\overline{X}}$, R is closely related to Ω_X. Dirac neutrinos and sneutrinos with masses 0.012–20 TeV have already been excluded by double-β decay experiments. Axions could be detected by their expected coherent conversion to microwave photons in a tuned cavity. Products of DM annihilation in the halo (e.g., cosmic ray $\overline{p}$'s, e^+'s, γ's) and the core of the Sun (ν's) would indirectly signal the existence of particle DM. The absence of a signal in high energy solar-ν searches using underground detectors rules out sneutrinos whereas cosmic ray searches do not constrain theory so far.

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* Written September 1989 by R. Flores and K.A. Olive.

INTERNATIONAL SYSTEM (SI) NOMENCLATURE

Complete Set of Units

Physical Quantity	Name of Unit	Symbol for Unit	Physical Quantity	Name of Unit	Symbol for Unit
Base units			***Derived units (cont'd)***		
length	meter	m	electric charge	coulomb	C
mass	kilogram	kg	electric potential	volt	V
time	second	s	electric resistance	ohm	Ω
electric current	ampere	A	electric conductance	siemens	S
thermodynamic temperature	kelvin	K	electric capacitance	farad	F
amount of substance	mole	mol	magnetic flux	weber	Wb
luminous intensity	candela	cd	inductance	henry	H
Supplementary units			magnetic flux density	tesla	T
plane angle	radian	rad	luminous flux	lumen	lm
solid angle	steradian	sr	illuminance	lux	lx
Derived units			*activity (of a radioactive source)	becquerel	Bq
frequency	hertz	Hz	*absorbed dose (of ionizing radiation)	gray	Gy
energy	joule	J			
force	newton	N			
pressure	pascal	Pa			
power	watt	W			

See *Quantities, Units, and Symbols*, report of the Symbols Committee of the Royal Society, 2^{nd} ed. (Royal Society, London, 1975).
*See Radioactivity and Radiation Protection Section.

COMMONLY-USED METRIC PREFIXES

10^{-1} deci (d)	10^{-2} centi (c)	10^{-3} milli (m)	10^{-6} micro (μ)	10^{-9} nano (n)	10^{-12} pico (p)	10^{-15} femto (f)	10^{-18} atto (a)
10 deca (da)	10^2 hecto (h)	10^3 kilo (k)	10^6 mega (M)	10^9 giga (G)	10^{12} tera (T)	10^{15} peta (P)	10^{18} exa (E)

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS*

Material	Z	A	Nuclear[a] total cross section σ_T [barn]	Nuclear[b] inelastic cross section σ_I [barn]	Nuclear[c] collision length λ_T [g/cm^2]	Nuclear[c] interaction length λ_I [g/cm^2]	$\left.\frac{dE}{dx}\right\vert_{\text{min}}$ [d] $\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$	Radiation length[e] X_0 [g/cm^2] () is for gas	[cm]	Density[f] [g/cm^3] () is for gas [g/ℓ]	Refractive index n[f] () is $(n-1)\times10^6$ for gas
H_2	1	1.01	0.0387	0.033	43.3	50.8	4.12	61.28	865	0.0708(0.090)	1.112(140)
D_2	1	2.01	0.073	0.061	45.7	54.7	2.07	122.6	757	0.162(0.177)	1.128
He	2	4.00	0.133	0.102	49.9	65.1	1.94	94.32	755	0.125(0.178)	1.024(35)
Li	3	6.94	0.211	0.157	54.6	73.4	1.58	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.61	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.78	42.70	18.8	2.265[g]	—
N_2	7	14.01	0.379	0.265	61.4	87.8	1.82	37.99	47.0	0.808(1.25)	1.205(300)
O_2	8	16.00	0.420	0.292	63.2	91.0	1.82	34.24	30.0	1.14(1.43)	1.22(266)
Ne	10	20.18	0.507	0.347	66.1	96.6	1.73	28.94	24.0	1.207(0.90)	1.092(67)
Al	13	26.98	0.634	0.421	70.6	106.4	1.62	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.66	21.82	9.36	2.33	—
Ar	18	39.95	0.868	0.566	76.4	117.2	1.51	19.55	14.0	1.40(1.78)	1.233(283)
Ti	22	47.88	0.995	0.637	79.9	124.9	1.51	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.48	13.84	1.76	7.87	—
Cu	29	63.55	1.232	0.782	85.6	134.9	1.44	12.86	1.43	8.96	—
Ge	32	72.59	1.365	0.858	88.3	140.5	1.40	12.25	2.30	5.323	—
Sn	50	118.69	1.967	1.21	100.2	163	1.26	8.82	1.21	7.31	—
Xe	54	131.29	2.120	1.29	102.8	169	1.24	8.48	2.77	3.057(5.89)	(705)
W	74	183.85	2.767	1.65	110.3	185	1.16	6.76	0.35	19.3	—
Pt	78	195.08	2.861	1.708	113.3	189.7	1.15	6.54	0.305	21.45	—
Pb	82	207.19	2.960	1.77	116.2	194	1.13	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.09	6.00	≈0.32	≈18.95	—
Air, 20°C, 1 atm. (STP in paren.)					62.0	90.0	1.82	36.66	(30420)	0.001205(1.29)	1.000273(293)
H_2O					60.1	84.9	2.03	36.08	36.1	1.00	1.33
Shielding concrete[h]					67.4	99.9	1.70	26.7	10.7	2.5	—
SiO_2 (quartz)					67.0	99.2	1.72	27.05	12.3	2.64	1.458
H_2 (bubble chamber 26°K)					43.3	50.8	4.12	61.28	≈1000	≈ 0.063[i]	1.100
D_2 (bubble chamber 31°K)					45.7	54.7	2.07	122.6	≈900	≈ 0.140[i]	1.110
H-Ne mixture (50 mole percent)[j]					65.0	94.5	1.84	29.70	73.0	0.407	1.092
Ilford emulsion G5					82.0	134	1.44	11.0	2.89	3.815	
NaI					94.8	152	1.32	9.49	2.59	3.67	1.775
BaF_2					92.1	146	1.35	9.91	2.05	4.89	1.56
BGO ($Bi_4Ge_3O_{12}$)					97.4	156	1.27	7.98	1.12	7.1	2.15
Polystyrene, scintillator (CH)[k]					58.4	82.0	1.95	43.8	42.4	1.032	1.581
Lucite, Plexiglas ($C_5H_8O_2$)					59.2	83.6	1.95	40.55	≈34.4	1.16–1.20	≈ 1.49
Polyethylene (CH_2)					56.9	78.8	2.09	44.8	≈47.9	0.92–0.95	—
Mylar ($C_5H_4O_2$)					60.2	85.7	1.86	39.95	28.7	1.39	—
Borosilicate glass (Pyrex)[ℓ]					66.2	97.6	1.72	28.3	12.7	2.23	1.474
CO_2					62.4	90.5	1.82	36.2	(18310)	(1.977)	(410)
Ethane C_2H_6					55.73	75.71	2.25	45.66	(34035)	0.509(1.356)[m]	(1.038)[m]
Methane CH_4					54.7	74.0	2.41	46.5	(64850)	0.423(0.717)	(444)
Isobutane C_4H_{10}					56.3	77.4	2.22	45.2	(16930)	(2.67)	(1270)
NaF					66.78	97.57	1.69	29.87	11.68	2.558	1.336
LiF					62.00	88.24	1.66	39.25	14.91	2.632	1.392
Freon 12 (CCl_2F_2) gas, 26°C, 1 atm.[n]					70.6	106	1.62	23.7	4810	(4.93)	1.001080
Silica Aerogel[o]					65.5	95.7	1.83	29.85	≈150	0.1–0.3	$1.0+0.25\rho$
NEMA G10 plate[p]					62.6	90.2	1.87	33.0	19.4	1.7	—

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS (Cont'd)

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is ($\kappa$ 1)$\times 10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(253.9)					
He	(64)					
Li			56	0.86	8.55(0°)	0.17
Be		37	12.4	0.436	5.885(0°)	0.38
C		0.7	0.6 4.3	0.165	1375(0°)	0.057
N_2	(548.5)					
O_2	(495)					
Ne	(127)					
Al		10	23.9	0.215	2.65(20°)	0.53
Si	11.9	16	2.8 7.3	0.162		0.20
Ar	(517)					
Ti		16.8	8.5	0.126	50(0°)	
Fe		28.5	11.7	0.11	9.71(20°)	0.18
Cu		16	16.5	0.092	1.67(20°)	0.94
Ge	16.0		5.75	0.073		0.14
Sn		6	20	0.052	11.5(20°)	0.16
Xe						
W		50	4.4	0.032	5.5(20°)	0.48
Pt		21	8.9	0.032	9.83(0°)	0.17
Pb		2.6	29.3	0.038	20.65(20°)	0.083
U			36.1	0.028	29(20°)	0.064

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* Table revised April 1988 by R.W. Kenney. σ_T, σ_I, λ_T, and λ_I are energy dependent. Values quoted apply to high energy range given in footnote *a* or *b*, where energy dependence is weak.

a. σ_{total} at 80 240 GeV for neutrons ($\approx\sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$.

b. $\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{quasielastic}}$; for neutrons at 60 375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

c. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda = A/(N \times \sigma)$, where N is Avogadro's number.

d. For minimum-ionizing protons and pions from Barkas and Berger, *Tables of Energy Losses and Ranges of Heavy Charged Particles*, NASA-SP-3013 (1964). For electrons and positrons see: M.J. Berger and S.M. Seltzer, *Stopping Powers and Ranges of Electrons and Positrons (2^{nd}* Ed.), U.S. National Bureau of Standards report NBSIR 82 2550 A (1982).

e. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium may be found here. Corrections for molecular binding applied for H_2 and D_2. Parentheses refer to gaseous form at STP (0°C, 1 atm.).

f. Values for solids, or the liquid phase at boiling point, except as noted. Values in parentheses for gaseous phase at STP (0°C, 1 atm.). Refractive index given for sodium *D* line.

g. For pure graphite; industrial graphite density may vary 2.1 2.3 g/cm^3.

h. Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN LRL RHEL Shielding exp., UCRL 17841 (1968).

i. Density may vary about ±3%, depending on operating conditions.

j. Values for typical working conditions with H_2 target: 50 mole percent, 29°K, 7 atm.

k. Typical scintillator; e.g., PILOT B and NE 102A have an atomic ratio H/C = 1.10.

ℓ. Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

m. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

n. Used in Čerenkov counters. Values at 26°C and 1 atm. Indices of refraction from E.R. Hayes, R.A. Schluter, and A. Tamosaitis, ANL 6916 (1964).

o. $n(SiO_2) + 2n(H_2O)$ used in Čerenkov counters. ρ = density in g/cm^3. From M. Cantin *et al.*, Nucl. Instr. and Meth. **118**, 177 (1974).

p. G10-plate, typical 60% SiO_2 and 40% epoxy.

PERIODIC TABLE OF THE ELEMENTS

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosph. 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Mangan. 54.93805	26 Fe Iron 55.847	27 Co Cobalt 58.93320	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (98)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.82	50 Sn Tin 118.710	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57–71 Rare Earths	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.96654	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium 226.0254	89–103 Actinides	104 (Rf) (Ruther.)† (261)	105 (Ha) (Hahn.)† (262)	106 (263)	107 (262)	108 (265)	109 (266)									

57 La Lanthan. 138.9055	58 Ce Cerium 140.115	59 Pr Praseody. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (145)	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967

Rare earths
(Lanthanide
series)

89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium (244)	95 Am Americ. (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californ. (251)	99 Es Einstein. (252)	100 Fm Fermium (257)	101 Md Mendel. (258)	102 No Nobelium (259)	103 Lr Lawrenc. (260)

Actinide
series

*Revised 1990.

†Names of elements 104 (Rutherfordium) and 105 (Hahnium) have not been accepted because of conflicting claims of discovery.

The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundance in the earth's surface, relative to the mass of the carbon 12 isotope, which is assigned a mass of exactly 12 unified atomic mass units (u, formerly called amu). Standard errors range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in naturally occurring specimens and in commercially available samples. Numbers in parentheses are mass numbers (the whole number nearest the atomic mass, in u) of the most stable isotope of that element. Some elements without stable nuclides nevertheless exhibit a range of characteristic terrestrial compositions of long-lived radionuclides such that a meaningful atomic weight can be given. Adapted from the Table of Standard Atomic Weights of the Elements, 1987 [*Pure and Applied Chemistry* **60**, 841 (1988)].

ELECTRONIC STRUCTURE OF THE ELEMENTS

The electron configurations and most of the ionization energies below are taken from S. Ruben, *Handbook of the Elements*, 3rd ed. (Open Court, La Salle, IL, 1985). Twenty eight of the ionization energies have been changed slightly to bring them up to date (changes from W.C. Martin and B.N. Taylor of the National Institute of Standards and Technology, January 1990). The electron configuration for, say, iron indicates an argon electronic core (see argon), plus six $3d$ electrons and two $4s$ electrons. The ionization energy is the least energy necessary to remove to infinity one electron from an *atom* of the element.

Element			Electron configuration ($3d^5$ = five $3d$ electrons, etc.)		Ground state $^{2S+1}L_J$	Ionization energy (eV)
1	H	Hydrogen	$(1s)$		$^2S_{1/2}$	13.60
2	He	Helium	$(1s)^2$		$^1S_0$	24.59
3	Li	Lithium	(He) $(2s)$		$^2S_{1/2}$	5.39
4	Be	Beryllium	(He) $(2s)^2$		$^1S_0$	9.32
5	B	Boron	(He) $(2s)^2$ $(2p)$		$^2P_{1/2}$	8.30
6	C	Carbon	(He) $(2s)^2$ $(2p)^2$		$^3P_0$	11.26
7	N	Nitrogen	(He) $(2s)^2$ $(2p)^3$		$^4S_{3/2}$	14.53
8	O	Oxygen	(He) $(2s)^2$ $(2p)^4$		$^3P_2$	13.62
9	F	Fluorine	(He) $(2s)^2$ $(2p)^5$		$^2P_{3/2}$	17.42
10	Ne	Neon	(He) $(2s)^2$ $(2p)^6$		$^1S_0$	21.56
11	Na	Sodium	(Ne) $(3s)$		$^2S_{1/2}$	5.14
12	Mg	Magnesium	(Ne) $(3s)^2$		$^1S_0$	7.65
13	Al	Aluminum	(Ne) $(3s)^2$ $(3p)$		$^2P_{1/2}$	5.99
14	Si	Silicon	(Ne) $(3s)^2$ $(3p)^2$		$^3P_0$	8.15
15	P	Phosphorus	(Ne) $(3s)^2$ $(3p)^3$		$^4S_{3/2}$	10.49
16	S	Sulfur	(Ne) $(3s)^2$ $(3p)^4$		$^3P_2$	10.36
17	Cl	Chlorine	(Ne) $(3s)^2$ $(3p)^5$		$^2P_{3/2}$	12.97
18	Ar	Argon	(Ne) $(3s)^2$ $(3p)^6$		$^1S_0$	15.76
19	K	Potassium	(Ar) $(4s)$		$^2S_{1/2}$	4.34
20	Ca	Calcium	(Ar) $(4s)^2$		$^1S_0$	6.11
21	Sc	Scandium	(Ar) $(3d)$ $(4s)^2$	T	$^2D_{3/2}$	6.56
22	Ti	Titanium	(Ar) $(3d)^2$ $(4s)^2$	r e	$^3F_2$	6.83
23	V	Vanadium	(Ar) $(3d)^3$ $(4s)^2$	a l	$^4F_{3/2}$	6.75
24	Cr	Chromium	(Ar) $(3d)^5$ $(4s)$	n e	$^7S_3$	6.77
25	Mn	Manganese	(Ar) $(3d)^5$ $(4s)^2$	s m	$^6S_{5/2}$	7.43
26	Fe	Iron	(Ar) $(3d)^6$ $(4s)^2$	i e	$^5D_4$	7.90
27	Co	Cobalt	(Ar) $(3d)^7$ $(4s)^2$	t n	$^4F_{9/2}$	7.88
28	Ni	Nickel	(Ar) $(3d)^8$ $(4s)^2$	i t	$^3F_4$	7.64
29	Cu	Copper	(Ar) $(3d)^{10}(4s)$	o s	$^2S_{1/2}$	7.73
30	Zn	Zinc	(Ar) $(3d)^{10}(4s)^2$	n	$^1S_0$	9.39
31	Ga	Gallium	(Ar) $(3d)^{10}(4s)^2$ $(4p)$		$^2P_{1/2}$	6.00
32	Ge	Germanium	(Ar) $(3d)^{10}(4s)^2$ $(4p)^2$		$^3P_0$	7.90
33	As	Arsenic	(Ar) $(3d)^{10}(4s)^2$ $(4p)^3$		$^4S_{3/2}$	9.82
34	Se	Selenium	(Ar) $(3d)^{10}(4s)^2$ $(4p)^4$		$^3P_2$	9.75
35	Br	Bromine	(Ar) $(3d)^{10}(4s)^2$ $(4p)^5$		$^2P_{3/2}$	11.81
36	Kr	Krypton	(Ar) $(3d)^{10}(4s)^2$ $(4p)^6$		$^1S_0$	14.00
37	Rb	Rubidium	(Kr) $(5s)$		$^2S_{1/2}$	4.18
38	Sr	Strontium	(Kr) $(5s)^2$		$^1S_0$	5.69
39	Y	Yttrium	(Kr) $(4d)$ $(5s)^2$	T	$^2D_{3/2}$	6.22
40	Zr	Zirconium	(Kr) $(4d)^2$ $(5s)^2$	r e	$^3F_2$	6.63
41	Nb	Niobium	(Kr) $(4d)^4$ $(5s)$	a l	$^6D_{1/2}$	6.76
42	Mo	Molybdenum	(Kr) $(4d)^5$ $(5s)$	n e	$^7S_3$	7.09
43	Tc	Technetium	(Kr) $(4d)^6$ $(5s)$	s m	$^6D_{9/2}$	7.28
44	Ru	Ruthenium	(Kr) $(4d)^7$ $(5s)$	i e	$^5F_5$	7.36
45	Rh	Rhodium	(Kr) $(4d)^8$ $(5s)$	t n	$^4F_{9/2}$	7.46
46	Pd	Palladium	(Kr) $(4d)^{10}$	i t	$^1S_0$	8.34
47	Ag	Silver	(Kr) $(4d)^{10}(5s)$	o s	$^2S_{1/2}$	7.58
48	Cd	Cadmium	(Kr) $(4d)^{10}(5s)^2$	n	$^1S_0$	8.99

ELECTRONIC STRUCTURE OF THE ELEMENTS (Cont'd)

49	In	Indium	(Kr) $(4d)^{10}(5s)^2$ $(5p)$		$^2P_{1/2}$	5.79
50	Sn	Tin	(Kr) $(4d)^{10}(5s)^2$ $(5p)^2$		$^3P_0$	7.34
51	Sb	Antimony	(Kr) $(4d)^{10}(5s)^2$ $(5p)^3$		$^4S_{3/2}$	8.64
52	Te	Tellurium	(Kr) $(4d)^{10}(5s)^2$ $(5p)^4$		$^3P_2$	9.01
53	I	Iodine	(Kr) $(4d)^{10}(5s)^2$ $(5p)^5$		$^2P_{3/2}$	10.45
54	Xe	Xenon	(Kr) $(4d)^{10}(5s)^2$ $(5p)^6$		$^1S_0$	12.13
55	Cs	Cesium	(Xe) $(6s)$		$^2S_{1/2}$	3.89
56	Ba	Barium	(Xe) $(6s)^2$		$^1S_0$	5.21
57	La	Lanthanum	(Xe) $(5d)$ $(6s)^2$		$^2D_{3/2}$	5.58
58	Ce	Cerium	(Xe) $(4f)^2$ $(6s)^2$	R	$^3H_4$	5.54
59	Pr	Praseodymium	(Xe) $(4f)^3$ $(6s)^2$	a	$^4I_{9/2}$	5.46
60	Nd	Neodymium	(Xe) $(4f)^4$ $(6s)^2$	r	$^5I_4$	5.52
61	Pm	Promethium	(Xe) $(4f)^5$ $(6s)^2$	e	$^6H_{5/2}$	5.55
62	Sm	Samarium	(Xe) $(4f)^6$ $(6s)^2$		$^7F_0$	5.64
63	Eu	Europium	(Xe) $(4f)^7$ $(6s)^2$	e	$^8S_{7/2}$	5.67
64	Gd	Gadolinium	(Xe) $(4f)^7$ $(5d)$ $(6s)^2$	a	$^9D_2$	6.15
65	Tb	Terbium	(Xe) $(4f)^9$ $(6s)^2$	r	$^6H_{15/2}$	5.86
66	Dy	Dysprosium	(Xe) $(4f)^{10}$ $(6s)^2$	t	$^5I_8$	5.94
67	Ho	Holmium	(Xe) $(4f)^{11}$ $(6s)^2$	h	$^4I_{15/2}$	6.02
68	Er	Erbium	(Xe) $(4f)^{12}$ $(6s)^2$	s	$^3H_6$	6.11
69	Tm	Thulium	(Xe) $(4f)^{13}$ $(6s)^2$		$^2F_{7/2}$	6.18
70	Yb	Ytterbium	(Xe) $(4f)^{14}$ $(6s)^2$		$^1S_0$	6.25
71	Lu	Lutetium	(Xe) $(4f)^{14}(5d)$ $(6s)^2$	T	$^2D_{3/2}$	5.43
72	Hf	Hafnium	(Xe) $(4f)^{14}(5d)^2$ $(6s)^2$	r	$^3F_2$	6.83
73	Ta	Tantalum	(Xe) $(4f)^{14}(5d)^3$ $(6s)^2$	a	$^4F_{3/2}$	7.89
74	W	Tungsten	(Xe) $(4f)^{14}(5d)^4$ $(6s)^2$	n	$^5D_0$	7.98
75	Re	Rhenium	(Xe) $(4f)^{14}(5d)^5$ $(6s)^2$	s	$^6S_{5/2}$	7.88
76	Os	Osmium	(Xe) $(4f)^{14}(5d)^6$ $(6s)^2$	i	$^5D_4$	8.7
77	Ir	Iridium	(Xe) $(4f)^{14}(5d)^7$ $(6s)^2$	t	$^4F_{9/2}$	9.1
78	Pt	Platinum	(Xe) $(4f)^{14}(5d)^9$ $(6s)$	i	$^3D_3$	9.0
79	Au	Gold	(Xe) $(4f)^{14}(5d)^{10}(6s)$	o	$2S_{1/2}$	9.23
80	Hg	Mercury	(Xe) $(4f)^{14}(5d)^{10}(6s)^2$	n	$^1S_0$	10.44
81	Tl	Thallium	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)$		$^2P_{1/2}$	6.11
82	Pb	Lead	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^2$		$^3P_0$	7.42
83	Bi	Bismuth	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^3$		$^4S_{3/2}$	7.29
84	Po	Polonium	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^4$		$^3P_2$	8.42
85	At	Astatine	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^5$		$^2P_{3/2}$	9.65
86	Rn	Radon	(Xe) $(4f)^{14}(5d)^{10}(6s)^2(6p)^6$		$^1S_0$	10.75
87	Fr	Francium	(Rn) $(7s)$		$^2S_{1/2}$	3.97
88	Ra	Radium	(Rn) $(7s)^2$		$^1S_0$	5.28
89	Ac	Actinium	(Rn) $(6d)$ $(7s)^2$		$^2D_{3/2}$	5.17
90	Th	Thorium	(Rn) $(6d)^2$ $(7s)^2$		$^3F_2$	6.08
91	Pa	Protactinium	(Rn) $(5f)^2$ $(6d)$ $(7s)^2$	A	$^4K_{11/2}$	5.89
92	U	Uranium	(Rn) $(5f)^3$ $(6d)$ $(7s)^2$	c	$^5L_6$	6.19
93	Np	Neptunium	(Rn) $(5f)^4$ $(6d)$ $(7s)^2$	t	$^6L_{11/2}$	6.27
94	Pu	Plutonium	(Rn) $(5f)^6$ $(7s)^2$	i	$^7F_0$	6.06
95	Am	Americium	(Rn) $(5f)^7$ $(7s)^2$	n	$^8S_{7/2}$	5.99
96	Cm	Curium	(Rn) $(5f)^7$ $(6d)$ $(7s)^2$	i	$^9D_2$	6.02
97	Bk	Berkelium	(Rn) $(5f)^8$ $(6d)$ $(7s)^2$	d	$^8G_{15/2}$	6.23
98	Cf	Californium	(Rn) $(5f)^{10}$ $(7s)^2$	e	$^5I_8$	6.30
99	Es	Einsteinium	(Rn) $(5f)^{11}$ $(7s)^2$	s	$^4I_{15/2}$	6.42
100	Fm	Fermium	(Rn) $(5f)^{12}$ $(7s)^2$		$^3H_6$	6.50
101	Md	Mendelevium	(Rn) $(5f)^{13}$ $(7s)^2$		$^2F_{7/2}$	6.58
102	No	Nobelium	(Rn) $(5f)^{14}$ $(7s)^2$		$^1S_0$	6.65
103	Lr	Lawrencium	(Rn) $(5f)^{14}(6d)$ $(7s)^2$		$^2D_{3/2}$	
104		—	(Rn) $(5f)^{14}(6d)^2$ $(7s)^2$			

HIGH-ENERGY COLLIDER PARAMETERS

e^+e^- Colliders (I)

The numbers here were received from representatives of each collider by mid 1989. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions.

	SPEAR (SLAC)	DORIS (DESY)	CESR (Cornell)	PEP (SLAC)
Physics start date	1972	1973	1979	1980
Maximum beam energy (GeV)	4	5.6	6	15
Injection energy (GeV)	2.5	5.6	6	15
Luminosity (10^{30}cm^{-2}s^{-1})	10 at 3 GeV	33 at 5.3 GeV	100 at 5.3 GeV (200 in 1990)	60
Circumference (km)	0.234	0.288	0.768	2.2
Interaction regions	2	2	2 (→1 in 1990)	1 (6 before 1987)
Particles per bunch (units 10^{10})	15	27	17 (→15 in 1990)	35
Bunches per ring per species	1	1	7 (→14 in 1990)	3
Average beam current per species (mA)	30	35 at 5.3 GeV	73 (→ 130 in 1990)	21
Beam-beam tune shift per crossing (units 10^{-4})	300	$\leq$ 280 (space charge limit at 5.3 GeV)	150–250	550
Filling time (min)	15	1–2	20	15
Luminosity lifetime (hr)	≈ 3	1.0–1.5	3–4	4
Crossing angle (μ rad)	0	0	0	0
Energy spread (units 10^{-3})	1	1.2 at 5 GeV	0.6 at 5.3 GeV	1
Transverse emittance ($10^{-9}\pi$ rad-m)	$H \approx 430$	$\left.\begin{array}{l}H\text{: } 500\\ V\text{: } 5\text{–}50\end{array}\right\}$ at 5 GeV	H: 50 V: 3	$H \approx 120$
RF frequency (MHz)	358	500	500	352
Acceleration period (s)	≤ 100			≤ 100
Bunch length (cm)	$\sigma_z \approx 4$	$\sigma \sim 2$ at 5 GeV	1.7	$\sigma_z = 2$
β^*, amplitude function at interaction point (m)	H: 1.2 V: 0.08	H: 0.64 V: 0.05	H: 1.1 V: 0.015	H: 1.0 V: 0.05
Free space at interaction point (m)	±2.5	±1.2	±2.2 (±0.6 to REC quads)	±3.7 (±7 before 1987)
Beam radius (10^{-6} m)	H: 700 V: 50	$\left.\begin{array}{l}H\text{: } 570\\ V\text{: } \sim 30\end{array}\right\}$ at 5 GeV	H: 500 V: 11	H: 340 V: 14
Utility insertions	18	3	2	5
Length of standard cell (m)	11.4	13.2	16	14.35
Phase advance per cell (deg)	H: 79 V: 90	H: 140 V: 50	45–90 (no standard cell)	H: 56 V: 33
Magnetic length of dipole (m)	2.35	3.2	1.6–6.6	5.4
Dipoles in ring	36	H: 24 V: 8	86	192
Quadrupoles in ring	46	68	106	248
Peak magnetic field (T)	1.1	1.5	$\left.\begin{array}{l}\text{0.3 normal}\\ \text{0.8 high field}\end{array}\right\}$ at 8 GeV	0.36

HIGH-ENERGY COLLIDER PARAMETERS (Cont'd)

e^+e^- Colliders (II)

The numbers here were received from representatives of each collider by mid 1989. Numbers are subject to change, and many are only estimates. Quantities are, where appropriate, r.m.s. H, V, and s.c. indicate horizontal and vertical directions, and superconducting.

	TRISTAN (KEK)	SLC (SLAC)	BEPC (China)	VEPP-4M (Novosibirsk)	LEP (CERN)	VLEPP, INP (Serpukhov)
Physics start date	1987	1989	1989	1990	1989	1996 (1998) ?
Maximum beam energy (GeV)	32	50	1.6 2.8	6	60	500 (1000)
Injection energy (GeV)	8	50	1.1–1.4	2	20	1
Luminosity (10^{30}cm^{-2}s^{-1})	14	1.8×10^{-2}	2 17	50	17	100 (1000)
Circumference or length (km)	3.02	1.45 +1.47	0.2404	0.37	26.66	2×5 (2×10)
Interaction regions	4	1	2	1	4	5
Particles per bunch (units 10^{10})	22	2.4 e^- 1.6 e^+	8	15	41.6	100 (20)
Bunches per ring per species	2	1	1	2	4	1
Average beam current per species (mA)	7	0.0001	15	40	3	0.0016
Beam-beam tune shift per crossing (units 10^{-4})	350		320	500	300	
Filling time (min)	20		40	15	0.25 mA/min	
Luminosity lifetime (hr)	2 3		7	2	5	…
Crossing angle (μ rad)	0	0	0	0	0	0
Energy spread (units 10^{-3})	1.6	2	0.42–0.74	1	1.0	10
Transverse emittance ($10^{-9}\pi$ rad-m)	H:180 at 30 GeV	H: 0.6 V: 0.4	H: 231 V: 8	H: 400 V: 20	H: 52 V: 2.1	H: 2.0 V: 0.0005
RF frequency (MHz)	508.5808		199.53	180	352.2	0.7×10^4 (1.5×10^4)
Acceleration period (s)	120		120	150	80	·
Bunch length (cm)	1.2	0.1	5.2	5	1.8	0.15
β^*, amplitude function at interaction point (m)	H: 1.8 V: 0.1	0.01	H: 1.3 V: 0.085	H: 0.75 V: 0.05	H: 1.75 V: 0.07	0.01 (0.005)
Free space at interaction point (m)	±4.5	±2.8	±2.5	±2	±3.5	…
Beam radius (10^{-6} m)	H: 480 V: 12	2 3	H: 548 V: 26	H: 1000 V: 30	H: 300 V: 12	H: 4 V: 0.07
Utility insertions	8		2	1	2	…
Length of standard cell (m)	16.1	5.2	6.6	7.2	79	1
Phase advance per cell (deg)	60	108	60	65	60	…
Magnetic length of dipole (m)	5.86	2.5	1.6	2	11.66/pair	
Dipoles in ring	264 +8 weak	460+440	40 + 4 weak	78	3280+24 inj. + 64 weak	
Quadrupoles in ring	400		68	150	520+288 + 8 s.c.	
Peak magnetic field (T)	0.47 at 30 GeV	0.597	0.9028	0.6	0.135	

HIGH-ENERGY COLLIDER PARAMETERS (Cont'd)

pp, $\bar{p}p$, and *ep* Colliders

The numbers here were received from representatives of each collider by mid 1989. Numbers are subject to change, and many are only estimates Quantities are, where appropriate, r.m.s. *H*, *V*, and s.c. indicate horizontal and vertical directions, and superconducting.

	S$p\bar{p}$S (CERN)	TEVATRON (Fermilab)	HERA (DESY)	UNK (Serpukhov)	LHC (CERN)		SSC (USA)
Physics start date	1981	1987	1990	1995 ?	1996 ?		1999
Particles collided	$p\bar{p}$	$p\bar{p}$	ep	pp	pp	ep	pp
Maximum beam energy (TeV)	0.315 (0.45 in pulsed mode)	0.9 1.0	e: 0.026 p: 0.82	3	8	e: 0.05 p: 8	20
Injection energy (TeV)	0.026	0.15	e: 0.014 p: 0.040	0.4	0.450	e: 0.02 p: 0.450	2
Luminosity ($10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	3	2 (1989) 7 (1991)	16	400	4×10^4	200	1000, $\beta^* = 0.5$ m 55, $\beta^* = 10$ m
Circumference (km)	6.911	6.28	6.336	20.772	26.659		87.12
Interaction regions	2	2 high $\mathcal{L}$ 2 low $\mathcal{L}$	3	4	4 high $\mathcal{L}$ 2 med $\mathcal{L}$	3	4 max. simultaneous; 8 max. total
Particles per bunch (units 10^{10})	p: 15 $\bar{p}$: 8	p: 7 $\bar{p}$: 3	e: 3.65 p: 10	6	10	e: 8 p: 30	0.80
Bunches per ring per species	6	6	210	1980	4810	540	1.60×10^4
Average beam current per species (mA)	p: 6 $\bar{p}$: 3	p: 3.2 $\bar{p}$: 1.4	e: 58 p: 163	280	865	e: 80 p: 300	71
Beam-beam tune shift per crossing (units 10^{-4})	50	p: 12 $\bar{p}$: 21	e: $190(H), 210(V)$ p: $12(H), 9(V)$	10	34	e: 400 p: 33	$\beta^* = 0.5$ m: 9 head-on, 21 long-range
Filling time (min)	0.5	8	e: 15 p: 20	10	7	40	~60
Luminosity lifetime (hr)	20	15 40	>3	10	15	50	~24
Crossing angle (μ rad)	0	0	0	350	96	0	75
Energy spread (units 10^{-3})	0.35	0.15	e: 0.91 p: 1.3	0.05	0.1	0.1	0.058
Transverse emittance ($10^{-9}\pi$ rad-m)	p: 9 $\bar{p}$: 5	p: 4.3 $\bar{p}$: 3.1	e: $39(H), 2(V)$ p: $7(H), 7(V)$	2	0.45	e: $26(H), 3.4(V)$ p: $0.6(H), 0.6(V)$	0.047
RF frequency (MHz)	200	53	e: 499.7 p: 208.2/52.05	200	400	e: 352 p: 400	360
Acceleration period (s)	10	44		100	1200		1000
Bunch length (cm)	20	50	e: 0.83 p: 7.5	10	7.5		6.0
β^*, amplitude function at interaction point (m)	1 (H) 0.5 (V)	0.50	e: $2(H), 0.70(V)$ p: $10(H), 1.0\ (V)$	1	0.25 high $\mathcal{L}$ 0.5 med $\mathcal{L}$	e: $0.64(H), 0.20(V)$ p: $45(H), 2.8(V)$	0.5 at 2 IR's 10 at 2 IR's
Free space at interaction point (m)	28	±6.5	±5.5	±20	12 high $\mathcal{L}$ 40 med $\mathcal{L}$	20	±20, $\beta^* = 0.5$ m ±120, $\beta^* = 10$ m
Beam radius (10^{-6} m)	p: $95(H), 67(V)$ $\bar{p}$: $70(H), 50(V)$	43	e: $280(H), 37(V)$ p: $265(H), 84(V)$	50	10	230 (H) 57 (V)	4.8, $\beta^* = 0.5$ m 21.7, $\beta^* = 10$ m
Utility insertions		3	4	4	2		2
Length of standard cell (m)	64	59.5	e: 23.5 p: 47	91.8	100		180
Phase advance per cell (deg)	90	67.8	e: 60 p: 90	82.5	90		90
Magnetic length of dipole (m)	6.26	6.12	e: 9.23 p: 8.82	5.8	9.54		Mostly 14.98
Dipoles in ring	744	774	e: 396 p: 416	2194	1760		$\left.\begin{array}{l} H: 8662 \\ V: 276 \end{array}\right\}$ 2 rings
Quadrupoles in ring	232	216	e: 580 p: 280	496	560		2188 } 2 rings
Magnet type	*H* type with bent-up coil ends	s.c. $\cos\theta$ warm iron	e: C-shaped p: s.c., collared, cold iron	s.c.	s.c. 2 in 1 cold iron		s.c. $\cos\theta$ cold iron
Peak magnetic field (T)	1.4 (2 in pulsed mode)	4.4	e: 0.274 p: 4.65	5	10		6.60
p source accum. rate (hr^{-1})	3×10^{10}	2×10^{10}		—			—
Max. no. $\bar{p}$ in accum. ring	9×10^{11}	1×10^{12}			—		

PASSAGE OF PARTICLES THROUGH MATTER*

(1) Maximum energy transfer: The maximum kinetic energy which a point-charge particle with momentum $p = \gamma\beta cM$ can impart to a stationary unbound electron with mass m_e is given by

$$T_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}\ . \tag{1}$$

This kinetic energy appears several times in the following discussion. It is usual[1] to make the "low-energy" approximation $T_{\max} = 2m_ec^2\,\beta^2\gamma^2$, valid for $2\gamma m_e/M \ll 1$. For a pion, the error in this approximation reaches 1% at 20 GeV. On the other hand, if the energy transfer is much in excess of 1 MeV then the impact parameter is less than the "pion radius," so that our point-charge approximation is invalid. We use the approximation with the understanding that form-factor corrections are necessary if the energy transfer is large.

(2) Energy loss rates for ionizing particles: A moderately relativistic charged particle loses energy in matter primarily through ionization. If its velocity is larger than that of orbital electrons ($\sim \alpha c$) and small enough that radiative effects do not dominate, and it is not an electron, then the mean rate of energy loss is given by the Bethe-Bloch equation,[2] which we write as

$$-\frac{dE}{dx} = 4\pi N_A\, r_e^2\, m_ec^2\, z^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_ec^2\gamma^2\beta^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right] \tag{2}$$

for a particle with charge ze passing through an element with atomic number Z and atomic weight A. In this equation m_e is the electron mass, r_e is the classical radius of the electron, and the product $4\pi N_A\, r_e^2\, m_ec^2$ is equal to 0.3071 MeV cm^2 g^{-1}. The ***ionization constant*** I is approximately given by $16\,Z^{0.9}$ eV for $Z > 1$, but measurements and calculations which include atomic configuration effects yield results which differ by as much as 10% from this value. Hydrogen is the most sensitive to atomic effects; $I = 15$ eV for atomic hydrogen, 19.2 eV for H_2 gas, and 21.8 eV for H_2 liquid.[3]

In Eq. (2) dx is measured in mass per unit area, e.g. in g cm^{-2}. Except in hydrogen, particles of the same velocity have very similar rates of energy loss in different materials; there is a slow decrease in the rate of energy loss with increasing Z.

Plots of dE/dx and ranges obtained by integrating $(dE/dx)^{-1}$ are given in another section.

The extended transverse electric field of a relativistic incident particle is shielded by the charge density of atomic electrons, reducing its rate of energy loss. This ***density effect*** is represented by δ in Eq. (2), which for very energetic particles approaches $2\ln\gamma$ plus a constant.[4] As a result, the quantity in the square brackets in Eq. (2) asymptotically increases as $\ln\gamma$ instead of $2\ln\gamma$. The correction depends upon the chemical composition and density of the medium.

The first term in the square brackets of Eq. (2) is given more precisely by $\ln(2m_ec^2\gamma^2\beta^2T_{\max}/I^2)^{1/2}$, and so in the absence of corrections the logarithmic term is in error by a few percent at several hundred GeV. At low incident particle speeds (β/z close to α) atomic shell corrections and higher-order QED corrections also introduce errors of this magnitude. Equation (2) should thus be trusted only to a few percent at any velocity, and the literature should be consulted by those with more demanding needs.[2,5,6]

For particles moving more slowly than atomic electrons the above discussion is inapplicable. At velocities $\alpha z \gtrsim \beta \gtrsim 10^{-3}$ or slightly lower, the total energy loss rate is proportional to β, and non-ionizing nuclear recoil energy loss contributes substantially to the total.[7] For protons in silicon, $|dE/dx| = 61.2\,\beta$ GeV cm^2 g^{-1} for $\beta < 0.005$; the peak occurs at $\beta = 0.0126$, where $|dE/dx| = 522$ MeV cm^2 g^{-1}. In neutron-scattering experiments, light output in scintillator has been observed for recoil protons with energies as low as 30 eV.[8]

At velocities higher than $\sim cz/137$, $|dE/dx|$ initially falls as $1/\beta^2$, to a broad minimum at $\gamma \approx 3.2$, almost independently of the medium. In practical cases most relativistic particles (e.g. cosmic-ray muons) have energy loss rates close to this minimum, and are said to be ***minimum ionizing*** particles, or MIPs. The energy loss rate rises slowly for $\gamma > 4$, with the quantity in the square brackets of Eq. (2) increasing as $2\ln\gamma$. The density effect gradually limits the slope to $\ln\gamma$. Much of the relativistic rise can be attributed to large energy transfers to a few electrons in the medium. If these escape or are otherwise accounted for separately, the energy deposited in an absorbing layer (in contrast to the energy lost during its traversal) approaches a constant value, the ***Fermi plateau***. At extreme energies (e.g. 400 GeV for muons or pions in iron) radiative effects become important. These are especially relvant for high-energy muons, as discussed in Sec. (9).

Energy loss by electrons and positrons has been excluded from this discussion, since radiative effects (bremsstrahlung and pair production) usually contribute more than ionization. This important case is discussed below, and the relative contributions of various electron energy-loss processes in lead are shown in a figure given in the section "Photon and Electron Attenuation Plots."

The quantity $(dE/dx)\delta x$ is the ***mean*** energy loss via interaction with electrons in a layer of the medium with thickness δx. For finite δx, Poisson fluctuations vary the actual energy loss. Landau first remarked that the distribution is skewed toward high values.[9] Only for a very thick layer $[(dE/dx)\delta x \gg 2m_ec^2\,\beta^2\gamma^2]$ is the distribution nearly Gaussian. The large fluctuations in the energy loss are due to a small number of collisions involving large energy transfers. The fluctuations are greatly reduced for the so-called restricted energy loss rate, as discussed below.

In a mixture or compound, the rate of energy loss is approximately

$$\frac{dE}{dx} = \sum f_i\ \left.\frac{dE}{dx}\right|_i\ , \tag{3}$$

where f_i is the fraction by weight of the ith element and $dE/dx|_i$ the mean rate of energy loss (in g cm^{-2}) in this element. Atomic corrections to this additivity rule are discussed in Ref. 3. These are neglected in many widely-used computer codes.

(3) Energetic knock-on electrons (δ rays): For an incident relativistic particle with mass M, the distribution of secondary electrons with kinetic energy $T \gg I$ is given by Rossi[1] as

$$\frac{d^2N}{dTdx} = \frac{1}{2}\,4\pi N_A\, r_e^2\, m_ec^2\, z^2\frac{Z}{A}\frac{1}{\beta^2}\frac{F}{T^2} \tag{4}$$

for $I \ll T \le T_{\max}$, where $T_{\max}$ is given by Eq. (1) above. The factor F is spin-dependent, but is approximately unity for $T \ll T_{\max}$. It is evaluated for spins 0, 1/2, and 1 in Rossi. Other factors in the equation are defined above. For incident electrons, the indistinguishability of projectile and target means that the range of T extends only to half the kinetic energy of the incident particle. Additional formulae are given in Ref. 10. Our formula is inaccurate for T close to I; for $2I \lesssim T \lesssim 10I$, the $1/T^2$ dependence above becomes approximately $T^{-\eta}$, with $3 \lesssim \eta \lesssim 5$.[11]

(4) Restricted energy loss rates for relativistic ionizing particles: Fluctuations in energy loss are primarily due to the production of a few high-energy knock-on electrons. Practical detectors often measure the energy ***deposited*** as distinguished from the energy ***lost***. Since energy is carried off by energetic knock-on electrons, it is more appropriate to consider the mean energy loss for collisions which exclude energy transfers greater than some cutoff $E_{\max}$. The ***restricted energy loss rate*** is given by[2]

$$-\left.\frac{dE}{dx}\right|_{\le E_{\max}} = 4\pi N_A\, r_e^2\, m_ec^2\, z^2\frac{Z}{A}\frac{1}{\beta^2} \times\left[\ln\left(\frac{\sqrt{2m_e\beta^2\gamma^2E_{\max}}}{I}\right) - \frac{\beta^2}{2} - \frac{\delta}{2}\right]\ . \tag{5}$$

This expression is the same as that given by Eq. (2), except that $E_{\max}$ rather than $T_{\max}$ appears in the logarithmic term and β^2 is divided by 2. Distributions about the mean do not exhibit such an extreme "Landau tail" as does the distribution of $-dE/dx$. The density effect causes the restricted energy loss rate to approach a constant, the Fermi plateau value, at asymptotically high energies.

(5) Ionization yields: Physicists frequently relate total energy loss to the number of ion pairs produced near the particle's track. This relation becomes complicated for relativistic particles due to the wandering of energetic knock-on electrons whose ranges exceed the dimensions of the fiducial volume. For a qualitative appraisal of the nonlocality of energy deposition by such modestly energetic knock-on electrons in various media, see Ref. 12. Furthermore, the mean local energy dissipation per local ion pair produced, W, while essentially constant for relativistic particles, increases at slow particle speeds.[13] The numerical value of W for gases can be surprisingly sensitive to trace amounts of various contaminants.[13] In addition to these effects, ionization yields in practical cases may be greatly influenced by such factors as subsequent recombination.[14]

(6) Multiple scattering through small angles: As a charged particle traverses a medium it is deflected by many small-angle scatters. The bulk of this deflection is due to Coulomb scattering from the nuclei and the atomic electrons within the medium, hence the usual identification of this effect as multiple Coulomb scattering. (Note, however, that strong interactions do contribute to the total multiple scattering for hadronic projectiles.) The true Coulomb scattering distribution is well represented by the theory of Molière.[15] It is roughly Gaussian only for small deflection angles, while for large-angle scatters (greater than a few θ_0, defined below) it behaves like Rutherford scattering, having a relatively greater probability than would be the case for a Gaussian distribution. A simpler approach, which may suffice for many applications, is to use a Gaussian approximation for the central 98% of the projected angular distribution, with a width given by[16,17]

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.20 \ln(x/X_0)\Big] \tag{6}$$

where p, βc, and z are the momentum (in MeV/c), velocity, and charge number of the incident particle, and x/X_0 is the thickness of the scattering medium in radiation lengths (defined below). The angle θ_0 is a fit to Molière theory[15] for singly charged particles with $\beta = 1$ for all Z, and is accurate to 11% or better for $10^{-3} < x/X_0 < 100$.

Lynch and Dahl have extended this phenomenological approach, fitting Gaussian distributions to a variable fraction F of the Molière distribution for arbitrary scatterers.[17] They achieve accuracies of 2% or better by these methods.

In this Gaussian approximation, θ_0 has the meaning

$$\theta_0 = \theta^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{2}}\,\theta^{\text{rms}}_{\text{space}} \ . \tag{7}$$

The nonprojected (space) and projected (plane) angular distributions are given approximately[15] by

$$\frac{1}{2\pi\,\theta_0^2}\exp\left\{-\frac{\theta^2_{\text{space}}}{2\theta_0^2}\right\} d\Omega\ , \tag{8}$$

$$\frac{1}{\sqrt{2\pi}\,\theta_0}\exp\left\{-\frac{\theta^2_{\text{plane}}}{2\theta_0^2}\right\} d\theta_{\text{plane}}\ , \tag{9}$$

where θ is the deflection angle. In this approximation, $\theta^2_{\text{space}} \approx (\theta^2_{\text{plane},x} + \theta^2_{\text{plane},y})$, where the x and y axes are orthogonal to the direction of motion, and $d\Omega \approx d\theta_{\text{plane},x}\, d\theta_{\text{plane},y}$. Deflections into $\theta_{\text{plane},x}$ and $\theta_{\text{plane},y}$ are independent and identically distributed.

Other quantities defined in Fig. 1 are sometimes used to describe the amount of multiple Coulomb scattering. The auxiliary quantities ψ_{plane}, y_{plane}, and s_{plane} are given by

$$\begin{aligned}
\psi^{\text{rms}}_{\text{plane}} &= \frac{1}{\sqrt{3}}\,\theta^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{3}}\,\theta_0\ ,\\
y^{\text{rms}}_{\text{plane}} &= \frac{1}{\sqrt{3}}\,x\,\theta^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{3}}\,x\,\theta_0\ ,\\
s^{\text{rms}}_{\text{plane}} &= \frac{1}{4\sqrt{3}}\,x\,\theta^{\text{rms}}_{\text{plane}} = \frac{1}{4\sqrt{3}}\,x\,\theta_0\ .
\end{aligned} \tag{10}$$

All the quantitative estimates in this section apply only in the limit of small $\theta^{\text{rms}}_{\text{plane}}$ and in the absence of large-angle scatters. The random variables s, ψ, y, and θ in a given plane are distributed in a correlated fashion (see the section on Probability, Statistics, and Monte Carlo for the definition of the correlation coefficient). Obviously, $y \approx x\psi$. In addition, y and θ have correlation coefficient $\rho_{y\theta} = \sqrt{3}/2 \approx 0.87$. For Monte Carlo generation of a joint $(y_{\text{plane}}, \theta_{\text{plane}})$ distribution or for other calculations, it may be most convenient to work with independent Gaussian random variables (z_1, z_2) with mean zero and variance one and subsequently set

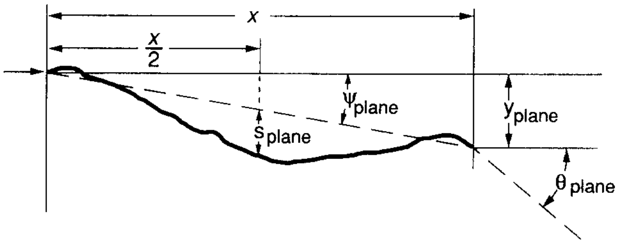

Fig. 1. Quantities useful in describing multiple Coulomb scattering. The particle is incident in the plane of the figure.

$$\begin{aligned}
y_{\text{plane}} &= z_1\, x\, \theta_0 (1 - \rho^2_{y\theta})^{1/2}/\sqrt{3} + z_2\, \rho_{y\theta} x\, \theta_0/\sqrt{3}\\
&= z_1\, x\, \theta_0/\sqrt{12} + z_2\, x\, \theta_0/2\ ; \qquad (11)\\
\theta_{\text{plane}} &= z_2\, \theta_0\ .
\end{aligned}$$

Note that the second term for y_{plane} equals $x\,\theta_{\text{plane}}/2$ and represents the displacement that would have occurred had the deflection θ_{plane} all occurred at the single point $x/2$.

(7) Radiation length and associated quantities: In dealing with electrons and photons at high energies, it is convenient to measure the thickness of the material in units of the radiation length X_0. It is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and in any case it is the appropriate scale length for describing high-energy electromagnetic cascades. X_0 is calculated and tabulated by Y.S. Tsai.[18] His formula is less than straightforward, but can be approximated by [19]

$$X_0 = \frac{716.4\ \text{g cm}^{-2}\, A}{Z(Z+1)\ln(287/\sqrt{Z})}\ . \tag{12}$$

where Z is the atomic number and A the atomic weight of the medium. Results obtained with this formula agree with Tsai's values to better than 2.5% for all elements except helium, where the result is low by about 5%. The radiation length in a mixture or compound, may be approximated by

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i}\ . \tag{13}$$

where f_i and X_i are the fraction by weight and radiation length for the ith element.

Radiative energy losses scale nearly proportionally to incident energy, while the dependence of ionization is only logarithmic. The energy at which the two are equal is called the ***critical energy*** E_c. For electrons it is given approximately by[20]

$$E_c = \frac{800\ \text{MeV}}{Z + 1.2}\ . \tag{14}$$

In an electromagnetic cascade E_c defines the dividing line between shower multiplication and energy dissipation through ionization.

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Molière radius* R_M, given by[21]

$$R_M = X_0\, E_s/E_c\ . \tag{15}$$

where $E_s = \sqrt{4\pi/\alpha}\; m_e c^2 = 21.2$ MeV. The Molière radius in a material containing a weight fraction f_i of the element with critical energy E_{ci} and radiation length X_i is given by

$$\frac{1}{R_M} = \frac{1}{E_s}\sum \frac{f_i\, E_{ci}}{X_i}\ . \tag{16}$$

PASSAGE OF PARTICLES THROUGH MATTER (Cont'd)

For photons of infinite energy, the total e^+e^- pair-production cross section is approximately

$$\sigma = \tfrac{7}{9}(A/X_0 N_A) \ , \tag{17}$$

where A is the atomic weight of the material and N_A is Avogadro's number. This cross section is accurate to within a few percent down to energies as low as 1 GeV; it decreases at lower energies, as shown in the figure "Fractional Energy Loss for Electrons and Positrons in Lead." As the energy decreases a number of other processes become important, as is also shown in the figures "Contributions to the Photon Cross Section in Carbon and Lead."

(8) Electromagnetic cascades: When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and they dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is therefore convenient to introduce the scale variables

$$\begin{aligned} t &= x/X_0 \\ y &= E/E_c \ , \end{aligned} \tag{18}$$

so that distance is measured in units of radiation length and energy in units of critical energy.

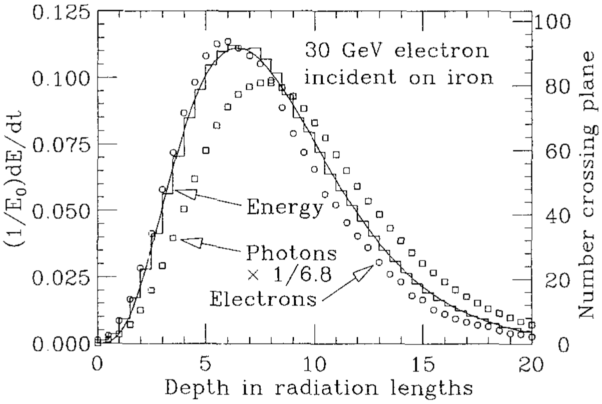

Fig. 2. An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

Longitudinal profiles for an EGS4[22] simulation of a 30 GeV electron-induced cascade in iron are shown in Fig. 2. The number of particles crossing a plane (very close to Rossi's $\prod$ function[1]) is sensitive to the cutoff energy, here chosen as a total energy of 1.5 MeV for both electrons and photons. The electron number falls off more quickly than energy deposition; this is because a larger fraction of the cascade energy is carried by photons with increasing depth. Exactly what a calorimeter measures depends on the device, but it is not likely to be exactly any of the profiles shown. In gas counters it may be very close to the electron number, but in glass Čerenkov detectors and other devices with "thick" sensitive regions it is closer to the energy deposition (total track length). In such detectors the signal is proportional to the "detectable" track length T_d, which is in general less than the total track length T. Practical devices are sensitive to electrons with energy above some detection threshold E_d, and $T_d = T\,F(E_d/E_c)$. An analytic form for $F(E_d/E_c)$ obtained by Rossi[1] is given by Fabjan;[23] see also Amaldi.[24]

The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution:[25]

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1}e^{-bt}}{\Gamma(a)} \tag{19}$$

The maximum $t_{\rm max}$ occurs at $(a-1)/b$. We have made fits to shower profiles in elements ranging from carbon to uranium, at energies from 1 GeV to 100 GeV. The energy deposition profiles are well described by Eq. (19) with

$$t_{\rm max} = (a-1)/b = 1.0 \times (\ln y + C_i) \ , \qquad i = e, \gamma \ , \tag{20}$$

where $C_e = -0.5$ for electron-induced cascades and $C_\gamma = +0.5$ for photon-induced cascades. The results are very similar for the electron number profiles, but there is some dependence on the atomic number of the medium. A similar form for the electron number maximum was obtained by Rossi in the context of his "Approximation B,"[1] (see Fabjan's review in Ref. 23), but with $C_e = -1.0$ and $C_\gamma = -0.5$; we regard this as superseded by the EGS4 result.

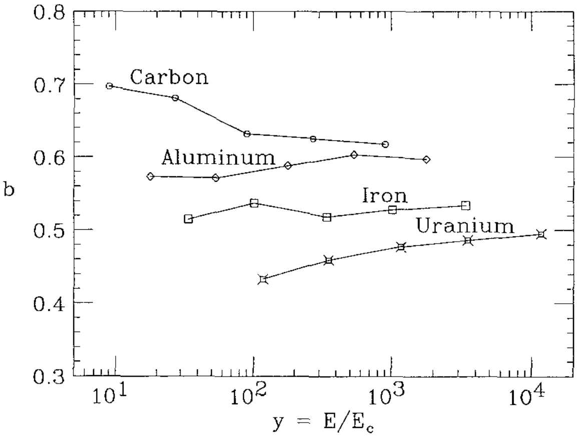

Fig. 3. Fitted values of the scale factor b for energy deposition profiles obtained with EGS4 for a variety of elements for E_0 ranging from 1 GeV to 100 GeV. Fits are for incident electrons, but values for incident photons are essentially the same.

The "shower length" $X_s = X_0/b$ is less conveniently parametrized, since b depends upon both Z and incident energy, as shown in Fig. 3. As corollary of this Z dependence, the number of electrons crossing a plane near shower maximum is underestimated using Rossi's approximation for carbon and seriously overestimated for uranium. Essentially the same b values are obtained for incident electrons and photons.

The gamma distribution is very flat near the origin, while the EGS4 cascade (or a real cascade) increases more rapidly. As a result Eq. (19) fails badly for about the first two radiation lengths; it was necessary to exclude this region in making fits.

Because of the importance of fluctuations, Eq. (19) should be used only in applications where average behavior is adequate. Grindhammer *et al.* have developed fast simulation algorithms in which the variance and correlation of a and b are obtained by fitting Eq. (19) to individually simulated cascades, then generating profiles for cascades using a and b chosen from the correlated distributions.[26]

Measurements of the lateral distribution in electromagnetic cascades are shown in Refs. 21 and 27. On the average only 10% of the energy lies outside the cylinder with radius R_M. About 99% is contained inside of $3.5R_M$, but at this radius and beyond composition effects become important and the scaling with R_M fails. The distributions are characterized by a narrow core, and broaden as the shower develops. They are often represented as the sum of two Gaussians, and Grindhammer describes them with the function

$$f(r) = \frac{2r\,R^2}{(r^2+R^2)^2} \;, \tag{21}$$

where R is a phenomenological function of x/X_0 and $\ln E$.

(9) Muon energy loss at high energy: At sufficiently high energies, radiative processes become more important than ionization for all charged particles. For muons and pions in materials such as iron, this "critical energy" occurs at several hundred GeV. For energetic muons found in cosmic rays or produced at the newest accelerators, radiative effects dominate. These processes are characterized by small cross sections, hard spectra, large energy fluctuations, and the associated generation of electromagnetic and (in the case of photonuclear interactions) hadronic showers. As a consequence, the treatment of energy loss as a uniform and continuous process at these energies is inadequate for many purposes.

It is convenient to write the average rate of muon energy loss as[28]

$$-dE/dx = a(E) + b(E)\,E \;. \tag{22}$$

Here $a(E)$ is the ionization energy loss given by Eq. (2), and $b(E)$ is the sum of e^+e^- pair production, bremsstrahlung, and photonuclear contributions. To the approximation that these slowly-varying functions are constant, the mean range x_0 of a muon with initial energy E_0 is given by

$$x_0 \approx (1/b)\ln(a + bE_0) \;. \tag{23}$$

Contributions to $b(E)$ are shown in Fig. 4 for iron. Since $a(E) \approx 0.002$ MeV g^{-1} cm^2, $b(E)E$ dominates the energy loss above several hundred GeV, where $b(E)$ is nearly constant. The rate of energy loss for muons in hydrogen, uranium, and iron is shown in Fig. 5.[29]

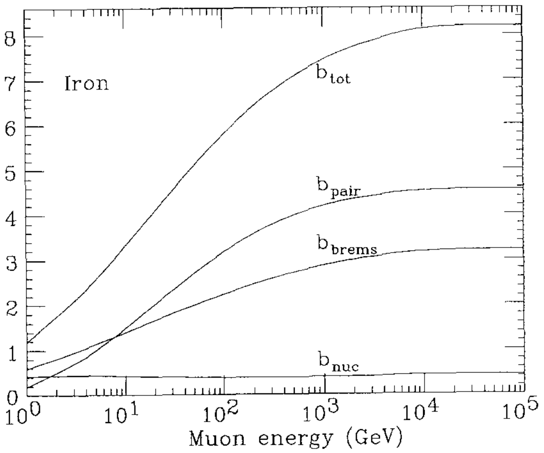

Fig. 4. Contributions to the fractional energy loss by muons due to e^+e^- pair production, bremsstrahlung, and photonuclear interactions in iron, as obtained from Lohmann *et al.*[29]

QED cross sections for bremsstrahlung and e^+e^- pair production have long been known, but were very much improved about 1970 to meet the needs of cosmic ray physics.[30–34] Rozental notes that the screened atomic electron contribution can be included by replacing Z^2 by $Z(Z+1.2)$ in the nuclear bremsstrahlung cross sections and by $Z(Z+1.3)$ in the case of e^+e^- pair production.[35] He also discusses other corrections which might reduce the cross section by as much as 5%, which we take as the present uncertainty. Cross sections for both processes have been evaluated independently by Tsai.[18]

A comparison of various improvements to the Bethe-Heitler formula is given by Wright.[36] For muon energies above 100 GeV, $\mu^+\mu^-$ pair production is also possible. Such $\mu^+\mu^-$ production by muons is a potentially troublesome process because it can lead to charge misassignment, but the mechanism contributes less than 0.01% to the the total energy loss.[29]

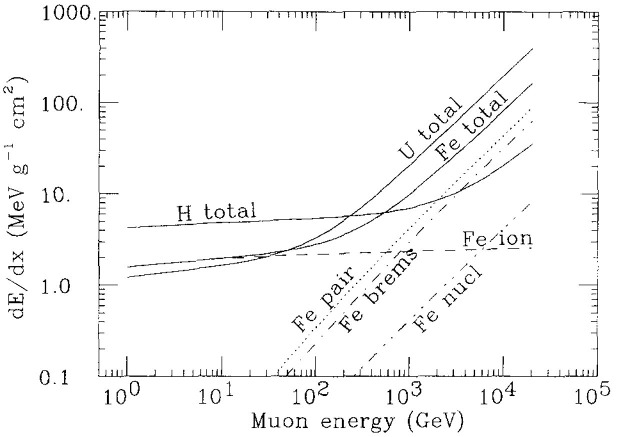

Fig. 5. The average energy loss of a muon in hydrogen, iron, and uranium as a function of muon energy. Contributions to dE/dx in iron from ionization and the processes shown in Fig. 4 are also shown.

Photonuclear interactions account for about 5% of the total energy loss of high-energy muons in iron, and about 2% in uranium.[37] The losses are concentrated in rare, relatively hard events.

These radiative cross sections are expressed as functions of the fractional energy loss ν. The bremsstrahlung cross section goes roughly as $1/\nu$ over most of the range, while in the pair production case the distribution goes as ν^{-3} to ν^{-2} (see Ref. 38). "Hard" losses are therefore more probable in bremsstrahlung, and in fact energy losses due to pair production may very nearly be treated as continuous. The momentum distribution of an incident 1 TeV/c muon beam after it crosses 3 m of iron is shown in Fig. 6. The most probable loss is 9 GeV, or 3.8 MeV $\mathrm{g}^{-1}\mathrm{cm}^2$. The full width at half maximum is 7 GeV/c, or 0.7%. The radiative tail is almost entirely due to bremsstrahlung; this includes most of the 10% which lost more than 2.8% of their energy. Most of the 3.3% which lost more than 10% of their incident energy experienced photonuclear interactions. The latter can exceed nominal detector resolution,[39] necessitating the reconstruction of lost energy. Electromagnetic and hadronic cascades in detector materials can obscure muon tracks in detector planes and reduce tracking efficiency.[40]

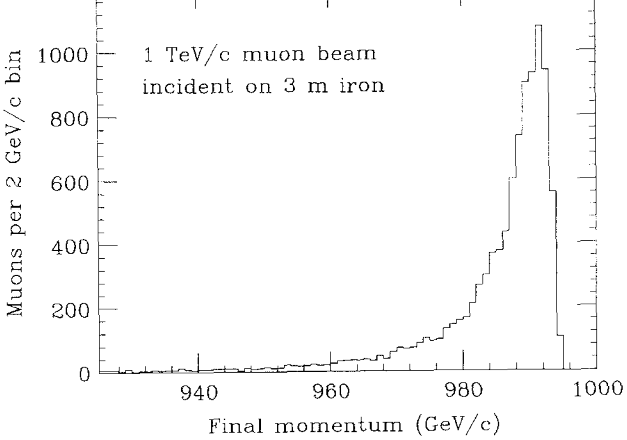

Fig. 6. The momentum distribution of 1 TeV/c muons after traversing 3 m of iron, as obtained with Van Ginniken's TRAMU muon transport code.[38]

PASSAGE OF PARTICLES THROUGH MATTER (Cont'd)

(10) Čerenkov radiation:[41] The half-angle θ_c of the Čerenkov cone for a particle with velocity βc in a medium with index of refraction n is

$$\theta_c = \arccos{(1/n\beta)} \approx \sqrt{2(1-1/n\beta)}\ .$$

The threshold velocity β_t is $1/n$, and $\gamma_t = 1/(1-\beta_t^2)^{1/2}$. Therefore, $\beta_t\gamma_t = 1/(2\delta+\delta^2)^{1/2}$, where $\delta = n-1$. Values of δ for various commonly used gases are given as a function of pressure and wavelength in Ref. 42. For values at atmospheric pressure, see the Table of Atomic and Nuclear Properties.

The number of photons N per cm of path length is given by

$$N = \frac{\alpha}{c}\int\left(1-\frac{1}{\beta^2 n^2}\right)2\pi\ d\nu = \frac{\alpha}{c}\,\beta_t^2\int\left(\frac{1}{\beta_t^2}-\frac{1}{\beta^2}\right)2\pi\ d\nu$$

$$\approx 500\sin^2\theta_c/\text{cm (visible spectrum)}.$$

---

* Revised April 1990 with the help of O. Dahl, R. Hagstrom, W.R. Nelson, and S.I. Parker.

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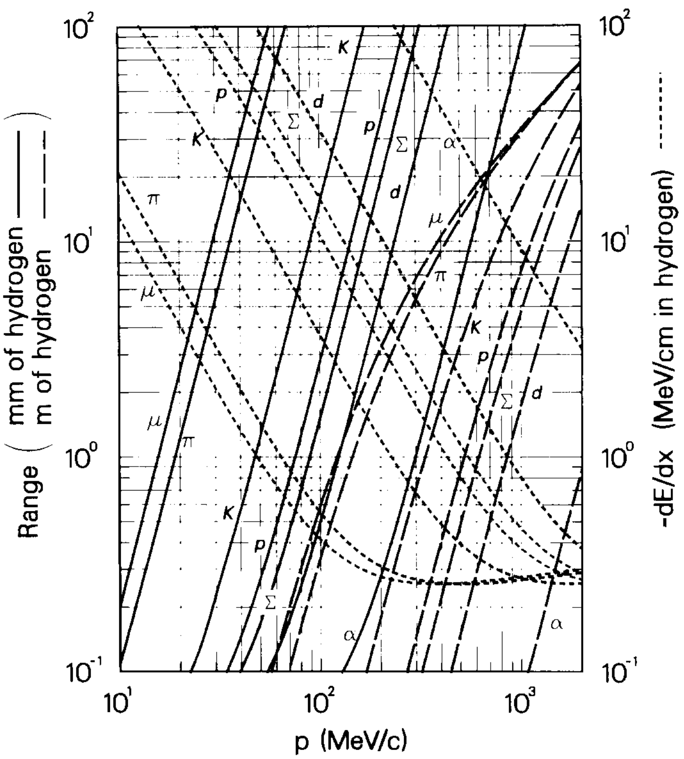
MEAN RANGE AND ENERGY LOSS

Mean Range and Energy Loss in Liquid Hydrogen

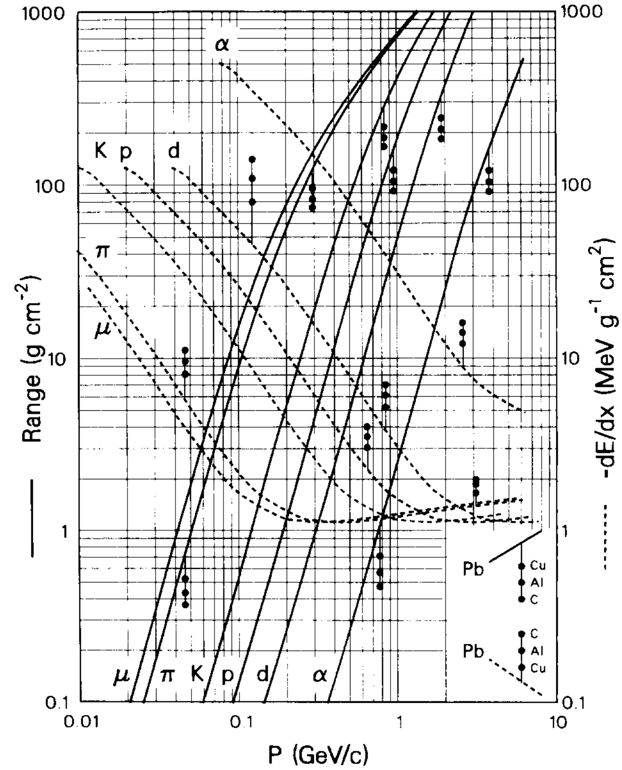


Range and energy loss in liquid hydrogen, based on Bethe-Bloch equation [See Sec. (1) of Passage of Particles Through Matter], using an average ionization potential for H_2 of $I = 20.0$ eV, which is an approximate average of the experimental result of Garbincius and Hyman [Phys. Rev. **A2**, 1834 (1970)] and the theoretical result of Ford and Browne [Phys. Rev. **A7**, 418 (1973)]. Bubble chamber conditions are chosen to be those of Garbincius and Hyman: parahydrogen of density = 0.0625 g/cm^3 (note: range $\propto$ 1/density), with vapor-pressure 60.8 lb/in^2 (absolute) and temperature 26.2°K. The functional dependence of the Bethe-Bloch equation is not experimentally verified to better than about ±1% over large momentum ranges. It should be noted that the number of bubbles per cm of a track in a bubble chamber is nearly proportional to $1/\beta^2$, not dE/dx. For the linear portions of the range curves, $R \propto p^{3.6}$. ***Scaling law for particles of other mass or charge*** *(except electrons)*: for a given medium, the range R_b of any beam particle with mass M_b, charge z_b, and momentum p_b is given in terms of the range R_a of any other particle with mass M_a, charge z_a, and momentum $p_a = p_b M_a / M_b$ (i.e., having the same velocity) by the expression:

$$R_b\,(M_b,\ z_b,\ p_b) =$$

$$\left(\frac{M_b/M_a}{z_b^2/z_a^2}\right) R_a\,(M_a,\ z_a,\ p_a = p_b M_a/M_b)\ .$$

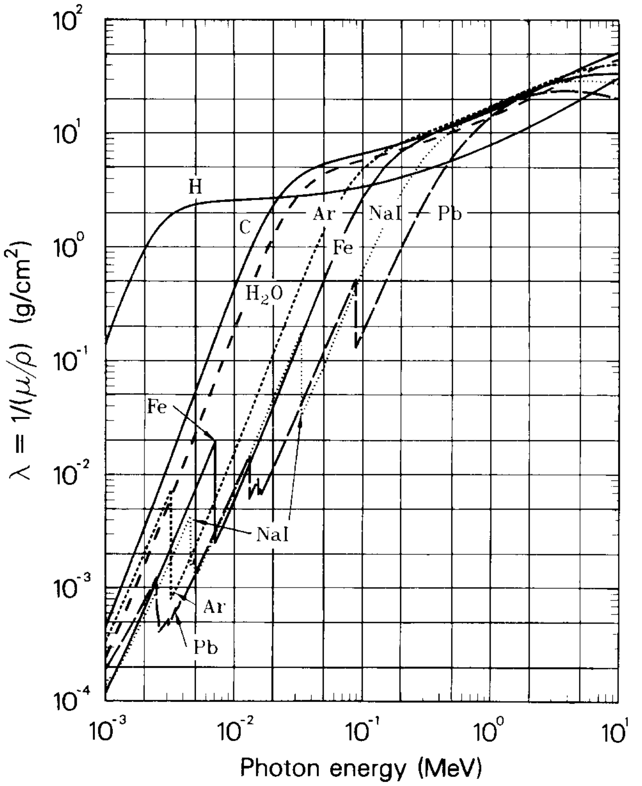
Mean Range and Energy Loss in Lead, Copper, Aluminum, and Carbon



Mean range and energy loss due to ionization for the indicated particles in Pb, with scaling to Cu, Al, and C indicated, using Bethe-Bloch equation [See Sec. (1) of Passage of Particles Through Matter] with corrections. Calculated by M.J. Berger, using ionization potentials and density effect corrections as discussed in M.J. Berger and S.M. Seltzer, "Stopping Powers and Ranges of Electrons and Positrons," (2^{nd} ed.). U.S. National Bureau of Standards Report NBSIR 82-2550-A (1982). The average ionization potentials (I) assumed were: Pb (823 eV), Cu (322 eV), Al (166 eV), and C (78.0 eV). Figure indicates total path length; observed range may be smaller (by ~ 1–2% in heavy elements) due to multiple scattering, primarily from small energy-loss collisions with nuclei. The functional forms have not been experimentally verified to better than roughly ±1%. For higher energies refer to discussion by Cobb ["A Study of Some Electromagnetic Interactions of High Velocity Particles with Matter," University of Oxford Report HEP/T/55 (1973)] and by Turner ["Penetration of Charged Particles in Matter: A Symposium," National Academy of Sciences, Washington D.C. (1970), p. 48]. For lower energies neither data nor theory are well understood. Scaling to other beam particles is, to a good approximation, described by the formula in the previous figure caption.

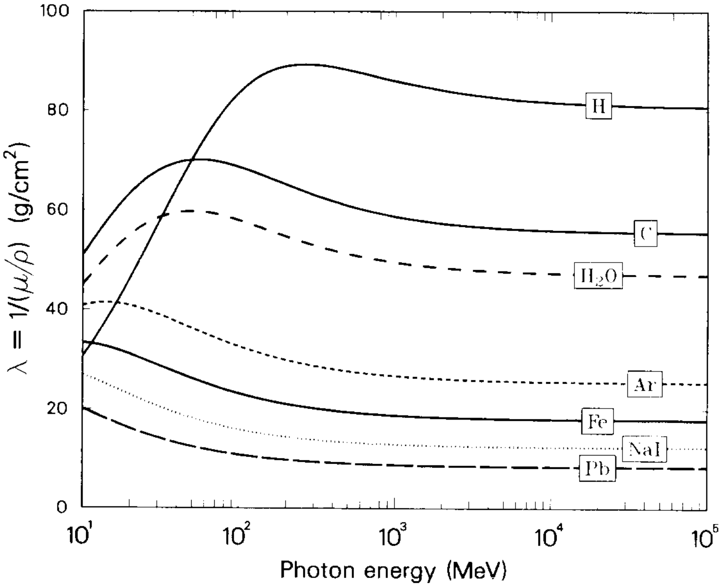
PHOTON AND ELECTRON ATTENUATION

Photon Attenuation Length



The photon mass attenuation length $\lambda = 1/(\mu/\rho)$ (also known as mfp, mean free path) for various absorbers as a function of photon energy, where μ is the mass attenuation coefficient. For a homogeneous medium of density ρ, the intensity I remaining after traversal of thickness t is given by the expression $I = I_0 \exp(-t\rho/\lambda)$. The accuracy is a few percent. Interpolation to other Z should be done in the cross section $\sigma = A/\lambda N_A$ cm^2/atom, where A is the atomic weight of the absorber material in grams and N_A is the Avogadro number. For a chemical compound or mixture, use $(1/\lambda)_{\text{eff}} \approx \sum w_i(1/\lambda)_i$, accurate to a few percent, where w_i is the proportion by weight of the i^{th} constituent. See next page for high energy range. The processes responsible for attenuation are given in a following figure. Not all of these processes necessarily result in detectable attenuation. For example, coherent Rayleigh scattering off an atom may occur at such low momentum transfer that the change in energy and momentum of the photon may not be significant. From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (1980). See also J.H. Hubbell, Int. J. of Applied Rad. and Isotopes **33**, 1269 (1982). Data courtesy J.H. Hubbell.

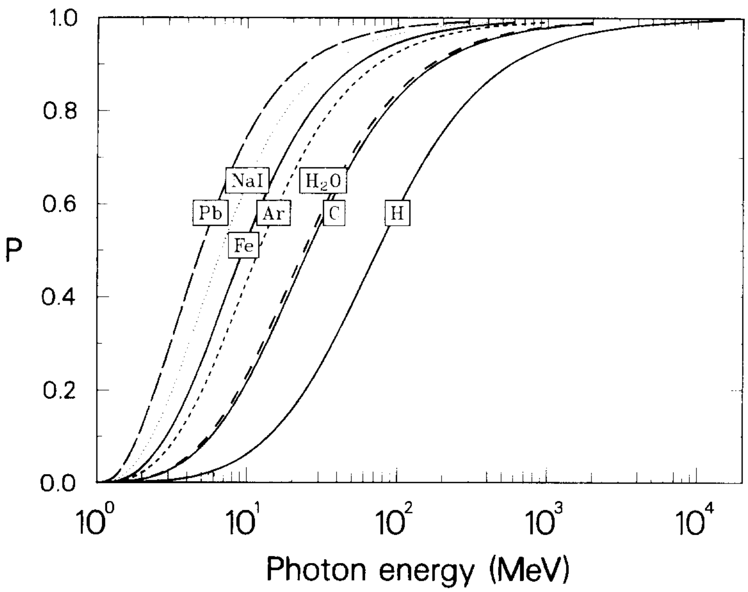
Photon Attenuation Length (High Energy)



The photon mass attenuation length, high energy range (note that ordinate is linear scale). See previous figure caption for details. The attenuation length is constant beyond the range shown for at least two decades in energy.

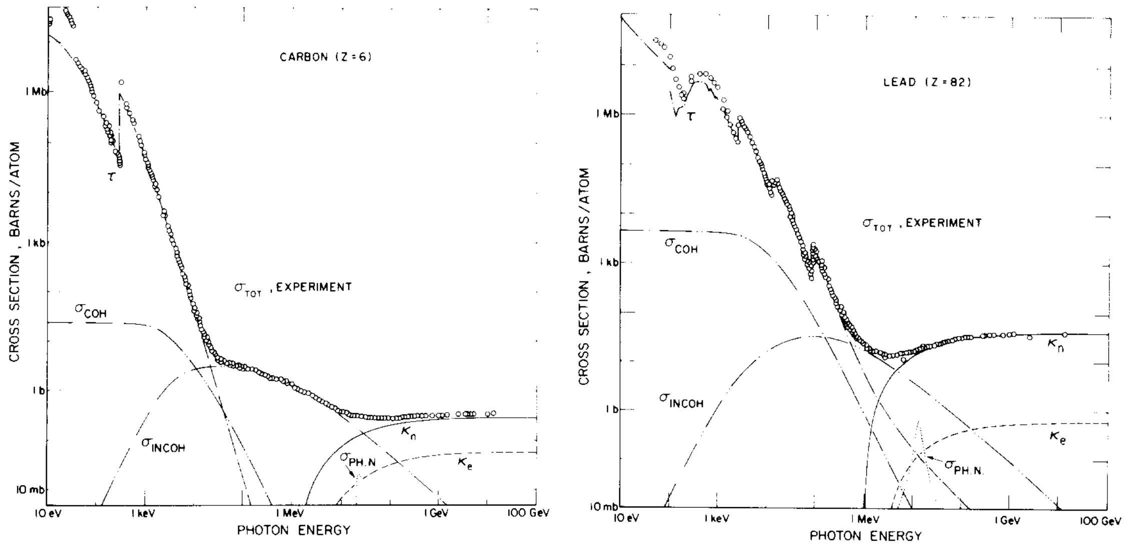
PHOTON AND ELECTRON ATTENUATION (Cont'd)

Photon Pair Conversion Probability



Probability P that a photon interaction will result in conversion to an e^+e^- pair. Except for a few-percent contribution from photonuclear absorption around 10 or 20 MeV, essentially all other interactions result in Compton scattering off an atomic electron. For a photon attenuation length λ (g/cm^2) (upper figure), the probability that a given photon will produce an electron pair (without first Compton scattering) in thickness t (cm) of absorber of density ρ (g/cm^3) is $P[1 - \exp(-t\rho/\lambda)]$.

Contributions to Photon Cross Section in Carbon and Lead



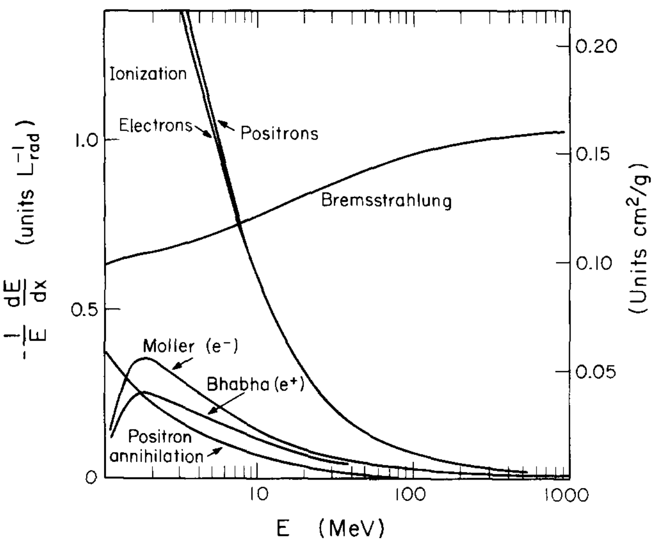
Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes.

τ = Atomic photo-effect (electron ejection, photon absorption)
σ_{COH} = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)
σ_{INCOH} = Incoherent scattering (Compton scattering off an electron)
κ_n = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{PH.N.}$ = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data 9, 1023 (1980). The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell.

PHOTON AND ELECTRON ATTENUATION (Cont'd)

Fractional Energy Loss for Electrons and Positrons in Lead



Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Moller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $L_r(\text{Pb}) = 5.82\ \text{g/cm}^2$, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials, namely $L_r(\text{Pb}) = 6.4\ \text{g/cm}^2$. The development of electron-photon cascades is approximately independent of absorber when the results are expressed in terms of inverse radiation lengths (i.e., scale on left of plot).

COSMIC RAY FLUXES*

The fluxes of particles of different types depend at the $\sim$ 10% level on the latitude, their energy, and the conditions of measurement. Some typical sea-level values[1] for charged particles are given below:

I_v flux per unit solid angle per unit horizontal area about vertical direction

$\equiv j(\theta = 0, \phi)[\theta = \text{zenith angle}, \phi = \text{azimuthal angle}]$;

J_1 total flux crossing unit horizontal area from above

$$\equiv \int_{\theta\le\pi/2} j(\theta,\phi)\ \cos\theta\ d\Omega\ [d\Omega = \sin\theta\ d\theta\ d\phi]\ ;$$

J_2 total flux from above (impinging on a sphere of unit cross-sectional area)

$$\equiv \int_{\theta\le\pi/2} j(\theta,\phi)\ d\Omega\ .$$

	Total Intensity	Hard Component	Soft Component
I_v	1.1×10^2	0.8×10^2	$0.3 \times 10^2\ \text{m}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$
J_1	1.8×10^2	1.3×10^2	$0.5 \times 10^2\ \text{m}^{-2}\ \text{sec}^{-1}$
J_2	2.4×10^2	1.7×10^2	$0.7 \times 10^2\ \text{m}^{-2}\ \text{sec}^{-1}$

Very approximately, about 75% of all particles at sea level are penetrating, and are muons (the dominant portion of the hard component at sea level). The sea-level vertical flux ratio for protons to muons (both charges together) is about 3.5% at 1 GeV/c, decreasing to about 0.5% at 10 GeV/c.

The muon flux at sea level has a mean energy of 2 GeV and a differential spectrum falling as E^{-2}, steepening smoothly to $E^{-3.6}$ above a few TeV. The angular distribution is $\cos^2\theta$, changing to $\sec\theta$ at energies above a TeV, where θ is the zenith angle at production. The ± charge ratio is 1.25–1.30. The mean energy of muons originating in the atmosphere is roughly 300 GeV at slant depths $\gtrsim$ a few hundred meters. Beyond slant depths of $\sim$ 10 km water-equivalent, the muons are due primarily to in-the-earth neutrino interactions (roughly 1/8 interaction $\text{ton}^{-1}\ \text{year}^{-1}$ for $E_\nu > 300$ MeV, $\sim$ constant throughout the earth).[2] Muons from this source arrive with a mean energy of 20 GeV, and have a flux of $2 \times 10^{-9}\ \text{m}^{-2}\ \text{sec}^{-1}\ \text{sterad}^{-1}$ in the vertical direction and about twice that in the horizontal,[3] down at least as far as the deepest mines.

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* Updated April 1986.

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PARTICLE DETECTORS*

In this section we give various parameters for common detector components. The quoted numbers are usually based on typical devices, and should be regarded only as rough approximations for new designs. A more detailed discussion of detectors can be found in Ref. 1. In Table 1 are given typical spatial and temporal resolutions of common detectors.

Table 1. Typical detector characteristics.

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	$\geq$ 300 μm[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator		150 ps	10 ns
Emulsion	1 μm		
Silicon strip	2.5 μm	[e]	[e]

[a] Multiple pulsing time.

[b] 300 μm is for 1 mm pitch.

[c] Delay line cathode readout can give ± 150 μm parallel to anode wire.

[d] For two chambers.

[e] Limited at present by noise and readout time of attached electronics.

(1) Scintillators: The photon yield in the frequency range of practical photomultiplier tubes is $\approx 1\gamma$ per 100 eV of charged particle ionization energy loss in plastic scintillator[2] and as given in Table 2 for some common inorganic scintillators.

In addition to the photon yield, one must take into account the light collection efficiency ($\lesssim 10\%$ for typical 1-cm-thick scintillator), the attenuation length (1 to 4 m for typical scintillators[3]), and the quantum efficiency of the photomultiplier cathode ($\lesssim 25\%$ when folded with a typical scintillator emission spectrum).

Table 2. Properties of four inorganic scintillators[2,4–9]

	BaF_2	BGO	NaI(Tl)	CsI(Tl)
Density (g/cm^3)	4.9	7.1	3.7	4.53
Radiation length (cm)	2.1	1.1	2.6	1.85
dE/dx (for MIP) (MeV/cm)	6.6	9.0	4.8	5.6
Peak emission (nm)	220[a] (310)	480	410	565
Decay constant (ns)	0.6 (620)	300	250	1000[b]
Index of refraction	1.56	2.15	1.85	1.80
Light yield (photons/MeV)[c]	2000 (6500)	2800	4000	4250
Hygroscopic	slightly	no	very	somewhat

[a] First number is for fast component, second (in parenthesis) for the slow component.

[b] Undoped CsI has time constants 10 ns and 36 ns.

[c] Obtained under "good" conditions; not necessarily comparable between columns. Under ideal conditions (small, high-quality crystals shaped for good light collection, *etc.*), yields 4–10 times higher have been obtained[10].

(2a) Electromagnetic shower detectors: The development of electromagnetic showers is discussed in the "Passage of Particles Through Matter" section. Formulae are given for the approximate description of average showers, but since the physics of electromagnetic showers is well understood, detailed and reliable Monte Carlo simulation is possible. EGS4 has emerged as the standard.[11]

The resolution of sampling calorimeters (hadronic and electromagnetic) is usually dominated by sampling fluctuations, leading to fractional resolution σ/E scaling inversely as the square root of the incident energy. Homogenous calorimeters, such as solid NaI(Tl), will in general not have resolution varying as $1/\sqrt{E}$. At high energies deviations from $1/\sqrt{E}$ occur because of noise, pedestal fluctuations, nonuniformities, calibration errors, and incomplete shower containment. Such effects are usually included by adding a constant term to σ/E, either in quadrature or (incorrectly) directly. In the case of the hadronic cascades discussed below, noncompensation also contributes to the constant term.

In Table 3 we give resolution as measured in detectors using typical EM calorimeter technologies. In almost all cases the installed calorimeters yield worse resolution than test beam prototypes for a variety of practical reasons. Where possible actual detector performance is given. For a fixed number of radiation lengths, the FWHM in sandwich detectors would be expected to be proportional to $\sqrt{t}$ for t (= plate thickness) ≥ 0.2 radiation lengths.[12]

Given sufficient transverse granularity early in the calorimeter, position resolution of the order of a millimeter can be obtained.

Table 3. Resolution of typical electromagnetic calorimeters. E is in GeV.

Detector	Resolution
NaI(Tl) (Crystal Ball:[13] 20 X_0)	$2.7\%/E^{1/4}$
Lead glass (OPAL[14])	$5\%/\sqrt{E}$
Lead-liquid argon (NA31;[15] 80 cells: 27 X_0, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)	$7.5\%/\sqrt{E}$
Lead-scintillator sandwich (ARGUS[16], LAPP-LAL[17])	$9\%/\sqrt{E}$
Lead-scintillator spaghetti (CERN test module)[18]	$13\%/\sqrt{E}$
Proportional wire chamber (MAC; 32 cells: 13 X_0, 2.5 mm typemetal + 1.6 mm Al)[19]	$23\%/\sqrt{E}$

(2b) Hadronic shower detectors:[20,21] The length scale appropriate for hadronic cascades is the nuclear interaction length, given very roughly by

$$\lambda_I \approx 35 \text{ g cm}^{-2} A^{1/3} .$$

Longitudinal energy deposition profiles are characterized by a sharp peak near the first interaction point (from the fairly local deposition of EM energy resulting from π^0's produced in the first interaction), followed by a more gradual development with a maximum at

$$x/\lambda_I \equiv t_{\max} \approx 0.2 \ln(E/1 \text{ GeV}) + 0.7$$

as measured from the front of the detector.

The depth required for containment of a fixed fraction of the energy also increases logarithmically with incident particle energy. The thickness of iron required for 95% and 99% containment of cascades induced by single hadrons is shown in Fig. 1.[22] Two of the sets of data are from large neutrino experiments, while the third is from a commonly used parametrization. Depths as measured in nuclear interaction lengths presumably scale to other materials. From the same data it can be concluded that the requirement that 95% of the energy in 95% of the showers be contained requires 40 to 50 cm (2.4 to 3.0 λ_I) more material material than for an average 95% containment.

The transverse dimensions of hadronic showers also scale as λ_I, although most of the energy is contained in a narrow core.

The energy deposit in a hadronic cascade consists of a prompt EM component due to π^0 production and a slower component mainly due to low-energy hadronic activity. In general, these energy depositions are converted to electrical signals with different efficiencies. The ratio of the conversion efficiencies is usually called the intrinsic e/h ratio. If $e/h = 1.0$ the calorimeter is said to be *compensating*. If it differs from unity by more than 5% or 10%, detector performance is compromised

PARTICLE DETECTORS (Cont'd)

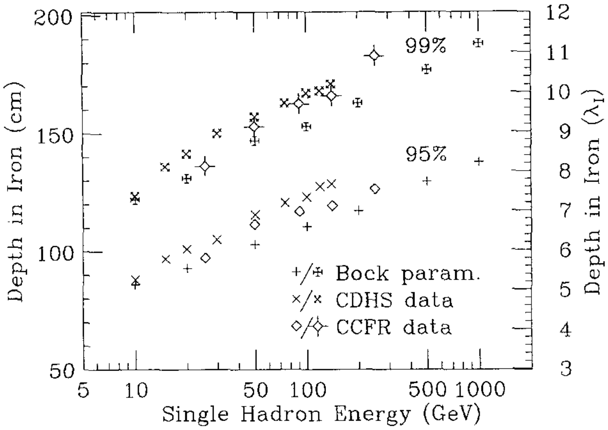

Fig. 1. Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and the parametrization of Bock *et al.*[22].

because of fluctuations in the π^0 content of the cascades. Problems include:

a) A skewed signal distribution;

b) A response ratio for electrons and hadrons (the "e/π ratio") which is different from unity and depends upon energy;

c) A nonlinear response to hadrons (the response per GeV is proportional to the reciprocal of e/π);

d) A constant contribution to detector resolution, almost proportional to the degree of noncompensation. The coefficient relating the constant term to $|1 - e/h|$ is 14% according to FLUKA simulations, and 21% according to Wigman's calculations.[20]

In most cases e/h is greater than unity, particularly if little hydrogen is present or if the gate time is short. This is because much of the low-energy hadronic energy is "hidden" in nuclear binding energy release, low-energy spallation products, etc. Partial correction for these losses occurs in a sampling calorimeter with thick plates, because a disproportionate fraction of electromagnetic energy is deposited in the inactive region. For this reason, it is very unlikely that a fully sensitive detector such as BGO or glass can be made compensating.

Compensation has been demonstrated in calorimeters with 2.5 mm scintillator sheets sandwiched between 3 mm depleted uranium plates[24] or 10 mm lead plates;[25] resolutions σ/E of $0.34/\sqrt{E}$ and $0.44/\sqrt{E}$ were obtained for these cases (E in GeV). The former was shown to be linear to within 2% over three orders of magnitude in energy, with approximately Gaussian signal distributions.

(3) *dE/dx* resolution in argon: Particle identification by dE/dx is dependent on the width of the distribution. For relativistic incident particles with charge e in a multiple-sample Ar gas counter with no lead,[26]

$$\left.\frac{dE}{dx}\right|_{\rm FWHM} \bigg/ \left.\frac{dE}{dx}\right|_{\rm most\ probable} = 0.96\,N^{-0.46}\,(xp)^{-0.32} ,$$

where N = number of samples, x = thickness per sample (cm), p = pressure (atm.). Most commonly used chamber gases (except Xe) give approximately the same resolution.

(4) Free electron drift velocities in liquid ionization chambers:[27–30] Velocity as a function of electric field strength is given in Fig. 2.

(5) Measurement of particle momenta in a uniform magnetic field:[31] The trajectory of a particle with momentum p (in GeV/c) and charge ze in a constant magnetic field $\vec{B}$ is a helix, with radius of curvature R and pitch angle λ. The radius of curvature and momentum component perpendicular to $\vec{B}$ are related by

$$p\cos\lambda = 0.3\,z\,B\,R ,$$

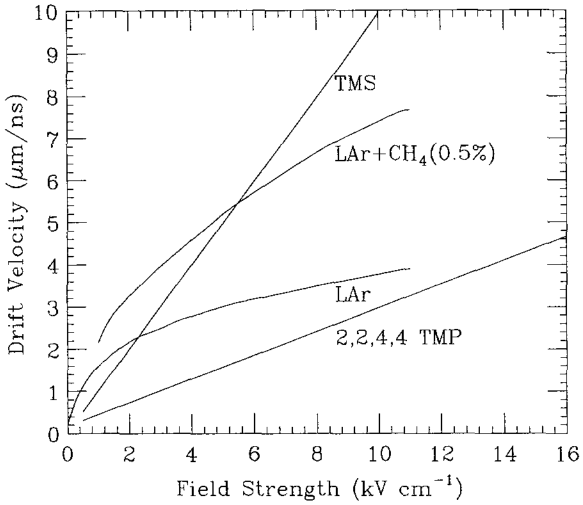

Fig. 2. Electron drift velocity as a function of field strength for commonly used liquids.

where B is in tesla and R is in meters.

The distribution of measurements of the curvature $k \equiv 1/R$ is approximately Gaussian. The curvature error for a large number of uniformly spaced measurements on the trajectory of a charged particle in a uniform magnetic field can be approximated by

$$(\delta k)^2 = (\delta k_{\rm res})^2 + (\delta k_{\rm ms})^2 ,$$

where δk = curvature error
$\delta k_{\rm res}$ = curvature error due to finite measurement resolution
$\delta k_{\rm ms}$ = curvature error due to multiple scattering.

If many (≥ 10) uniformly spaced position measurements are made along a trajectory in a uniform medium,

$$\delta k_{\rm res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+5}} .$$

If a vertex constraint is applied at the origin of the track, the coefficient under the radical becomes 320.

where N = number of points measured along track
L' = the projected length of the track onto the bending plane
ϵ = measurement error for each point, perpendicular to the trajectory.

The contribution due to multiple Coulomb scattering is approximately

$$\delta k_{\rm ms} \approx \frac{(0.016)({\rm GeV}/c)z}{Lp\beta\cos^2\lambda}\sqrt{\frac{L}{X_0}} ,$$

where p = momentum (GeV/c)
z = charge of incident particle in units of e
L = the total track length
X_0 = radiation length of the scattering medium (in units of length; the X_0 defined elsewhere must be multiplied by density)
β = the kinematic variable v/c.

More accurate approximations for multiple scattering may be found in the section on Passage of Particles Through Matter (following). The contribution to the curvature error is given approximately by $\delta k_{\rm ms} \approx 8 s^{\rm rms}_{\rm plane}/L^2$, where $s^{\rm rms}_{\rm plane}$ is defined there.

(6) Proportional chamber wire instability: The limit on the voltage V for a wire tension T, due to mechanical effects when the electrostatic repulsion of adjacent wires exceeds the restoring force of wire tension, is given by (MSKA)[32]

$$V \leq \frac{s}{\ell C}\sqrt{4\pi\epsilon_0 T} ,$$

where s, ℓ, and C are the wire spacing, length, and capacitance per unit length. An approximation to C for chamber half-gap t and wire diameter d (good for $s \lesssim t$) gives[33]

$$V \lesssim 59 T^{1/2} \left[\frac{t}{\ell} + \frac{s}{\pi \ell} \ln \left(\frac{s}{\pi d} \right) \right] ,$$

where V is in kV, and T is in grams-weight equivalent.

(7) Proportional and drift chamber potentials: The potential distributions and fields in a proportional or drift chamber can usually be calculated with good accuracy from the exact formula for the potential around an array of parallel line charges q (coul/m) along z and located at $y = 0$, $x = 0, \pm s, \pm 2s, \ldots$,

$$V(x,y) = -\frac{q}{4\pi \epsilon_0} \ln \left\{ 4 \left[\sin^2 \left(\frac{\pi x}{s} \right) + \sinh^2 \left(\frac{\pi y}{s} \right) \right] \right\} .$$

Errors from the presence of cathodes, mechanical defects, TPC-type edge effects, etc., are usually small and are beyond the scope of this review.

(8) Silicon strip detectors and photodiodes: These silicon diodes are operated with a reverse bias voltage V (typically 30–300 volts) sufficient to deplete the sensitive volume of most mobile charge carriers (electrons and holes). The active (depletion layer) thickness x (cm) is given in a simple model by

$$x = \sqrt{\frac{2\epsilon V}{ne}} = \sqrt{2\rho\mu\epsilon V} ,$$

where $n =$ number of impurity centers/cm^3
$e =$ electron charge
$\epsilon =$ dielectric constant ≈ 1 pF cm$^{-1} \approx 11.9\,\epsilon_0$
$\rho =$ resistivity $\approx$ 1–20 kΩ cm
$\mu =$ majority charge carrier mobility
$\approx$ 1300–1500 cm^2 V^{-1}s^{-1} (electrons)
$\approx$ 450–600 cm^2 V^{-1}s^{-1} (holes).

The capacitance of the diode is ϵ/x per unit area, or 106 pF $\times A(\text{cm}^2)/x(100\mu\text{m})$. In the case of microstrips this is usually dominated by the interstrip capacitance of ~ 1 pF per cm of strip length. A minimum-ionizing particle has a skewed energy-deposit distribution with average energy deposit 39 keV/100 μm and most probable energy deposit 26 keV in 100 μm (which scales within $\sim 10\%$ from ~ 20 to ~ 300 μm). It has a full width at half-maximum of roughly $0.1\,x/\beta^2$ keV, where x is the detector thickness in microns and $\beta = v_{\text{inc}}/c$. The width is usually increased further by electronic noise ($\sigma \sim$ 1–10 keV) and for thin layers by a Gaussian contribution due to atomic effects [$\sigma \sim (0.3\text{–}0.4)\sqrt{x}$ keV]. The average energy required to produce an electron-hole pair is 3.6 eV, from which one can estimate total charge of either sign released. Silicon detectors can still operate as efficient detectors in integrated charged-particle fluxes of up to 10^{10}–10^{14} cm^{-2}.

Typical photodiodes (e.g. Hamamatsu S1723) have quantum efficiencies in excess of 70% between 600 nm and 1000 nm, and UV extended photodiodes have useful efficiency down to 200 nm.

(9) Radiation levels in detectors at hadron colliders: An SSC Central Design Group task force made a study of radiation levels to be expected in SSC detectors.[34] Its model assumed

- The machine luminosity at $\sqrt{s} = 40$ TeV is $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}, and the p-p inelastic cross section is $\sigma_{\text{inel}} = 100$ mb. This luminosity is effectively achieved for 10^7 s yr^{-1}. The interaction rate is thus 10^8 s^{-1}, or 10^{15} yr^{-1};
- All radiation comes from p-p collisions at the interaction point;
- The charged particle distribution is (a) flat in pseudorapidity for $|\eta| < 6$ and (b) has a momentum distribution whose perpendicular component is independent of rapidity, which is taken as independent of pseudorapidity:
$$\frac{d^2 N_{\text{ch}}}{d\eta\, dp_\perp} = H\, f(p_\perp)$$
(where $p_\perp = p \sin\theta$). Integrals involving $f(p_\perp)$ are simplified by replacing $f(p_\perp)$ by $\delta(p_\perp - \langle p_\perp \rangle)$; in the worst case this approximation introduces an error of less than 10%;
- Gamma rays from π^0 decay are as abundant as charged particles. They have approximately the same η distribution, but half the mean momentum;
- At the SSC ($\sqrt{s} = 40$ TeV), $H \approx 7.5$ and $\langle p_\perp \rangle \approx 0.6$ GeV/c; assumed values at other energies are given in Table 5. Together with the model discussed above, these values are thought to describe particle production to within a factor of two or better.

It then follows that the flux of charged particles from the interaction point passing through a normal area da located a distance $r_\perp$ from the beam line is given by

$$\frac{dN_{\text{ch}}}{da} = \frac{1.2 \times 10^8\,\text{s}^{-1}}{r_\perp^2} .$$

In a typical organic material, a relativistic charged particle flux of 3×10^9 cm^{-2} produces an ionizing radiation dose of 1 Gy, where 1 Gy $\equiv$ 1 joule kg^{-1} (= 100 rads). The above result may thus be rewritten as dose rate,

$$\dot{D} = \frac{0.4 \text{ MGy yr}^{-1}}{(r_\perp/1\text{ cm})^2} .$$

If a magnetic field is present, "loopers" may increase this dose rate by a factor of two.

In a medium in which cascades can develop, the ionizing dose or neutron fluence is proportional to dN_{ch}/da multiplied by $\langle E \rangle^\alpha$, where $\langle E \rangle$ is the mean energy of the particles going through da and the power α is slightly less than unity. Since $E \approx p = p_\perp/\sin\theta$ and $r_\perp = r\sin\theta$, the above expression for dN_{ch}/da becomes

$$\text{Dose or fluence}^{**} = \frac{A}{r^2} \cosh^{2+\alpha} \eta = \frac{A}{r^2 \sin^{2+\alpha}\theta} .$$

The constant A contains the total number of interactions $\sigma_{\text{inel}} \int \mathcal{L} dt$, so the ionizing dose or neutron flux at another accelerator scales as $\sigma_{\text{inel}} \int \mathcal{L} dt\, H\, \langle p_\perp \rangle^\alpha$.

The dose or fluence in a calorimeter scales as $1/r^2$, as does the neutron fluence inside a central cavity with characteristic dimension r.

Under all conditions so far studied, the neutron spectrum shows a broad log-normal distribution peaking at just under 1 MeV. In a 2 m radius central cavity of a detector with coverage down to $|\eta| = 3$, the average neutron flux is 2×10^{12} cm^{-2}yr^{-1}, including secondary scattering contributions.

Values of A and α are given in Table 4 for several relevant situations. Examples of scaling to other accelerators are given in Table 5. It should be noted that the assumption that all radiation comes from the interaction point does not apply to the present generation of accelerators.

The constant A includes factors evaluated with cascade simulation programs as well as constants describing particle production at the interaction point. It is felt that each could introduce an error as large as a factor of two in the results.

Table 4. Coefficients $A/(100\text{ cm})^2$ and α for the evaluation of calorimeter radiation levels at cascade maxima under SSC nominal operating conditions. At a distance r and angle θ from the interaction point the annual fluence or dose is $A/(r^2 \sin^{2+\alpha}\theta)$.

Quantity	$A/(100\text{ cm})^2$	Units	$\langle p_\perp \rangle$	α
Neutron flux	1.5×10^{12}	cm^{-2}yr^{-1}	0.6 GeV/c	0.67
Dose rate from photons	400	Gy yr^{-1}	0.3 GeV/c	0.93
Dose rate from hadrons	29	Gy yr^{-1}	0.6 GeV/c	0.89

PARTICLE DETECTORS (Cont'd)

Table 5. A rough comparison of beam-collision induced radiation levels at the Tevatron, UNK, high-luminosity LHC, and SSC.

	Tevatron	UNK-3	LHC	SSC
$\sqrt{s}$ (TeV)	1.8	6	16	40
$\mathcal{L}_{\rm nom}$ (cm^{-2}s^{-1})	2×10^{30}	4×10^{32}	4×10^{34a}	1×10^{33}
$\sigma_{\rm inel}$	59 mb	80 mb	86 mb	100 mb
H	4.1	4.5	6.3	7.5
$\langle p_\perp \rangle$ (GeV/c)	0.46	0.52	0.55	0.60
Relative dose rate^b	5×10^{-4}	0.2	27	1

^{a} High-luminosity option.

^{b} Proportional to $\mathcal{L}_{\rm nom}\,\sigma_{\rm inel}\,H\,\langle p_\perp \rangle^{0.7}$

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* Updated 1989 by D. Anderson, G. Hall, J. Huston, and R. Wigmans.

** *Dose* is the time integral of *dose rate*, and *fluence* is the time integral of *flux*.

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COMMONLY USED RADIOACTIVE SOURCES*

			Particle		Photon	
Nuclide	Half-life	Type of decay	Energy (MeV)	Prob.	Energy (MeV)	Prob.
$^{22}_{11}$Na	2.602 y	β^+, EC	0.545	90%	0.511	Annih.
					1.275	100%
$^{54}_{25}$Mn	0.855 y	EC			0.835	100%
					Cr K X rays	24%
$^{55}_{26}$Fe	2.73 y	EC			Mn K X rays:	
					0.00589	24%
					0.00649	2.9%
$^{57}_{27}$Co	0.745 y	EC			0.014	10%
					0.122	86%
					0.136	11%
					Fe K X rays	55%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173	100%
					1.333	100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K X rays	44%
→ $^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511	Annih.
					1.077	3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
→ $^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
→ $^{106}_{45}$Rh		β^-	3.541	79%	0.512	21%
					0.622	10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^-	41%	0.088	3.6%
			0.084 e^-	45%	Ag K X rays	100%
			0.087 e^-	9%		
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^-	29%	0.392	64%
			0.388 e^-	6%	In K X rays	98%
$^{137}_{55}$Cs	30.0 y	β^-	0.514 e^-	94%	0.662	85%
			1.176 e^-	6%		
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^-	50%	0.081	34%
			0.075 e^-	6%	0.356	62%
					Cs K X rays	124%
$^{207}_{83}$Bi	32.2 y	EC	0.481 e^-	2%	0.569	98%
			0.975 e^-	7%	1.063	75%
			1.047 e^-	2%	1.770	7%
					Pb K X rays	75%
$^{228}_{90}$Th	1.913 y	6α:	5.341 to 8.785		0.239	44%
		3β^-:	0.334 to 2.246		0.583	31%
					2.614	36%
($\rightarrow ^{224}_{88}$Ra $\rightarrow ^{220}_{86}$Rn $\rightarrow ^{216}_{84}$Po $\rightarrow ^{212}_{82}$Pb $\rightarrow ^{212}_{83}$Bi $\rightarrow ^{212}_{84}$Po)						
$^{241}_{95}$Am	432.7 y	α	5.443	13%	0.060	36%
			5.486	85%	Np L X rays	39%
$^{241}_{95}$Am/Be	432.7 y	6×10^{-5} neutrons (4–8 MeV) and				
		4×10^{-5} γ's (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763	24%	Pu L X rays	~ 9%
			5.805	76%		
$^{252}_{98}$Cf	2.645 y	α (97%)	6.076	15%		
			6.118	82%		
		Fission (3.1%)				
		$\approx$ 20 γ's/fission; 80% < 1 MeV				
		$\approx$ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV				

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* Updated April 1989 by E. Browne and V. Shirley.

"Prob." is the probability per decay of a given emission; because of cascades these may total more than 100%. Only principal emissions are listed. EC means electron capture, and e^- means monoenergetic internal conversion (Auger) electron. The intensity of 0.511 MeV e^+e^- annihilation photons depends upon the number of stopped positrons. Endpoint $\beta^{\pm}$ energies are listed. In some cases when energies are closely spaced, the γ-ray values are approximate weighted averages. Radiation from short-lived daughter isotopes is included where relevant.

Half-lives, energies, and intensities are from E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York, 1986) or recent *Nuclear Data Sheets*.

Neutrons are from *Neutron Sources for Basic Physics and Applications* (Pergamon Press, 1983).

RADIOACTIVITY & RADIATION PROTECTION*

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

- **Unit of activity** = becquerel (curie):
  1 Bq = 1 disintegration/sec [= $1/(3.7 \times 10^{10})$ Ci].
- **Unit of exposure**, the quantity of X- or γ- radiation at a point in space integrated over time, in terms of charge of either sign produced by showering electrons in a small volume of air about the point:
  = 1 coul/kg of air (roentgen; 1 $R = 2.58 \times 10^{-4}$ coul/kg)
  = 1 esu/cm^3 = 87.8 erg released energy per g of air); implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving.
- **Unit of absorbed dose**= gray (rad):
  1 Gy = 1 joule/kg (= 10^4 erg/g = 10^2 rad)
  = 6.24×10^{12} MeV/kg deposited energy.
- **Unit of dose equivalent**(for biological damage) = sievert[= 10^2 rem (roentgen equivalent for man)]: Dose equivalent in Sv = grays $\times Q$, where Q (quality factor) expresses long-term risk (primarily cancer and leukemia) from low-level chronic exposure; it depends upon the type of radiation and other factors. For γ rays and β particles, $Q \approx 1$; for protons,[†] $Q \approx 1$ at $\sim$10 MeV, rising gradually to ≈ 2 at $\sim$ 1 GeV; for thermal neutrons,[†] $Q \approx 3$; for fast neutrons,[†] Q ranges up to 10; and for α particles and low-energy heavy ions (assuming internal deposition—skin and clothing are usually sufficient protection against external sources), $Q \approx 20$.
- **Natural annual background**, all sources: Most world areas, whole-body dose equivalent rate $\approx$ (0.4–4) mSv (40–400 millirems). Can range up to 50 mSv (5 rems) in certain areas. U.S. average $\approx$ 3.6 mSv, including $\approx$ 2 mSv ($\approx$ 200 mrem) from inhaled natural rdactivity, mostly radon and radon daughters (0.1–0.2 mSv in open areas; average is for typical house and varies by more than an order of magnitude; can be more than two orders of magnitude higher in poorly ventilated mines).
- **Cosmic ray background**in counters (Earth's surface): $\sim$ 1(min/cm^2/sr). For more accurate estimates and details, see Cosmic Rays section.
- **Fluxes** (per cm^2) to deposit one Gy, assuming uniform irradiation:
  $\approx$ **(charged particles)** $6.24 \times 10^9/(dE/dx)$, where dE/dx (MeV cm^2/g), the energy loss per unit length, may be obtained from the Mean Range and Energy Loss figures.
  $\approx 3.5 \times 10^9$ minimum-ionizing singly charged particles in carbon.
  $\approx$ **(photons)** $6.24 \times 10^9/[Ef/\lambda]$, for photons of energy E (MeV), attenuation length λ (g/cm^2) (see Photon Attenuation Length figure), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \lambda$ but large enough to contain the secondary electrons.
  $\approx 2 \times 10^{11}$ photons/cm^2 for 1 MeV photons on carbon. ($f \approx 1/2$).
  (Quoted fluxes good to about a factor of 2 for all materials.)
- **U.S. maximum permissible occupational whole-body dose:**
  50 mSv/year (5 rem/year).
- **Lethal dose**: Whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment), 2.5–3.0 Gy (250–300 rads) as measured internally on body longitudinal center line; surface dose varies due to variable body attenuation and may be a strong function of energy.

For a recent review, see E. Pochin, *Nuclear Radiation: Risks and Benefits* (Clarendon Press, Oxford, 1983).

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[*] Revised April 1990 with assistance from N.A. Greenhouse.

[†] The International Commission on Radiological Protection has provisionally recommended that these Q factors for protons and neutrons be doubled.

PROBABILITY, STATISTICS, AND MONTE CARLO*

I. PROBABILITY

I.A General

If x is the outcome of an observation, we define the probability of x as the relative frequency with which x occurs out of a (possibly hypothetical) large set of similar observations. If x may take any value from a ***continuous*** range, we write $f(x;\theta)\,dx$ as the probability of observing x between x and $x+dx$. The function $f(x;\theta)$ is the ***probability density function*** (p.d.f.) for the ***random variable*** x, which may depend upon a parameter θ. If x can take on only one of a set of ***discrete*** values (e.g., the non-negative integers), then $f(x;\theta)$ is itself a probability, but we still refer to it as a p.d.f. The p.d.f. is always normalized to unit area (unit sum, if discrete). Both x and θ may have multiple components and are then usually written as column vectors. If θ is unknown and we wish to estimate its value from a given set of data x, we may use statistics (Section II).

The ***cumulative distribution function*** $F(a)$ expresses the probability that $x \le a$:

$$F(a) = \int_{-\infty}^{a} f(x)\,dx \; . \tag{I.1}$$

Here and in what follows, if x is discrete-valued, the integral is replaced by a sum. The endpoint a is expressly included in the integral or sum. Then $0 \le F(x) \le 1$, $F(x)$ is nondecreasing, and $\text{Prob}(a < x \le b) = F(b) - F(a)$. If x is discrete, $F(x)$ is flat except at allowed values of x, where it has a discontinuous jump equal to $f(x)$.

Any function of random variables is itself a random variable, with (in general) a different p.d.f. The ***expectation value*** of any function $u(x)$ is

$$E\left[u(x)\right] = \int_{-\infty}^{\infty} u(x)\,f(x)\,dx \; . \tag{I.2}$$

The expectation value is said to exist only if it is finite. For x and y any two random variables, $E(x+y) = E(x) + E(y)$. For c and k constants, $E(cx+k) = cE(x) + k$. The most commonly used expectation values are the mean and variance:

$$\mu \equiv E(x) \tag{I.3a}$$

$$\sigma^2 \equiv \text{Var}(x) \equiv E\left[(x-\mu)^2\right] = E(x^2) - \mu^2 \; . \tag{I.3b}$$

The mean is the location of the "center of mass" of the distribution of x and the variance is a measure of the square of its width. Note that $\text{Var}(cx+k) = c^2\text{Var}(x)$.

In addition to the mean, another useful indicator of the x ***location*** near which most of the probability is likely to concentrate is the ***median*** x_{med}. This is that value of x such that $F(x_{\text{med}}) = 1/2$, i.e., exactly half of the probability lies above and half lies below x_{med}. For a given ***sample*** of events, x_{med} is that observed x such that half the events have larger x and half have smaller x (as closely as possible, not counting any that have the same x as the median). If this lies between two observed x values, the sample median is set by convention to be halfway between them. If the p.d.f. for x has the form $f(x-\mu)$ and μ is both mean and median, then for a large number of events N the variance of the median approaches $1/[4Nf^2(0)]$, provided $f(0) > 0$.

Let x and y be two random variables with joint p.d.f. $f(x,y)$. The ***marginal*** p.d.f. of, for example, x, expressing the p.d.f. for x with y unobserved, is

$$f_1(x) = \int_{-\infty}^{\infty} f(x,y)\,dy \tag{I.4}$$

and similarly for $f_2(y)$. If y is fixed, the ***conditional*** p.d.f. for x given the fixed y is given by

$$f(x|y) = f(x,y)/f_2(y) \; . \tag{I.5}$$

The x mean is

$$\mu_x = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\,f(x,y)\,dx\,dy = \int_{-\infty}^{\infty} x\,f_1(x)\,dx \tag{I.6}$$

and similarly for y. The ***correlation*** between x and y is a measure of the dependence of one on the other:

$$\rho_{xy} = E\left[(x-\mu_x)(y-\mu_y)\right]/\sigma_x\,\sigma_y \equiv \text{Cov}[x,y]/\sigma_x\,\sigma_y \; , \tag{I.7}$$

where σ_x, σ_y are defined in analogy with Eq. (I.3b); it can be shown that $-1 \le \rho_{xy} \le 1$. The symbol "Cov" represents the covariance of x and y, a 2-variable analogue to the variance, Eq. (I.3b). Two random variables are ***independent*** if and only if

$$f(x,y) = f_1(x)\,f_2(y) \; . \tag{I.8}$$

If x and y are independent then $\rho_{xy} = 0$; the converse is not necessarily true except for Gaussian-distributed x and y. If x and y are independent, $E[u(x)\,v(y)] = E[u(x)]\,E[v(y)]$ and $\text{Var}(x+y) = \text{Var}(x) + \text{Var}(y)$; otherwise, $\text{Var}(x+y) = \text{Var}(x) + \text{Var}(y) + 2\text{Cov}[x,y]$ and $E[u\,v]$ does not factor.

In a ***change of continuous random variables*** from, e.g., $\vec{x} \equiv (x_1,\ldots,x_n)$, with p.d.f. $f(x_1,\ldots,x_n)$, to $\vec{y} \equiv (y_1,\ldots,y_n)$, a one-to-one function of the x's, the p.d.f. $g(y_1,\ldots,y_n)$ is found by substitution for $(x_1,\ldots,x_n)$ in f followed by multiplication by the absolute value of the Jacobian of the transformation:

$$g(\vec{y}\,) = f\left[w_1(\vec{y}\,),\ldots,w_n(\vec{y}\,)\right]|J| \; . \tag{I.9}$$

The functions w_i express the ***reverse*** transformation $x_i = w_i(\vec{y}\,)$ for $i = 1,\ldots,n$, and $|J|$ is the absolute value of the determinant of the square matrix $J_{ij} = \partial x_i/\partial y_j$. Such transformations must always preserve the number of random variables, n. To transform to fewer variables, first perform (I.9) and then take the marginal (I.4) to eliminate unwanted variables. If the transformation from $\vec{x}$ to $\vec{y}$ is not one-to-one, the situation is more complex and a unique solution may not exist. To change variables for discrete random variables simply substitute; no Jacobian is necessary because in that case f is a probability rather than a probability density. If f depends upon a parameter set θ, we can change to a different parameter set $\phi = \phi(\theta)$ by simple substitution; no Jacobian is used.

I.B Specific Probability Density Functions

We describe here a few p.d.f.'s commonly encountered in physics applications. Tables for most of these distributions, relations among them, and further information may be found in Refs. 1 and 2. Monte Carlo techniques for generating each of them may be found in Section III.C below.

I.B.1 Uniform distribution (continuous)

This p.d.f. assumes equal probability density for any x in an allowed range $[a,b]$:

$$\begin{aligned} f(x) &= 1/(b-a) \; , && a \le x \le b \\ &= 0, && \text{otherwise;} \end{aligned} \tag{I.10}$$

$$E(x) = (b+a)/2 \; ; \qquad \text{Var}(x) = (b-a)^2/12 \; . \tag{I.11}$$

I.B.2 Binomial distribution (discrete)

Any random process with exactly two possible outcomes is a ***Bernoulli*** process. If the process is repeated n times independently, and if the probability of obtaining a certain outcome (a "success") in each trial is p, then the probability of obtaining exactly r successes is given by the binomial distribution:

$$f(r;n,p) = \binom{n}{r} p^r q^{n-r} = \frac{n!}{r!(n-r)!}\,p^r q^{n-r} \; , \qquad r = 0,1,2,\ldots,n \; , \tag{I.12}$$

where $q = 1-p$ and the order in which the successes and failures come is assumed irrelevant.

$$E(r) = np \; ; \quad \text{Var}(r) = npq \; . \tag{I.13}$$

If r successes are observed in n_r Bernoulli trials with probability p of success, and if s successes are observed in n_s similar trials, then $t = r + s$ is also binomial with $n_t = n_r + n_s$.

I.B.3 Poisson distribution (discrete)

The Poisson distribution with mean μ is:

$$f(n;\mu) = \frac{\mu^n e^{-\mu}}{n!}\ , \ n = 0, 1, 2, \dots\ . \tag{I.14}$$

The observed result of a Poisson process is a non-negative integer n; the parameter μ is any non-negative real number. The Poisson distribution describes the population of events in any interval of x (e.g., space or time) whenever: (a) the number of events in any interval of x is independent of that in any other non-overlapping interval; (b) in any small Δx, the probability of one event is $\lambda \Delta x$ and the probability of two or more vanishes at least as fast as $(\Delta x)^2$, as $\Delta x \to 0$; and (c) λ does not depend on x. Then $\mu \equiv \lambda x$;

$$E(n) = \mu\ ;\ \mathrm{Var}(n) = \mu\ . \tag{I.15}$$

When μ is large ($\gtrsim 7$ or 8), it is often useful to approximate the distribution of n by a Gaussian distribution of mean μ and variance $\sigma^2 = \mu$, as though n were a continuous variable. Two or more Poisson processes (e.g., ***signal*** + ***background***, with parameters μ_S and μ_B, respectively) which independently contribute amounts n_S and n_B to a given measurement will produce an observed number $n = n_S + n_B$, which is distributed according to a new Poisson distribution with parameter $\mu = \mu_S + \mu_B$.

I.B.4 Normal or Gaussian distribution (continuous)

The Gaussian distribution is

$$f(x;\ \mu,\ \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}\ ,\ -\infty < x < \infty\ ; \tag{I.16}$$

$$E(x) = \mu\ ;\ \mathrm{Var}(x) = \sigma^2\ . \tag{I.17}$$

For x and y independent and normally distributed, $z = x + y$ obeys $f(z;\ \mu_x + \mu_y,\ \sigma_x^2 + \sigma_y^2)$.

The integrated probability for x to fall in the range $\mu - \sigma$ to $\mu + \sigma$ is 0.683. Other measures of width commonly encountered are: probable error (central region containing 0.50 of the probability) $= \mu \pm 0.67\sigma$; mean absolute deviation: $E\left[|x - \mu|\right] = 0.80\sigma$; rms deviation $= \sigma$; half-width at half-maximum $= 1.18\sigma$.

The Gaussian gets its importance in large part from the ***central limit theorem***: if a continuous random variable x is distributed according to ***any*** p.d.f. with finite mean and variance, then the sample mean, $\overline{x}_n$ of n observations of x will have a p.d.f. that approaches a Gaussian as n increases. Therefore the end result $\sum^n x_i \equiv n\overline{x}_n$ of a large number of small fluctuations x_i will be distributed as a Gaussian, even if the x_i themselves are not.

The cumulative distribution (I.1) for a Gaussian with $\mu = 0$ and $\sigma^2 = 1$ is given by the ***error function***, erf(a), through the following ugly relation:

$$F(a; 0, 1) = 0.5\left[1 + \mathrm{erf}(a/\sqrt{2})\right]\ . \tag{I.18}$$

The function erf(a) is tabulated in Ref. 1 and is available as a FORTRAN function on many computers [caution: other definitions of erf(a) are sometimes used]; for mean μ and variance σ^2 replace a by $[(a - \mu)/\sigma]$.

For $\overrightarrow{x}$ a set of n (not necessarily independent) Gaussian random variables x_i arranged into a column vector, their joint p.d.f. is the ***multivariate Gaussian***:

$$f(\overrightarrow{x};\overrightarrow{\mu}, V) = \frac{1}{(2\pi)^{n/2}}\ |V|^{-1/2} \tag{I.19a}$$

$$\times\ \exp\left[-\frac{1}{2}(\overrightarrow{x} - \overrightarrow{\mu})^T\ V^{-1}\ (\overrightarrow{x} - \overrightarrow{\mu})\right]\ ,\ |V| \neq 0\ ,$$

where V is the ***covariance matrix*** of the x's, $V_{ii} = \mathrm{Var}(x_i)$ and $V_{ij} = E[(x_i - \mu_i)(x_j - \mu_j)] \equiv \rho_{ij}\ \sigma_i \sigma_j$, and $|V|$ is the determinant of V. The quantity ρ_{ij} is the correlation coefficient for x_i and x_j; $|\rho_{ij}|^2 \leq 1$. For $n = 2$ this becomes

$$f(x_1, x_2;\ \mu_1, \mu_2, \sigma_1, \sigma_2, \rho) = \frac{1}{2\pi\ \sigma_1\ \sigma_2 \sqrt{1 - \rho^2}} \tag{I.19b}$$

$$\times\ \exp\left\{\frac{-1}{2(1 - \rho^2)}\left[\frac{(x_1 - \mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1 - \mu_1)(x_2 - \mu_2)}{\sigma_1\sigma_2} + \frac{(x_2 - \mu_2)^2}{\sigma_2^2}\right]\right\}\ .$$

The special case $\sigma_1 = \sigma_2$ and $\rho = 0$ is called the ***Rayleigh distribution***. If V is singular, there is a linear relation among some variables; in this case one usually wants to eliminate completely dependent variables and work in a smaller number of dimensions. The marginal distribution of any x_i is a Gaussian with mean μ_i and variance V_{ii}. V is $n \times n$, symmetric, and positive definite. Therefore for any vector $\overrightarrow{X}$, the quadratic form $\overrightarrow{X}^T\ V^{-1}\ \overrightarrow{X} = c$ traces an n-dimensional ellipsoid as $\overrightarrow{X}$ varies for any given $c > 0$. If $X_i = (x_i - \mu_i)/\sigma_i$, then c is a random variable obeying the $\chi^2(n)$ distribution, which is discussed in the following section. The probability that $\overrightarrow{X}$ corresponding to a set of Gaussian random variables $\overrightarrow{x}_i$ lies ***outside*** the ellipsoid characterized by a given value of $c\,(= \chi^2)$ is given by Eq. (I.22) and may be read from Fig. 1. For example, the "s-standard-deviation ellipsoid" occurs at $c = s^2$. For the two-variable case ($n = 2$) the point $\overrightarrow{X}$ lies outside the one-standard-deviation ellipsoid with 61% probability, so both X_1 and X_2 lie inside the ellipsoid with 39% probability. This assumes that μ_i and σ_i are correct. For $X_i = x_i/\sigma_i$, the ellipsoids of constant χ^2 have the same size and orientation but are centered at $\overrightarrow{\mu}$. The use of these ellipsoids as indicators of probable error is described in Sec. II.E.1.

It is a characteristic of the multivariate Gaussian that $\rho_{ij} = 0$ is necessary and sufficient for x_i and x_j to be independent. For a given covariance matrix V, there always exist nonsingular $n \times n$ matrices H such that $HH^T = V$; H is usually upper or lower triangular in the most efficient algorithms. Then $\overrightarrow{z} = H^{-1}(\overrightarrow{x} - \overrightarrow{\mu})$ is a vector of n independent Gaussian random variables with zero mean and with covariance matrix equal to the identity.

I.B.5 The χ^2 distribution (continuous)

If $x_1, \dots, x_n$ are independent Gaussian distributed random variables, the sum $z = \sum^n (x_i - \mu_i)^2/\sigma_i^2$ is distributed as a χ^2 with n ***degrees of freedom*** $[\chi^2(n)]$:

$$f(z;\ n) = \frac{1}{2^{n/2}\Gamma(n/2)}\ z^{n/2-1}\, e^{-z/2}\ ,\quad z \geq 0\ ; \tag{I.20}$$

$$E(z) = n\ ;\ \mathrm{Var}(z) = 2n\ . \tag{I.21}$$

Under a linear transformation to n ***dependent*** Gaussian variables x_i', the χ^2 at each transformed point retains its value; then $z = \overrightarrow{X}'^T\ V^{-1}\ \overrightarrow{X}'$ as in the previous section. For a set of z_i, each of which is $\chi^2(n_i)$, $\sum z_i$ is a new random variable which is $\chi^2\left(\sum n_i\right)$.

Fig. 1 shows the Confidence Level (CL) obtained by integrating the tail of the function given in Eq. (I.20) for n_D degrees of freedom:

$$\mathrm{CL}(\chi^2) = \int_{\chi^2}^{\infty} f(z;\ n_D)\ dz\ ; \tag{I.22}$$

this area is shown schematically in Fig. 2. It is equal to 1.0 minus the cumulative distribution function $F(z = \chi^2;\ n_D)$. It is useful in evaluating the consistency of data with a model (see Sec. II): CL is the probability that a random repeat of the given experiment would observe a ***worse*** χ^2, assuming the correctness of the model. It is also useful for confidence intervals for statistical estimators (Sec. II.E), when one is interested in the unshaded area of Fig. 2.

I.B.6 Student's t (continuous)

Suppose that x and $x_1, \dots, x_n$ are independent and normal with mean 0 and variance 1. We then define $z = \sum_1^n x_i^2$, and

$$t = x/\sqrt{z/n}\ . \tag{I.23}$$

The variable z thus belongs to a $\chi^2(n)$ distribution. Then t is distributed according to a Student's t distribution with n degrees of freedom:

$$f(t;\ n) = \frac{1}{\sqrt{n\pi}}\ \frac{\Gamma\left[(n+1)/2\right]}{\Gamma(n/2)}\ \left(1 + \frac{t^2}{n}\right)^{-(n+1)/2}\ , \tag{I.24}$$

$$-\infty < t < \infty\ .$$

PROBABILITY, STATISTICS, AND MONTE CARLO (Cont'd)

χ^2 Confidence Level vs. χ^2 for n_D Degrees of Freedom

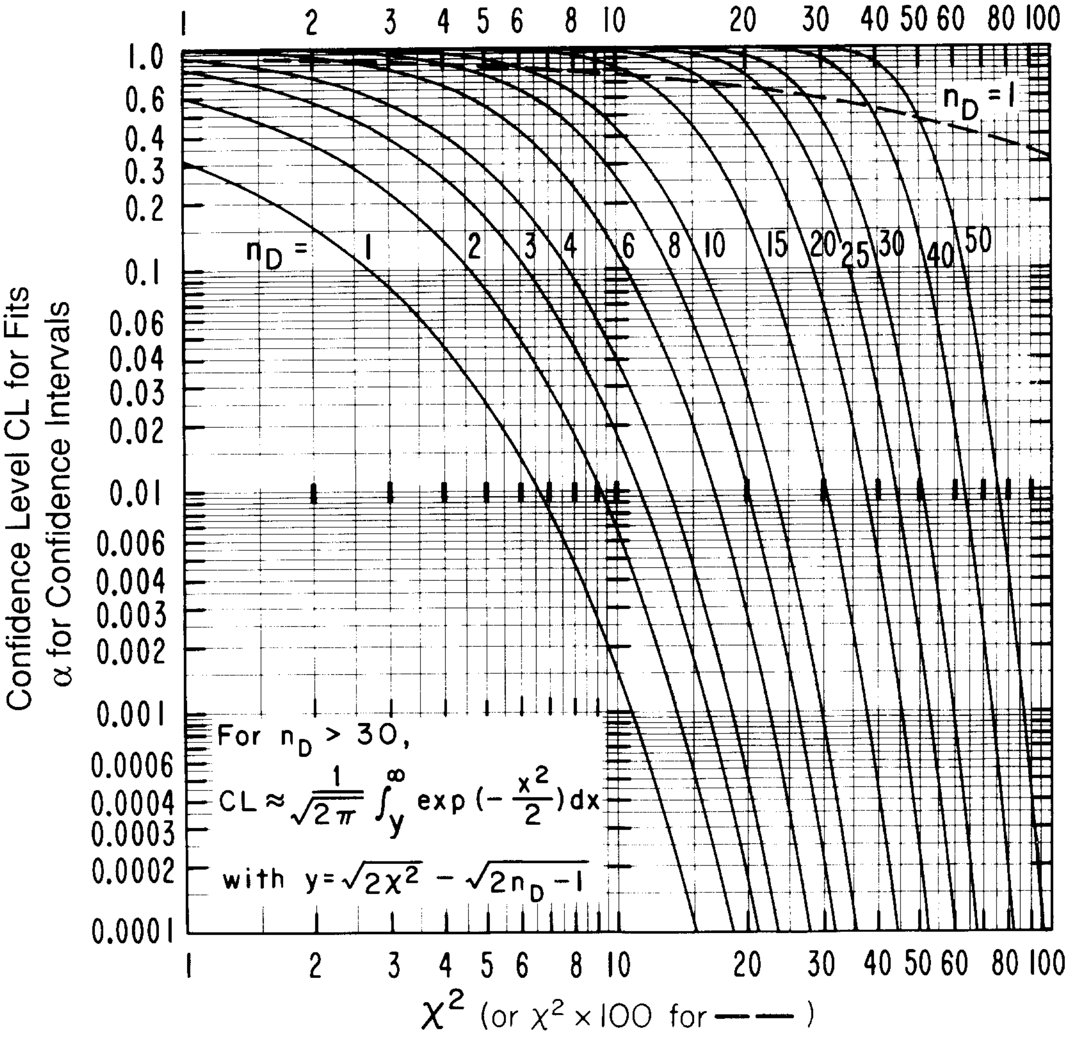

Fig. 1. Confidence level vs. χ^2 for n degrees of freedom, as defined in Eq. (I.22). The curve for a given n expresses the probability that a value at least as large as χ^2 will be obtained in an experiment. For a fit, CL is a measure of goodness-of-fit in that a good fit to a correct model is expected to yield a low χ^2 (Sec. II.C). For a confidence interval, α measures the probability that the interval ***does not*** cover the true value of the quantity being estimated (Sec. II.E).

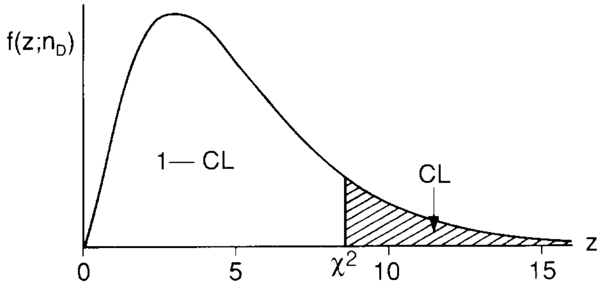

Fig. 2. Schematic illustration of the confidence level integral given in Eq. (I.22).

and

$$E(t) = 0 \text{ for } n > 1 \; ; \quad \mathrm{Var}(t) = \frac{n}{n-2} \text{ for } n > 2 \; . \qquad \text{(I.25)}$$

Here $\Gamma(k)$ is the gamma function, equal to $(k-1)!$ if k is an integer. Student's t distribution resembles a Gaussian distribution with wide tails. As $n \to \infty$, the distribution approaches a Gaussian, and if $n = 1$, the distribution is ***Cauchy***, or ***Breit-Wigner***. The mean is finite for $n > 1$ and the variance is finite for $n > 2$, so for $n = 1$ or $n = 2$, t does not obey the central limit theorem.

As an example, consider the ***sample mean*** $\overline{x} = \sum x_i/n$ and the ***sample variance*** $s^2 = \sum(x_i - \overline{x})^2/(n-1)$ for normally distributed random variables x_i with unknown mean μ and variance σ^2. The sample mean has a Gaussian distribution with a variance σ^2/n, so the variable $(\overline{x} - \mu)/\sqrt{\sigma^2/n}$ is normal with mean 0 and variance 1.

Similarly, $(n-1)\,s^2/\sigma^2$ is independent of this and is χ^2 distributed with $n-1$ degrees of freedom. The ratio

$$t = \frac{(\bar{x}-\mu)/\sqrt{\sigma^2/n}}{\sqrt{(n-1)\,s^2/\sigma^2\,(n-1)}} = \frac{\bar{x}-\mu}{\sqrt{s^2/n}} \tag{I.26}$$

distributes as $f(t;\, n-1)$. The unknown true variance σ^2 cancels, and t can be used to test the probability that the true mean is some particular value μ.

The distribution (I.24) is written such that n is not required to be an integer. A Student's t distribution with nonintegral $n > 0$ is useful in certain applications.

I.B.7 The gamma distribution (continuous)

If a process generating events as a function of x (e.g., space or time) satisfies conditions (a)-(c) of the Poisson distribution, then the x distance from an arbitrary starting point (which may be some particular event) to the k^{th} event is belongs to a ***gamma*** distribution:

$$f(x;\,\lambda,k) = \frac{x^{k-1}\,\lambda^k\,e^{-\lambda x}}{\Gamma(k)}\ ,\ 0 < x < \infty\ . \tag{I.27}$$

$\Gamma(k)$ is the gamma function, equal to $(k-1)!$ if k is an integer. The Poisson parameter μ is λ per unit x;

$$E(x) = k/\lambda\ ;\ \mathrm{Var}(x) = k/\lambda^2\ . \tag{I.28}$$

The special case $k = 1$ is called the ***exponential*** distribution. A sum of k' exponential random variables x_i is distributed as $f(\Sigma x_i;\ \lambda, k')$. Eq. (I.27) allows $k > 0$ to be nonintegral. If $\lambda = 1/2$ and $k = n/2$, the gamma and $\chi^2(n)$ distributions are identical.

II. STATISTICS

II.A General

A probability density function with known parameters enables us to predict the frequency with which a random variable will take on a particular value (if discrete) or lie in a given range (if continuous). In ***parametric*** statistics we have the opposite problem of estimating the parameters of the p.d.f. from a set of actual observations.

We refer to the true p.d.f. as the ***population***; the data form a ***sample*** from this population. A ***statistic*** is any function of the data, plus known constants, which does not depend upon any of the unknown parameters. A statistic is a random variable if the data have random errors. An ***estimator*** is any statistic whose value is intended as a meaningful guess for the value of an unknown parameter; we denote estimators with hats, e.g., $\hat{\theta}$.

Often it is possible to construct more than one reasonable estimator. Let θ represent the true value of a parameter to be estimated; θ is a vector if there is more than one. Then if $\hat{\theta}$ is an estimator for θ, desirable properties for $\hat{\theta}$ are: (a) ***Unbiased***; bias $b = E(\hat{\theta}) - \theta$, where the expectation value is taken over a hypothetical set of similar experiments in which $\hat{\theta}$ is constructed the same way. The bias may be due to statistical properties of the estimator or to ***systematic*** errors in the experiment. If we can estimate the average bias b we usually subtract it from $\hat{\theta}$ to obtain a new $\hat{\theta}' \equiv \hat{\theta} - b$. However, b may depend upon θ or other unknowns, in which case we usually try to choose an estimator which minimizes its average size. (b) ***Minimum variance***; the minimum possible value of $\mathrm{Var}(\hat{\theta})$ is given by the Rao-Cramér-Frechet bound:

$$\mathrm{Var}_{\mathrm{min}} = \left[1 + \partial b/\partial\theta\right]^2 / I(\theta)\ ; \tag{II.1}$$

$$I(\theta) = E\left\{\left[\frac{\partial}{\partial\theta}\sum_{i=1}^{n} \ln f(x_i;\,\theta)\right]^2\right\}\ .$$

The sum is over all data and b is the bias, if any; the x_i are assumed independent and distributed as $f(x_i;\theta)$, and the allowed range of x must not depend upon θ. The ratio $\epsilon = \mathrm{Var}_{\mathrm{min}}/\mathrm{Var}(\hat{\theta})$ is the ***efficiency***. An ***efficient*** estimator (with $\epsilon = 1$) exists only for certain cases. The square root of the variance expresses the expected spread of $\hat{\theta}$ about its average value, as would be observed in a large number of repeats of the same measurement. (c) ***Minimum mean-squared error*** (mse); mse $= E[(\hat{\theta} - \theta)^2] = V(\hat{\theta}) + b^2$. The mse combines the error due to any bias quadratically with the variance, which expresses only the spread about $E(\hat{\theta})$, as distinct from θ, the true value. (d) ***Robust***; a robust estimator is not sensitive to errors in our assumptions, e.g., to departures from the assumed p.d.f. due to such factors as noise.

These criteria (and others) allow us to evaluate any procedure for obtaining $\hat{\theta}$. In many cases these criteria conflict. The bias, variance, and mse may depend on the unknown θ. In this case the optimum prescription for $\hat{\theta}$ may depend on the range in which we assume θ to lie.

Following are techniques in common use for obtaining estimators and their standard errors $\sigma(\hat{\theta}) = \sqrt{\mathrm{Var}(\hat{\theta})}$. When the conditions of the central limit theorem are satisfied, the interval $\hat{\theta} \pm \sigma(\hat{\theta})$ forms a 68.3% ***confidence interval***. This is a random interval in that its endpoints depend upon the randomly sampled data; its meaning here will be taken to be that in 68.3% of all similar experiments the interval will include the true value θ. One should be aware that in most practical cases the central limit theorem is only approximately satisfied and accordingly confidence intervals which depend on that are only approximate. Confidence intervals are discussed in Section II.E below.

II.B Data with a Common Mean

(1) Suppose we have a set of N independent measurements y_i assumed to be unbiased measurements of the same unknown quantity μ with a common, but unknown, variance σ^2 resulting from measurement error. Then

$$\hat{\mu} = \frac{1}{N}\sum_{i=1}^{N} y_i \tag{II.2}$$

$$\hat{\sigma}^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \hat{\mu})^2 = \frac{N}{N-1}\left(E(y^2) - \hat{\mu}^2\right) \tag{II.3}$$

are unbiased estimators of μ and σ^2. The variance of $\hat{\mu}$ is σ^2/N. If the common p.d.f. of the y_i is Gaussian, these statistics are independent. Then, for large N, the variance of $\hat{\sigma}^2$ is $2\sigma^4/N$. If the y_i are Gaussian or N is large enough that the central limit theorem applies, then $\hat{\mu}$ is an efficient estimator for μ. Otherwise $\hat{\mu}$ is sometimes subject to large fluctuations, e.g., if the p.d.f. for y_i has long tails. In this case the median of the y_i may be a more ***robust*** estimator for μ, provided the median and mean are expected to lie at the same point in the p.d.f. for y. For Gaussian y, the median has asymptotic (large-N) efficiency $2/\pi \approx 0.64$. The Student's t distribution provides an example in which there are large tails. In this case, for large N the efficiency of the sample median relative to the sample mean is (∞, ∞, 1.62, 1.12, 0.96, 0.80, 0.64) for (1, 2, 3, 4, 5, 8, ∞) degrees of freedom.

If σ^2 is known, $\hat{\mu}$ as given in Eq. (II.2) is still the best estimator for μ; if μ is known, substitute it for $\hat{\mu}$ in Eq. (II.3) and replace $N-1$ by N, to obtain a somewhat better estimator $\hat{\sigma}^2$.

(2) If the y_i have different, known, variances σ_i^2, then

$$\hat{\mu} = \frac{1}{w}\sum^{N} w_i\, y_i\ , \tag{II.4}$$

is an unbiased estimator for μ with smaller variance than Eq. (II.2), where $w_i = 1/\sigma_i^2$ and $w = \sum w_i$. The variance of $\hat{\mu}$ is $1/w$.

II.C Least-Squares Fit

We wish to determine the best fit of unbiased data y_i, measured at N points x_i (assumed known with negligible error), to the form $y(x) = \Sigma a_n\, f_n(x)$, where the f_n are any known, linearly independent functions (e.g., 1, x, x^2, ..., or Legendre polynomials) which are single-valued over the allowed range of x, and the sum runs from 1 to k. We require $k \le N$, and at least k of the x_i must be distinct. We wish to estimate the linear coefficients a_n. Later we will discuss the nonlinear case.

In the method of least squares, it is assumed that each measured y_i is equal to this sum plus a random error ϵ_i. If the distribution of ϵ_i has an expectation value of zero (unbiased) and has a finite, known variance σ_i^2 which is fixed (does not depend on the parameters of the fit), then the estimates of a_n obtained by minimizing the sum of squares which physicists call $\chi^2 = \sum_i \left[y_i - \sum_n a_n\, f_n(x_i)\right]^2 / \sigma_i^2$ will be unbiased and have the smallest possible variance of all linear unbiased estimates (Gauss-Markov Theorem). If the point errors ϵ_i are Gaussian, then the minimum χ^2 will be distributed as a χ^2 random variable with $N - k$ degrees of freedom. We can then evaluate the goodness-of-fit from Fig. 1. The observed χ^2 for $n_D = N - k$ can be used to find the "confidence level" CL. This expresses the probability that a ***worse*** fit would be obtained in a large number of similar experiments under the assumptions that: (a) the model $y = \sum a_n\, f_n$ is correct and (b) the errors ϵ_i are Gaussian and unbiased with variance σ_i^2. If this probability is larger than an agreed-upon value (0.001, 0.01, or 0.05 are common choices), the data are ***consistent*** with the assumptions; otherwise we may want to find improved assumptions. As for the converse, most people do not regard a model as being truly ***inconsistent*** unless the probability is as low as corresponds to four or five standard deviations for a Gaussian (6×10^{-3} or 6×10^{-5}, see Sec. II.E.1). If the ϵ_i are not Gaussian, the method of least squares still works, but the goodness-of-fit test would have to be done using the correct distribution of the random variable we will continue to call "χ^2."

Finding the minimum of χ^2 is straightforward:

$$-\frac{1}{2}\frac{\partial \chi^2}{\partial a_m} = \sum_i f_m(x_i) \left(\frac{y_i - \sum_n a_n\, f_n(x_i)}{\sigma_i^2} \right)$$

$$= \sum_i \frac{y_i\, f_m(x_i)}{\sigma_i^2} - \sum_n a_n \sum_i \frac{f_n(x_i)\, f_m(x_i)}{\sigma_i^2} \; . \qquad \text{(II.5)}$$

With the definitions

$$g_m = \sum_i y_i\, f_m(x_i)/\sigma_i^2 \qquad \text{(II.6)}$$

and

$$\left(V_{\widehat{a}}^{-1} \right)_{mn} = \sum_i f_n(x_i)\, f_m(x_i)/\sigma_i^2 \; , \qquad \text{(II.7)}$$

the k-element vector of solutions $\widehat{a}$ (all vectors are column vectors), for which $\partial\chi^2/\partial a_m = 0$ for all m, is given by

$$\widehat{a} = V_{\widehat{a}}\, \vec{g} \; . \qquad \text{(II.8)}$$

More generally, the measured y_i's are not independent. Then the set of σ_i^2's must be replaced by the $N \times N$ covariance matrix V_y. Then, if H is the $N \times k$ matrix with element $H_{in} = f_n(x_i)$, the solution $\widehat{a}$ is given by the solution to the ***normal equation***

$$(H^T\, V_y^{-1}\, H)\, \widehat{a} = H^T\, V_y^{-1}\, \vec{y} \; , \qquad \text{(II.9a)}$$

or, formally,

$$\widehat{a} = (H^T\, V_y^{-1}\, H)^{-1}\, H^T\, V_y^{-1}\, \vec{y} \equiv D\, \vec{y} \; , \qquad \text{(II.9b)}$$

where $\vec{y}$ is the N-element vector of measured y_i's. The normal equations may be solved by numerical methods much more computationally efficient than brute application of Eq. (II.9b). In particular, $H^T\, V_y^{-1}\, H$ is sometimes singular or nearly singular. In such cases there is at least one f_n which may be expressed as a linear combination of others (or nearly so) when evaluated at the data points. The best procedure is usually to drop such functions from the expansion (or set $\widehat{a}_n = 0$). See Press,[3] Maindonald,[4] or Basilevsky[5] for discussions.

In terms of the $k \times N$ matrix D, the standard covariance matrix for the $\widehat{a}$ is estimated by

$$V_{\widehat{a}} = D\, V_y\, D^T \; . \qquad \text{(II.10)}$$

If the measured y_i's are independent, V_y is diagonal with ii^{th} element σ_i^2 and $V_{\widehat{a}}$ is obtained from Eq. (II.7) above.

The expected covariance [see Eq. (I.7)] of $\widehat{a}_n$ and $\widehat{a}_m$ is estimated by

$$E\left[(a_n - \widehat{a}_n)(a_m - \widehat{a}_m) \right] = (V_{\widehat{a}})_{nm} \; . \qquad \text{(II.11)}$$

Even when the y_i's are independent (diagonal V_y), $\widehat{a}_n$ and $\widehat{a}_m$ may not be (nondiagonal $V_{\widehat{a}}$). For the model function $y = \sum a_n\, f_n(x)$, the estimated variance of an interpolated or extrapolated value of y at a point x is

$$E\left[(y - \widehat{y})^2 \right] = \sigma^2(y)$$

$$= \sum_{n,m} (V_{\widehat{a}})_{nm}\, f_n(x)\, f_m(x) \; . \qquad \text{(II.12)}$$

If y is not linear in the fitting parameters a_n, or if the errors σ_i depend upon y and therefore on a_n, the solution vector may have to be found by iteration of Eqs. (II.6)-(II.8) or Eq. (II.9b). The same results may be obtained by numerical techniques from the sum of squares, χ^2, directly, if we have a reasonable first guess $\vec{a}_0$ for the solution vector:

$$\widehat{a} = \vec{a}_0 - \left(\frac{\partial^2 \chi^2}{\partial a^2} \right)^{-1}_{\vec{a}_0} \cdot \left. \frac{\partial \chi^2}{\partial a} \right|_{\vec{a}_0} \qquad \text{(II.13a)}$$

and

$$V_{\widehat{a}} = 2 \left(\frac{\partial^2 \chi^2}{\partial a^2} \right)^{-1}_{\widehat{a}} \; , \qquad \text{(II.13b)}$$

where $\partial\chi^2/\partial a$ is a k-element vector whose n^{th} element is $\partial\chi^2/\partial a_n$, $\partial^2\chi^2/\partial a^2$ is a $k \times k$ matrix with mn^{th} element $\partial^2\chi^2/(\partial a_m \cdot \partial a_n)$, and all derivatives are to be evaluated at the points indicated. If "χ^2" is a true χ^2, the second-derivative matrix is independent of $\vec{a}$; therefore the shape of the χ^2 as a function of $\vec{a}$ is a paraboloid and Eq. (II.13a) will give the solution immediately. Otherwise one may need to iterate Eq. (II.13a) to arrive at a solution (Newton-Raphson method).

Note that in Eq. (II.9b), one needs only a matrix proportional to V_y to find $\widehat{a}$. Hence, for example, if the variances σ_i^2 of the errors are unknown but assumed equal and independent, and $E(\epsilon_i) = 0$, one can still solve for $\widehat{a}$. One cannot, however, solve for $V_{\widehat{a}}$ or evaluate goodness-of-fit. These can be estimated from the ***residuals***, $r_i = \widehat{y}(x_i) - y_i$, where $\widehat{y}(x_i)$ is the fitted curve at x_i, because study of the r_i enables one to estimate V_y. In addition, the residuals can be used to look for evidence of bias such as trends in the data not incorporated in the model.[2]

Note that the errors on the solution $\widehat{a}$ are independent of the value of χ^2 at minimum—they depend only upon the shape about the minimum. Eq. (II.13b) implies that one-standard-deviation limits on the elements of $\widehat{a}$ are given by the set of $\vec{a}\,'$ such that

$$\chi^2(\vec{a}\,') = \chi^2_{\min} + 1 \qquad \text{(II.14)}$$

(compare with the corresponding relation for maximum-likelihood estimation, Sec. II.D.2). This equation, which defines a contour in $\vec{a}$-space, is often convenient for estimating errors in applications of least-squares techniques to ***nonlinear*** cases, where the second derivative [Eq. (II.13b)] may be a rapidly varying function of $\vec{a}$. In general, contours at s standard deviations may be found by replacing the 1 in Eq. (II.14) by s^2. If the problem is highly nonlinear, all such contours are at best only approximations to desired exact confidence regions which would have some given probability of covering the true value of $\vec{a}$. It may be that Eq. (II.14) will define a set of disjoint regions. In addition, iteration of Eq. (II.13a) may require sophisticated techniques[3] to reach convergence in a practical amount of computation. For example, in cases involving many variables in $\vec{a}$, especially if the correlations are not small, simplex or other techniques which do not involve explicit calculation of derivatives are often to be preferred. Such techniques are designed to find their way through complicated nonlinear problems without diverging to infinite $\vec{a}$ (unless the minimum is actually at infinity).

Least-squares estimation, unlike maximum likelihood (Sec. II.D), requires that an error matrix V_y be known (a matrix proportional to V_y will suffice to find an estimator). For counting experiments it is therefore necessary to group the data in bins in order to associate a Poisson error with each bin. In this case y_i is the bin height and the error depends on the expectation value of the theory in each bin, N_i^{th}, as estimated by the best fit of the model. Thus the requirements of the Gauss-Markov theorem are not satisfied, since the errors are not fixed. Many experimenters arrange the bins to contain enough expected events (say $\gtrsim 7$ or 8) that the Gaussian approximation to the Poisson (Sec. I.B.3) is accurate, in which case the expected error is the square root of the theoretical height and "χ^2" is approximately a true χ^2. If an approximate error is used, based on the actual observed height $N_i^{\rm obs}$ rather than the theoretical height N_i^{th}, the Gauss-Markov conditions would be satisfied except that a bias favoring downward fluctuations will occur. This is because a fluctuation in the data which goes down from the true expectation value will be assigned a smaller error and therefore a greater weight than an equal fluctuation upward.

For bins with few events, a procedure that converges to the above when N_i^{th} is large and yields correct error estimates for all N_i^{th} is to define

$$\chi^2 = \sum_i \left[2(N_i^{th} - N_i^{\rm obs}) + 2N_i^{\rm obs} \ln (N_i^{\rm obs}/N_i^{th})\right] . \tag{II.15}$$

This assumes that $N_i^{\rm obs}$ is the outcome of a Poisson process, with Poisson parameter $\mu = N_i^{th}$, in the i^{th} bin. In bins where $N_i^{\rm obs} = 0$, the second term is zero. For any N_i^{th}, s-standard-deviation error estimates are constructed as in Eq. (II.14) and subsequent discussion. If we drop the requirement that χ^2 converge to a true χ^2 for large numbers of events in each bin, then minimizing "χ^2" $= 2\sum_i [N_i^{th} - N_i^{\rm obs} \ln (N_i^{th})]$ will give the same answer and errors, with slightly faster execution, as the above.

Example—Straight-Line Fit

For the case of a ***straight-line fit***, $y(x) = a_1 + a_2\, x$, one obtains, for independent measurements y_i, the following estimates of a_1 and a_2,

$$\begin{aligned} \widehat{a}_1 &= (S_y\, S_{xx} - S_x\, S_{xy})/D \ , \\ \widehat{a}_2 &= (S_1\, S_{xy} - S_x\, S_y)/D \ , \end{aligned} \tag{II.16}$$

where

$$S_1,\, S_x,\, S_y,\, S_{xx},\, S_{xy} = \sum (1,\, x_i,\, y_i,\, x_i^2,\, x_i\, y_i)/\sigma_i^2 \ , \tag{II.17}$$

respectively, and

$$D = S_1\, S_{xx} - S_x^2 \ .$$

The covariance matrix of the fitted parameters is:

$$\begin{pmatrix} V_{11} & V_{12} \\ V_{12} & V_{22} \end{pmatrix} = \frac{1}{D} \begin{pmatrix} S_{xx} & -S_x \\ -S_x & S_1 \end{pmatrix} \ . \tag{II.18}$$

The estimated variance of an interpolated or extrapolated value of y at point x is:

$$(\widehat{y} - y_{\rm true})^2 \Big|_{\rm est} = \frac{1}{S_1} + \frac{S_1}{D}\left(x - \frac{S_x}{S_1}\right)^2 \ . \tag{II.19}$$

II.D The Method of Maximum Likelihood

II.D.1 General

This is often the simplest method—in many cases the only practical method—for estimating the unknown values of a set of parameters $\vec{\theta}$. We suppose that a set of measured quantities $\vec{x}$ came from a particular p.d.f. f which depends upon $\vec{\theta}$; hence $f(\vec{x};\, \vec{\theta})$. Now we assume that the probable range of values of $\vec{\theta}$ is restricted by the condition that it must not have been too unlikely that $\vec{x}$ could have come from our f. The principle of maximum likelihood (M.L.) asserts that the best explanation for a set of data is provided by that value of $\vec{\theta}$ which maximizes the joint probability density for all the data $\vec{x}$. If we have a set of measured $\vec{x}_i$ values which we assume were ***independently*** sampled from f, then the joint probability density is

$$\mathcal{L}(\vec{\theta}) = \prod_i f(\vec{x}_i;\, \vec{\theta}) \ . \tag{II.20}$$

$\mathcal{L}$ is called the likelihood; it is a function of $\vec{\theta}$ for the fixed set of measured $\vec{x}_i$'s. Although it is computed from a probability density for the data $\vec{x}$, it is not a probability density for $\vec{\theta}$, even when normalized to unit area.

In evaluating the $\mathcal{L}$, it is important that any normalization factors in the f's which involve $\vec{\theta}$ be included. However, we will only be interested in the maximum of $\mathcal{L}$ and in ratios of $\mathcal{L}$ at different $\vec{\theta}$'s; hence any multiplicative factors which do not involve the parameters we want to estimate may be dropped; this includes factors which depend on the data but not on $\vec{\theta}$.

It is often more convenient to work with

$$\ell(\vec{\theta}) = \ln \mathcal{L}(\vec{\theta}) \tag{II.21}$$

since the product in Eq. (II.20) is converted into a sum; also the p.d.f.'s f often involve exponentials. The maximum of ℓ is at the same $\vec{\theta}$ as that of $\mathcal{L}$. The extremum for both is found from

$$\frac{\partial \ell}{\partial \theta_n} = \frac{1}{\mathcal{L}} \frac{\partial \mathcal{L}}{\partial \theta_n} \equiv S_n = 0 \ . \tag{II.22}$$

S is called the *score* function. Eq. (II.22) is called the ***likelihood condition*** for the optimal solution $\widehat{\theta}$. At solution, the score will have a negative slope through zero. We must be alert to various possibilities for error: (a) Eq. (II.22) may yield a minimum, therefore one must check the second derivative; (b) there may be more than one maximum—one must try to find the global maximum; (c) the global maximum may lie at a boundary of the physical region, in which case Eq. (II.22) will not find it.

If an unbiased, efficient estimator exists, M.L. will find it. A linear score function will guarantee that the estimator is efficient; other efficient cases are discussed in the literature.[2] For large amounts of data, the central limit theorem will usually assure this condition in some significant neighborhood of zero; hence the M.L. estimator is usually efficient in that case, provided certain conditions are met (e.g., that the solution does not lie on a boundary). In this case, in the neighborhood of the maximum, the shape of ℓ is a downward parabola and $\mathcal{L}$ is proportional to a Gaussian. However, "large" is not well defined, and in many practical situations the M.L. estimator may be neither unbiased nor efficient.

The results of two or more experiments may be combined by adding the score functions, adding the ℓ's, or multiplying the $\mathcal{L}$'s.

Under a one-to-one change of parameters from $\vec{\theta}$ to $\vec{\phi} = \vec{\phi}(\vec{\theta})$, the M.L. estimate is simply $\widehat{\phi} = \vec{\phi}(\widehat{\theta})$, given the solution for $\widehat{\theta}$ for $\vec{\theta}$. That is, the M.L. solution for $\vec{\phi}$ is found by simple substitution of $\widehat{\theta}$ into the transformation equation. It is possible that the new solution $\widehat{\phi}$ will be a biased solution for the true value of $\vec{\phi}$ even if $\widehat{\theta}$ is not biased, and vice-versa. In the asymptotic limit (of large amounts of data) both $\widehat{\theta}$ and $\widehat{\phi}$ will (usually) converge to unbiased solutions, but at different rates.

Unlike least-squares estimation, the value of the likelihood at the solution does not tell us whether the final fit was a sensible description of the data or not. To evaluate this, one may: (a) prepare histograms of the data projected on various axes and make χ^2 (or other) comparisons with the fitted model projected upon the same axes; and/or (b) do numerous Monte Carlo simulations of the experiment under the hypothesis that the fitted parameters are correct, fit each of these, and compare the experimental likelihood (or ℓ) with those obtained from these simulations. If the experimental likelihood is lower than that of some agreed-upon fraction of these results, one should question the appropriateness of the p.d.f. f. At the same time one can check for bias in the solution.

The likelihood approach has the advantage over least-squares methods that no binning of the data, with its consequent loss of information, is required. For small data samples this may be very important. Additionally, the p.d.f. f may depend on a number of measured quantities. For least-squares fitting it may be necessary to project the data onto a histogram in one or more dimensions and fit to this histogram. This loses the information about any variables not in the histogram, in addition to that lost by the binning. It is often not even clear what variables one should look at and include in the χ^2. When using the sum of two or more projections, if the variables are not completely independent, their fitted χ^2's will be correlated and one must take this into account in deriving error estimates. M.L. requires no such projection; it uses the full multidimensional information in the data. However, M.L. estimation requires that the form of f be known; the results may be sensitive to deviations from this form. That is, M.L. estimators may not be robust. Least-squares fitting only requires that the point errors ϵ_i be unbiased and of finite variance (to go further and evaluate goodness-of-fit, one needs to know f). In the linear least squares problem of Sec. II.C, if the ϵ_i are Gaussian-distributed, $\ell = -\frac{1}{2}\chi^2 +$ *constant* and both least squares and M.L. will give the same estimators.

II.D.2 Error estimates

The covariance matrix V may be estimated from

$$V_{nm} = \left(E\left[-\frac{\partial^2 \ell}{\partial\theta_n\, \partial\theta_m}\bigg|_{\widehat{\theta}} \right]\right)^{-1} . \qquad \text{(II.23)}$$

If the score, Eq. (II.22), is linear, the "expectation" operation in Eq. (II.23) has no effect because the second derivative of ℓ is constant. Otherwise, it may be approximated by taking the average of the quantity in square brackets over a range of θ_n and θ_m near the solution. For complex cases it may be more practical to evaluate s-standard-deviation errors from the contour

$$\ell(\overrightarrow{\theta}) = \ell_{\max} - s^2/2 \ ,$$

where $\ell_{\max}$ is the value of ℓ at the solution point (compare with Eq. (II.14) and the comments following, for least-squares fitting). The extreme limits of this contour parallel to the θ_n axis give an approximate s-standard-deviation confidence interval in θ . These intervals may not be symmetric and they may even consist of two or more disjoint intervals. This procedure gives one-standard-deviation errors in θ_n equal to $\sqrt{V_{nn}}$ of Eq. (II.23) if the estimator is efficient. If it is not efficient, the level of confidence implied by the value of s is only approximate.

II.E Errors and Confidence Intervals

II.E.1 Gaussian errors

If the data are such that the distribution of the estimator(s) satisfies the central limit theorem discussed in Sec. I.B.4, the Gaussian distribution is the basis of the error analysis. If there is more than one parameter being estimated, the multivariate Gaussian is used. We define a ***confidence interval*** as being an interval constructed from the data to have probability ***at least*** $1-\alpha$ (α is called the ***confidence coefficient***) of covering the true value of θ. For the univariate case with known σ,

$$1 - \alpha = \int_{\widehat{\mu}-\delta}^{\widehat{\mu}+\delta} f(x; \widehat{\mu}, \sigma^2)\, dx \qquad \text{(II.24)}$$

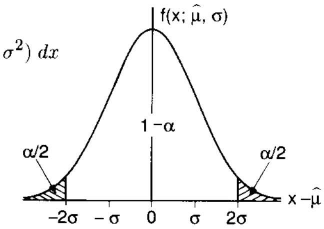

Fig. 3. Illustration of a two standard-deviation confidence interval (unshaded) for a measurement of a single quantity with Gaussian errors. Integrated probabilities, defined by α, are as shown.

is the probability that the true value of μ will fall within $\pm\delta$ ($\delta > 0$) of the measured $\widehat{\mu}$. This interval will cover μ in a fraction $1-\alpha$ of all similar measurements. Fig. 3 shows a $\delta = 2\sigma$ confidence interval unshaded. The choice $\delta = \sqrt{\mathrm{Var}(\widehat{\mu})} \equiv \sigma$ gives an interval called the ***standard error*** which has $1 - \alpha = 68.33\%$ if σ is known. Other frequently used choices for δ, in terms of α are:

α (%)	δ	α (%)	δ
31.67	1σ	20	1.28σ
4.55	2σ	10	1.64σ
0.27	3σ	5	1.96σ
6.4×10^{-3}	4σ	1	2.58σ
5.8×10^{-5}	5σ	0.1	3.29σ
2.0×10^{-7}	6σ	0.01	3.89σ

For other δ, find α as the ordinate of Fig. 1 on the $n_D = 1$ curve at $\chi^2 = (\delta/\sigma)^2$. We can set a one-sided (upper or lower) limit by excluding above $\widehat{\mu} + \delta$ (or below $\widehat{\mu} - \delta$); α's for such limits are 1/2 the values in the table above.

Note that we have increased confidence that the interval covers the true value as $1 - \alpha$ increases, or χ^2 increases. We must be careful to distinguish this case from the other major use of Fig. 1, evaluation of goodness-of-fit (Sec. II.C). In that case we have increased confidence in the fit as χ^2 decreases. In an attempt to reduce possible confusion in this discussion, we will use the α notation (which corresponds to notation used in hypothesis testing[2]) when discussing confidence intervals and CL notation when discussing goodness-of-fit. Elsewhere in this Review, where the confusion between fit confidence level and interval (usually an upper or lower limit) confidence level does not arise, we follow the common practice of using "CL" to refer to the confidence level of the interval. This CL is understood to represent $1-\alpha$.

If the variance σ^2 of the estimator is not known, but must be estimated from the data, then we need to incorporate the error in $\widehat{\sigma}$ into our confidence interval using Student's t distribution. If we have N data points with which we estimate k parameters, the Gaussian approximation is adequate for $N - k \gg 1$. Otherwise replace δ by a factor $T\widehat{\sigma}$, T being defined by

$$1 - \alpha = \int_{-T}^{T} f(x; N-k)\, dx \ , \qquad \text{(II.25)}$$

where f is defined in Eq. (I.24). T is tabulated in Ref. 1 and here:

	α (%)					
$N-k$	31.67	10.00	5.00	4.55	1.00	0.27
1	1.84	6.31	12.71	13.97	63.66	235.78
2	1.32	2.92	4.30	4.53	9.92	19.21
3	1.20	2.35	3.18	3.31	5.84	9.22
4	1.14	2.13	2.78	2.87	4.60	6.62
5	1.11	2.01	2.57	2.65	4.03	5.51
10	1.05	1.81	2.23	2.28	3.17	3.96
20	1.03	1.72	2.09	2.13	2.85	3.42
∞	1.00	1.64	1.96	2.00	2.58	3.00

For multivariate θ we must consider pairwise correlations. Assuming a multivariate Gaussian, Eq. (I.19a), and subsequent discussion the standard error ellipse for the pair $(\widehat{\theta}_m, \widehat{\theta}_n)$ may be drawn as in Fig. 4.

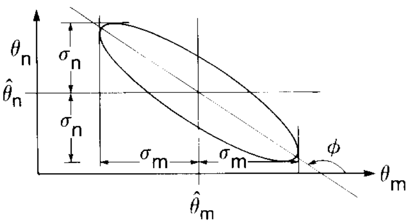

Fig. 4. Standard error ellipse for the estimators $\widehat{\theta}_m$ and $\widehat{\theta}_n$. In this case the correlation is negative.

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The minimum χ^2 or maximum likelihood solution is at $(\widehat{\theta}_m, \widehat{\theta}_n)$. The standard errors σ_m and σ_n are defined as shown, where the ellipse is at a constant value of $\chi^2 = \chi^2_{\rm min} + 1$ or $\ell = \ell_{\rm max} - 1/2$. The angle of the major axis of the ellipse is given by

$$\tan 2\phi = \frac{2\rho_{mn}\,\sigma_m\,\sigma_n}{\sigma_m^2 - \sigma_n^2} \; . \tag{II.26}$$

For non-Gaussian or nonlinear cases, one may construct an analogous contour from the same χ^2 or ℓ relations. Any other parameters $\widehat{\theta}_\ell, \ell \neq m, n$, must be allowed freely to find their optimum values for every trial point.

For any unbiased procedure (e.g., least squares or M.L.) being used to estimate k parameters θ_i, $i = 1, \ldots, k$, the probability $1 - \alpha$ that the true values of all k lie within the s-standard deviation ellipsoid may be found from Fig. 1. Read the ordinate as α; the correct value of α occurs on the $n_D = k$ curve at $\chi^2 = s^2$. For example, for $k = 2$, the probability that the true values of θ_1 and θ_2 simultaneously lie within the one-standard-deviation error ellipse ($s = 1$), centered on $\widehat{\theta}_1$ and $\widehat{\theta}_2$, is 39%. This probability only assumes Gaussian errors, unbiased estimators, and that the model describing the data in terms of the θ_i is correct.

II.E.2 Gaussian errors—bounded physical region

In certain statistical problems the true value of the parameter to be estimated, μ, is constrained to lie within a bounded ***physical region*** (e.g., the mass of a neutrino is bounded from below by 0). However, due to random measurement error, real measured values may or may not occur inside the physical region. For this case no completely satisfactory approach exists, but here we suggest a technique for obtaining limits within the physical region approximately at specified confidence levels. The "classical" statistical techniques of the previous section can still be used for confidence intervals at some exact α. However, such limits are useful mainly in the statistical sense where it is assumed that no bound exists. In bad cases, the limit may exclude the physical region entirely, or extend into it a small distance and create the false impression of a powerful limit close to the edge of the physical region.

We assume a measurement x, which represents one observation (or the result of combining multiple measurements as in Sec. II.B) from a Gaussian of true (but unknown) mean μ and known, fixed, variance σ^2. We ***estimate*** μ by $\widehat{\mu} = x$ and attempt to construct a confidence interval for μ from the resultant Gaussian, as above. If $\widehat{\mu}$ or a significant portion of the probability lies in the unphysical region (Fig. 5), the result, while statistically perfectly correct as stated, is physically unsatisfactory.

If we assume μ is bounded from below by $\mu_{\rm min}$ (the argument for μ bounded from above is similar), we may estimate a reasonable upper limit for μ at the $1 - \alpha$ (e.g., 90% or 95%) level by the following procedure: (1) ***renormalize*** the Gaussian probability distribution for x such that the integral of Eq. (I.16) with $\mu = \widehat{\mu}$ over x from $\mu_{\rm min}$ to infinity (i.e., over the physical region), unshaded in the figure below, is equal to 1.0; (2) find the value μ_1 such that the integral over x of the renormalized distribution from $\mu_{\rm min}$ to μ_1 is equal to the desired value of $1 - \alpha$; (3) set μ_1 to be the desired upper limit with confidence $1 - \alpha$. In fact, it can be shown that this is ***conservative***, in the sense that the probability that this interval actually covers the true value of μ is $\geq 1 - \alpha$.

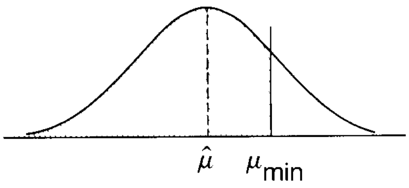

Fig. 5. An example of a bounded physical region with Gaussian errors. In this case the estimator $\widehat{\mu}$ has fallen within the unphysical region due to random error.

For $\mu - \mu_{\rm min} \gg \sigma$, this technique, which may be applied for any measured x (physical or unphysical), converges smoothly to that of the previous section since x is then effectively confined to the physical region.

One should exercise caution for values of x which lie many standard deviations outside the physical region. It may be that the particular probability model (Gaussian with variance σ^2) may not be a correct description of the measurement process (e.g., the true variance may have unanticipated components and be $> \sigma^2$, or there may be a bias), in which case confidence levels of this sort will not be correct.

If $\widehat{\mu} < \mu_{\rm min}$, some authors prefer to use a fixed upper limit calculated for $\widehat{\mu} = \mu_{\rm min}$ or $\widehat{\mu} = \mu_{\rm min} + \sigma$, rather than allow the upper limit to decrease as $\widehat{\mu}$ decreases. In any case, averaging of experiments requires that $\widehat{\mu}$ and its variance be quoted, in addition to any upper limits, even if $\widehat{\mu}$ is unphysical.

II.E.3 Poisson processes—upper limits

Because the outcome of a Poisson process is an integral number of events, n_0, it is usually not possible to set confidence intervals for the true Poisson parameter μ at a certain exact α. For large n_0 an approximate interval can be set using the Gaussian approximation, Sec. I.B.3, and the techniques of Sec. II.E.1.

For small n_0 we can define an upper limit N for μ as being that value of μ such that it would be at least $1 - \alpha$ (e.g., 90% or 95%) probable that a random observation of n would then lie above the observed n_0. Thus

$$1 - \alpha = \sum_{n=n_0+1}^{\infty} f(n; N) \; ; \qquad \alpha = \sum_{n=0}^{n_0} f(n; N) \; . \tag{II.27}$$

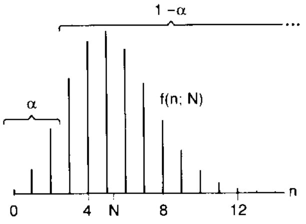

Fig. 6. Illustration of Eq. (II.27) Poisson probabilities for an assumed mean of N. With an observed count $n_0 = 2$, $N = 5.3$ as shown gives summed probability $1 - \alpha = 90\%$.

Fig. 6 illustrates the case with $n_0 = 2$ and $1 - \alpha = 90\%$, for which it may be shown that $N = 5.3$. For any given n_0 and desired α we can obtain N from the χ^2 Confidence Level figure because of a relation between the Poisson and the χ^2: read the ordinate as α, find χ^2 on the curve for $n_D = 2(n_0 + 1)$; then $N = \chi^2/2$. Some useful values are:

Poisson upper limits N for n_0 observed events

	$\alpha =$	$\alpha =$		$\alpha =$	$\alpha =$
n_0	10%	5%	n_0	10%	5%
0	2.30	3.00	6	10.53	11.84
1	3.89	4.74	7	11.77	13.15
2	5.32	6.30	8	13.00	14.44
3	6.68	7.75	9	14.21	15.71
4	7.99	9.15	10	15.41	16.96
5	9.27	10.51			

The meaning of these upper limits is that, for a given true μ, the probability is ***at least*** $1 - \alpha$ that one will observe n_0 which will result in N which is $\geq \mu$. The probability for that to occur may be higher than $1 - \alpha$: for example, if $\mu \leq 2.30$ a "90%" upper limit will actually exceed μ 100% of the time. Note from Eq. (II.27) that for $n_0 = 0$, $N = \ln[1/(1 - \alpha)]$.

II.E.4 Poisson processes with background[6]

If we observe n_0 events in a Poisson process which has two components, signal and background, estimating a limit on the signal is more complicated. Let μ_S be the unknown mean (the Poisson parameter) for the signal and μ_B be the mean for the sum of all backgrounds. Assume μ_B is known with negligible error; however we don't know n_B, the actual number of events resulting from the background. We do know that $n_B \le n_0$. If $\mu_B + \mu_S$ is large, the Gaussian approximation to the Poisson distribution (see Sec. I.B.3) is usually adequate, and one can define confidence intervals or limits as above, assuming $\widehat{n}_B \approx \mu_B$ and therefore $\widehat{\mu}_S = n_0 - \mu_B$ with variance equal to n_0 (larger than $\widehat{\mu}_S$ to allow for the error in $\widehat{n}_B$).

Otherwise an upper limit can be defined by extension of the argument of the preceding section. Let N be the desired upper limit on μ_S with confidence coefficient α. Set N to be that value of μ_S such that any random repeat of the current experiment with $\mu_S = N$ and the same μ_B would observe ***more*** than n_0 events in total ***and*** would have $n_B \le n_0$, all with probability $1-\alpha$. For any assumed N and μ_B we can calculate this probability:

$$1-\alpha = 1 - \frac{e^{-(\mu_B+N)} \displaystyle\sum_{n=0}^{n_0} \frac{(\mu_B+N)^n}{n!}}{e^{-\mu_B} \displaystyle\sum_{n=0}^{n_0} \frac{\mu_B^n}{n!}} \; . \tag{II.28}$$

We adjust N to obtain a desired α. For $\mu_B = 0$ this converges to (II.27). As in that case (see the last paragraph of Section II.E.3) this gives a ***conservative*** upper limit in that for any given true μ_S we get a true probability $\ge 1-\alpha$ that $N \ge \mu_S$, averaged over a large set of identically performed experiments. For $\alpha = 0.10$, Fig. 7 shows N as a function of n_0 and μ_B.

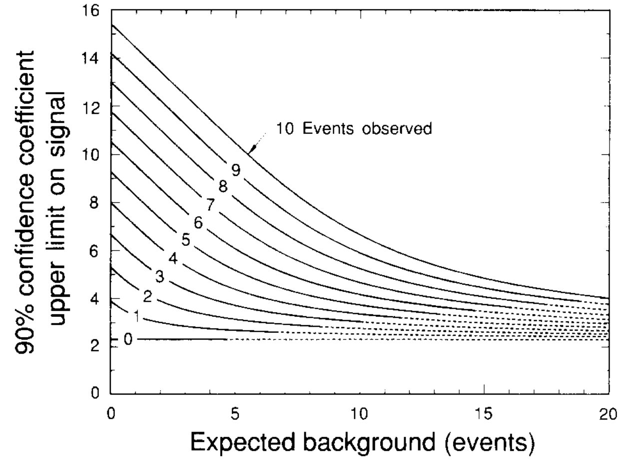

Fig. 7. 90% confidence coefficient upper limit on the number of signal events as a function of the expected number of background events. For example, if the expected background is 8 events and 5 events are observed, then the signal is 4.0 (approximately) or less with 90% confidence. Dashed portions indicate regions where it is to be expected that the number observed would exceed the number actually observed $\ge$ 99% of the time, even in the complete absence of signal.

Averaging of experiments and other comparisons require that n_0 and μ_B be quoted and the technique used for upper limit extraction be given.

If $\mu_B \gg n_0$ the experimenter should question the probability of observing n_B as that n_0. If this is very small the background, μ_B, may not have been calculated properly and the upper limit for μ_S obtained under those assumptions may be too low. For example, in Fig. 7, the dashed portions of the curves lie in the region where n_0 is expected to exceed the observed value 99% of the time (or more), even in the complete absence of signal. In these regions one should be cautious about accepting the results of the measurement.

As in the Gaussian case (II.E.2), whenever $n_0 < \mu_B$ some experimenters may prefer to use N calculated as if $n_0 \approx \mu_B$ rather than the smaller value obtained from the observed n_0.

II.F Propagation of Errors

Suppose we have a set of N random variables y_i which may be direct measurements or derived estimators $\widehat{\theta}$, and we have a covariance matrix $V(y)$ for these. We can make a transformation to a different set of variables $f_j \equiv f_j(y)$, $j = 1, \ldots, M$ ($M \le N$) and obtain best estimates for the f_j from

$$\widehat{f}_j \approx f_j(\widehat{y}) + \frac{1}{2}\sum_{k,n}^{N} V_{kn}(\widehat{y}) \left[\frac{\partial^2 f_j}{\partial y_k \, \partial y_n}\right]_{\widehat{y}} \tag{II.29}$$

with covariance matrix

$$V_{ij}(\widehat{f}\,) \approx \sum_{n,m} \left.\frac{\partial f_i}{\partial y_n}\right|_{\widehat{y}} \left.\frac{\partial f_j}{\partial y_m}\right|_{\widehat{y}} V_{nm}(\widehat{y}) \; . \tag{II.30}$$

For a single-valued function f of a single measurement y with variance σ^2 (i.e., $M = 1, N = 1$), this becomes

$$\begin{aligned} \widehat{f} &\approx f(\widehat{y}) + \frac{1}{2}\sigma^2 f''(\widehat{y}) \\ V(\widehat{f}\,) &\approx \sigma^2 [f'(\widehat{y})]^2 \; , \end{aligned} \tag{II.31}$$

where the primes denote differentiation with respect to y, evaluated at $\widehat{y}$.

These approximations are based on a Taylor expansion of f about the true value of y. If f is approximately linear in y over a range of roughly $\widehat{y}_i \pm \sigma(y_i)$, the approximation is good and the second-order terms in (II.29) and (II.31) can be neglected. This is what is usually done. However, if linearity is badly violated (e.g., $f \propto 1/y$ and $\widehat{y}$ is no more than a few σ from zero), it should be recognized that propagation of errors will give very approximate results. In such cases $\widehat{f} \approx f(\widehat{y})$ may be a biased estimator for f even if $\widehat{y}$ is unbiased for y, and the second-order terms in (II.29) and (II.31) will help to reduce that bias.

III. MONTE CARLO TECHNIQUES

Monte Carlo techniques are used to simulate on a computer random behavior which is too complex to be derived analytically. Most calculations are based upon ***pseudorandom*** numbers, a reproducible sequence of numbers generated on the open interval (0,1) in such a way that they satisfy various statistical tests for a uniform distribution, with independent numbers. (Caution: some commercial random number generators fill the ***closed*** interval [0,1]. The occurrence of 0 or 1 can sometimes cause problems for the algorithms below). No such numbers are truly uniform and independent. Many commercial random number generators sacrifice randomness in favor of speed. It is not rare that unforeseen correlations will introduce non-negligible errors in the results. A useful test for this is to recompute the same results with a different algorithm for the pseudorandom numbers. To improve the performance of an existing generator one may use the ***Bays-Durham algorithm*** [see Ref. 3 for discussion]: (a) Initialize by generating and storing N (e.g., $N = 97$) random numbers in an array v, using the available generator. Generate a new random number u and save it. (b) On the next call, use this u as an address $j = 1+$ (integer part of Nu) to select v_j as the random number to be returned. Also save this v_j as u for the next call. Replace v_j in the array with a new random number using the available generator. On the next call, go to (b).

A second problem sometimes encountered in computations requiring long sequences of random numbers is that all pseudorandom number generators will eventually begin over and repeat the same sequence. One may choose algorithms which minimize the number used. One may also use two or three different generators in different parts of the program.

Monte Carlo simulations of complex processes break them down into a sequence of steps. At each step a particular outcome is chosen from a set of possibilities according to a certain p.d.f. To do this we must transform our uniform random numbers into random numbers sampled from different distributions on different ranges.

Two techniques are in wide use to do this. We will discuss only single variable cases; multiple variable cases use straightforward extensions of these techniques. We assume we are in possession of a random number u chosen from a uniform distribution on (0,1).

III.A Inverse Transform Method

If the desired probability density function is $f(x)$ on the range $-\infty < x < \infty$, its cumulative distribution function (expressing the probability that $x \leq a$) is given by Eq. (I.1). If a is chosen with probability density $f(a)$, then the integrated probability up to point a, $F(a)$, is itself a random variable which will occur with uniform probability density on $[0,1]$. Ignoring the endpoints, we can then find a unique x distributed as $f(x)$ for $f(x)$ ***continuous***, for a given u if we set

$$u = F(x) \ , \qquad \text{(III.1)}$$

provided we can find an inverse of F, defined by

$$x = F^{-1}(u) \ , \qquad \text{(III.2)}$$

as is illustrated in Fig. 8

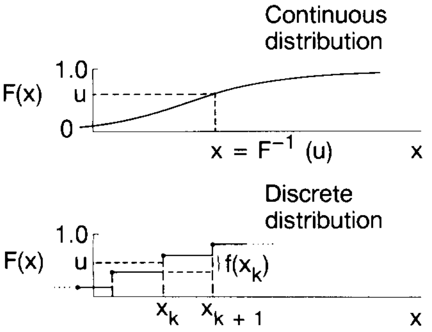

Fig. 8. Use of a random number u chosen from a uniform distribution (0,1) to find a random number x from a distribution with cumulative distribution function $F(x)$.

For a ***discrete*** distribution, $F(x)$ will have a discontinuous jump of size $f(x_k)$ at each allowed $x_k, k = 1, 2, \cdots$. Choose u from a uniform distribution on (0,1) as before. Find x_k such that

$$F(x_{k-1}) < u \leq F(x_k) \equiv \text{Prob}\ (x \leq x_k) = \sum_{i=1}^{k} f(x_i) \ ; \qquad \text{(III.3)}$$

then x_k is the value we seek (note: $F(x_0) \equiv 0$).

III.B Acceptance-Rejection Method (Von Neumann)

Very commonly an analytic form for $F(x)$ is unknown or too complex to work with, so that obtaining an inverse as in Eq. (III.2) is impractical. We suppose that for any given value of x the probability density function $f(x)$ can be computed and further that enough is known about $f(x)$ that we can enclose it entirely inside a shape which is C times an easily generated distribution $h(x)$ as illustrated in Fig. 9.

Frequently $h(x)$ is uniform or is a normalized sum of uniform distributions. Note that both $f(x)$ and $h(x)$ must be normalized to unit area and therefore the proportionality constant $C > 1$. To generate $f(x)$, first generate a candidate x according to $h(x)$. Calculate $f(x)$ and the height of the envelope $C\,h(x)$; generate u and ***test*** if $f(x) \leq uC\,h(x)$. If so, accept x; if not reject x and try again. If we regard x and $uC\,h(x)$ as the abscissa and ordinate of a point in a two-dimensional plot, these points will populate the entire area $C\,h(x)$ in a smooth manner; then we accept those which fall under $f(x)$. The efficiency is the ratio of areas, which must equal $1/C$; therefore we must keep C as close as possible to 1.0. Therefore we try to choose $C\,h(x)$ to be as close to $f(x)$ as convenience dictates, as in the lower part of Fig. 9. This practice is called ***importance sampling***, because we generate more trial values of x in the region where $f(x)$ is most important.

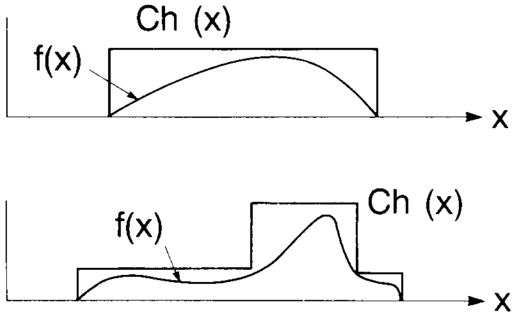

Fig. 9. Illustration of the acceptance-rejection method. Random points are chosen inside the upper bounding figure, and rejected if the ordinate exceeds $f(x)$. Lower figure illustrates importance sampling.

III.C Algorithms

Many algorithms for generating common distributions are given by Rubinstein (1981),[7] Devroye (1986),[8] Press (1986),[3] Walck (1987),[9] and Everett (1983);[10] a few of these are reproduced here. For many distributions alternative algorithms exist, varying in complexity, speed, and accuracy. For time-critical applications, these algorithms may be coded in-line to remove the significant overhead often encountered in making function calls. Variables named "u" are assumed to be independent and uniform on (0,1).

III.C.1 Sine and cosine of random angle

Generate u_1 and u_2. Then $v_1 = 2u_1 - 1$ is uniform on (−1,1), and $v_2 = u_2$ is uniform on (0,1). Calculate $r^2 = v_1^2 + v_2^2$. If $r^2 > 1$, start over. Otherwise, the sine (S) and cosine (C) of a random angle are given by

$$S = 2v_1v_2/r^2 \quad \text{and} \quad C = (v_1^2 - v_2^2)/r^2 \ .$$

III.C.2 Gaussian distribution

If u_1 and u_2 are uniform on (0,1), then

$$z_1 = \sin 2\pi u_1 \sqrt{-2\ln u_2} \quad \text{and} \quad z_2 = \cos 2\pi u_1 \sqrt{-2\ln u_2}$$

are independent and Gaussian distributed with mean 0 and $\sigma = 1$.

There are many faster variants of this basic algorithm. For example, construct $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$, which are uniform on (−1,1). Calculate $r^2 = v_1^2 + v_2^2$, and if $r^2 > 1$ start over. If $r^2 < 1$, it is uniform on (0,1). Then

$$z_1 = v_1\sqrt{\frac{-2\ln r^2}{r^2}} \quad \text{and} \quad z_2 = v_2\sqrt{\frac{-2\ln r^2}{r^2}}$$

are independent numbers chosen from a normal distribution with mean 0 and variance 1. $z_i' = \mu + \sigma z_i$ distributes with mean μ and variance σ^2.

For a multivariate Gaussian it often is simplest to find a transformation matrix H as described at the end of Sec. I.B.4 and generate n independent z_i's with zero means and unit variances; then return $\vec{x} = H\vec{z} + \vec{\mu}$. For $n = 2$ it is convenient to choose H such that $x_1 = z_1\sigma_1 + \mu_1$ and

$$x_2 = V_{12}\, x_1/\sigma_1^2 + z_2\left[(\sigma_1^2\,\sigma_2^2 - V_{12}^2)/\sigma_1^2\right]^{1/2} + \mu_2 \ , \quad \text{where } \sigma_i^2 = V_{ii}.$$

III.C.3 $\chi^2(n_D)$ distribution

For n_D even, generate $n_D/2$ uniform numbers u_i; then

$$y = -2\ln\left(\prod_{i=1}^{n_D/2} u_i\right) \quad \text{is} \quad \chi^2(n_D) \ .$$

PROBABILITY, STATISTICS, AND MONTE CARLO (Cont'd)

For n_D odd, generate $(n_D - 1)/2$ uniform numbers u_i and one Gaussian z as in III.C.2: then

$$y = -2\ln\left(\prod_{i=1}^{(n_D-1)/2} u_i\right) + z^2 \quad \text{is} \quad \chi^2(n_D)\ .$$

For $n_D \gtrsim 30$ the much faster Gaussian approximation for the χ^2 may be preferable: generate z as in III.C.2 and use $y = \left[z + \sqrt{2n_D - 1}\right]^2/2$; if $z < -\sqrt{2n_D - 1}$ reject and start over.

III.C.4 Gamma distribution

- **If** $k = 1$ in Eq. (I.27) (the ***exponential*** distribution), accept $x = -(\ln u)/\lambda$.
- **If** $0 < k < 1$, initialize with $d = (1 - k)\ k^{k/(1-k)}$. $\boxed{A}$ Generate $v_1 = -(\ln u_1)/\lambda$ and $v_2 = -(\ln u_2)/\lambda$. If $v_1 + v_2 \leq d + v_1^{1/k}$, accept $x = v_1^{1/k}$ and stop; otherwise go back to $\boxed{A}$.
- **If** k is a small integer, repeat the $k = 1$ case k times and add the results.
- Otherwise, **if** $k > 1$ initialize with $c = 3k - 0.75$. $\boxed{B}$ Generate $v_1 = u_1(1 - u_1)$ and $v_2 = (u_1 - 0.5)\sqrt{c/v_1}$. If $x = k + v_2 - 1 < 0$, go back to $\boxed{B}$: otherwise compute $v_3 = 64v_1^3u_2^2$. If $v_3 \leq 1 - 2v_2^2/x$ ***or*** if $\ln v_3 \leq 2\{[k - 1]\ \ln[x/(k - 1)] - v_2\}$, accept x and stop; otherwise go back to $\boxed{B}$.

III.C.5 Binomial distribution

If $p \leq 1/2$ in Eq. (I.12), iterate until a successful choice is made: begin with $k = 1$; compute $P_k = q^n$ [for $k \neq 1$ use $P_k \equiv f(r_k; n, p)$, Eq. (I.12)] and store P_k into B; generate u. If $u \leq B$ accept $r_k = k - 1$ and stop; otherwise increment k by 1 and compute next P_k and add to B; generate a new u and repeat. If we arrive at $k = n + 1$, stop and accept $r_{n+1} = n$. If $p > 1/2$ it will be more efficient to generate r from $f(r; n, q)$, i.e., with p and q interchanged, and then set $r_k = n - r$.

III.C.6 Poisson distribution

Iterate until a successful choice is made: Begin with $k = 1$ and set $A = 1$ to start. Generate u. Replace A with uA; if now $A < \exp(-\mu)$, where μ is the Poisson parameter, accept $n_k = k - 1$ and stop. Otherwise increment k by 1, generate a new u and repeat, always starting with the value of A left from the previous try. For large $\mu(\gtrsim 10)$ it may be satisfactory (and much faster) to approximate the Poisson distribution by a Gaussian distribution [Sec. I.B.4] and generate z from $f(z;0,1)$; then accept $x = \max(0, [\mu + z\sqrt{\mu} - 0.5])$ where [ ] signifies the greatest integer $\leq$ the expression.

III.C.7 Student's *t* distribution

For $n > 0$ degrees of freedom (n not necessarily integer), generate x from a Gaussian with mean 0 and $\sigma^2 = 1$ according to the method of III.C.2. Next generate y, an independent gamma random variate with $k = n/2$ degrees of freedom according to the method of III.C.4. Then $z = x\sqrt{2n}/\sqrt{y}$ is distributed as a t with n degrees of freedom.

For the special case $n = 1$, the ***Breit-Wigner*** distribution, generate u_1 and u_2; set $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$. If $v_1^2 + v_2^2 \leq 1$ accept $z = v_1/v_2$ as a Breit-Wigner distribution with unit area, center at 0.0, and FWHM 2.0. Otherwise start over. For center M_0 and FWHM Γ, use $W = z\Gamma/2 + M_0$.

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[*] Revised April 1990 with the assistance of L. Lyons and A.P.T. Palounek.

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ELECTROMAGNETIC RELATIONS*

Quantity	Gaussian CGS	SI
Units and conversions:		
Charge:	2.99792×10^9 esu	$= 1$ coul $= 1$ amp-s
Potential:	$(1/299.792)$ statvolt $= (1/299.792)$ erg/esu	$= 1$ volt $= 1$ joule/coul
Magnetic field:	10^4 gauss $= 10^4$ dyne/esu	$= 1$ tesla $= 1$ nt/amp-m
Electron charge:	$e = 4.803\ 242 \times 10^{-10}$ esu	$= 1.602\ 189\ 2 \times 10^{-19}$ coul
Lorentz force:	$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$	$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
Maxwell equations:	$\nabla \cdot \mathbf{D} = 4\pi\rho$ $\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{H} = \frac{4\pi\mathbf{j}}{c} + \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t}$	$\nabla \cdot \mathbf{D} = \rho$ $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}$
Materials:	$\mathbf{D} = \epsilon\mathbf{E},\ \ \mathbf{B} = \mu\mathbf{H}$	$\mathbf{D} = \epsilon\mathbf{E},\ \ \mathbf{B} = \mu\mathbf{H}$
Permitivity of free space:	$\epsilon_{\text{vac}} = 1$	$\epsilon_{\text{vac}} = \epsilon_0$
Permeability of free space:	$\mu_{\text{vac}} = 1$	$\mu_{\text{vac}} = \mu_0$
Fields:	$\mathbf{E} = -\nabla V - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$	$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$
Static potentials: (coulomb gauge)	$V = \sum_{\text{charges}} \frac{q}{r}$ $\mathbf{A} = \frac{1}{c} \sum_{\text{currents}} \frac{\mathbf{I}}{r}$	$V = \frac{1}{4\pi\epsilon_0} \sum_{\text{charges}} \frac{q}{r}$ $\mathbf{A} = \frac{\mu_0}{4\pi} \sum_{\text{currents}} \frac{\mathbf{I}}{r}$
Relativistic transformations: ($\mathbf{v}$ is the velocity of primed system as seen in unprimed system)	$\mathbf{E}'_{\parallel} = \mathbf{E}_{\parallel}$ $\mathbf{E}'_{\perp} = \gamma(\mathbf{E}_{\perp} + \frac{1}{c}\mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_{\parallel} = \mathbf{B}_{\parallel}$ $\mathbf{B}'_{\perp} = \gamma(\mathbf{B}_{\perp} - \frac{1}{c}\mathbf{v} \times \mathbf{E})$	$\mathbf{E}'_{\parallel} = \mathbf{E}_{\parallel}$ $\mathbf{E}'_{\perp} = \gamma(\mathbf{E}_{\perp} + \mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_{\parallel} = \mathbf{B}_{\parallel}$ $\mathbf{B}'_{\perp} = \gamma(\mathbf{B}_{\perp} - \frac{1}{c^2}\mathbf{v} \times \mathbf{E})$
$4\pi\epsilon_0 = \frac{1}{c^2}10^7\frac{\text{coul}^2}{\text{nt s}^2} = \frac{1}{8.987\ 55} \times 10^{-9}\frac{\text{coul}^2}{\text{nt m}^2}$ $\frac{\mu_0}{4\pi} = 10^{-7}\frac{\text{nt s}^2}{\text{coul}^2}$; $c = 2.997\ 924\ 58 \times 10^8$ m s^{-1}		

ELECTROMAGNETIC RELATIONS (Cont'd)

Impedances (SI)

ρ = resistivity at room temperature in $10^{-8}\,\Omega$ m:

~ 1.7 for Cu	~ 5.5 for W
~ 2.4 for Au	~ 73 for SS 304
~ 2.8 for Al	~ 100 for Nichrome

(Al alloys may have double the Al value.)

For alternating currents, instantaneous current I, voltage V, angular frequency ω:

$$V = V_0\, e^{j\omega t} = ZI\ .$$

Impedance of self-inductance L: $Z = j\omega L$.

Impedance of capacitance C: $Z = 1/j\omega C$.

Impedance of free space: $Z = \sqrt{\mu_0/\epsilon_0} = 376.7\ \Omega$.

Impedance per unit length of a flat conductor of width w (high frequency, ν):

$$Z = \frac{(1+j)\,\rho}{w\,\delta}\ , \quad \text{where } \delta = \text{effective skin depth :}$$

$$\delta = \sqrt{\frac{\rho}{\pi\nu\mu}} \approx \frac{6.6 \text{ cm}}{\sqrt{\nu\,(\text{Hz})}} \quad \text{for Cu .}$$

Capacitance $\widehat{C}$ and inductance $\widehat{L}$ per unit length (SI)

Flat rectangular plates of width w, separated by $d \ll w$:

$$\widehat{C} = \epsilon\,\frac{w}{d}\ ; \quad \widehat{L} = \mu\,\frac{d}{w}\ ;$$

$\frac{\epsilon}{\epsilon_0}$ = 2 to 6 for plastics; 4 to 8 for porcelain, glasses.

Coaxial cable of inner radius r_1, outer radius r_2:

$$\widehat{C} = \frac{2\pi\,\epsilon}{\ln\,(r_2/r_1)}\ ; \quad \widehat{L} = \frac{\mu}{2\pi}\,\ln\,(r_2/r_1)\ .$$

Transmission lines (no loss):

Impedance: $Z = \sqrt{\widehat{L}/\widehat{C}}$.

Velocity: $v = 1/\sqrt{\widehat{L}\,\widehat{C}} = 1/\sqrt{\mu\epsilon}$.

Synchrotron radiation (CGS)

For a particle of charge e, velocity β, γ, energy E, traveling in a circular orbit of radius R:

$$\text{Energy loss/revolution (MeV)} = \frac{4\pi}{3}\,\frac{e^2}{R}\,\beta^3\,\gamma^4$$

$$\approx 0.0885\ [E(\text{GeV})]^4/R(\text{m}) \text{ for } e^{\pm} \text{ if } \beta \approx 1.$$

Energy spectrum: For $\gamma \gg 1$, the energy radiated per particle per revolution into the photon energy interval $d(\hbar\omega)$ is

$$dI = \frac{8\pi}{9}\alpha\,\gamma\,F(\omega/\omega_c)\,d(\hbar\omega)\ .$$

where $\alpha = e^2/\hbar c$ is the fine-structure constant. The normalized function $F(y)$ is

$$F(y) = \frac{9}{8\pi}\sqrt{3}\,y\int_y^{\infty} dx\,K_{5/3}(x)\ ,$$

where $K_{5/3}(x)$ is a modified Bessel function of the third kind, and

$$\omega_c = \frac{3\gamma^3 c}{2R} \text{ is the critical frequency;}$$

$$\hbar\omega_c\,(\text{keV}) \approx 2.22\ [E(\text{GeV})]^3/R(\text{m}) \text{ for } e^{\pm}\ .$$

Fig. 1 shows $F(y)$ over its important range of y.

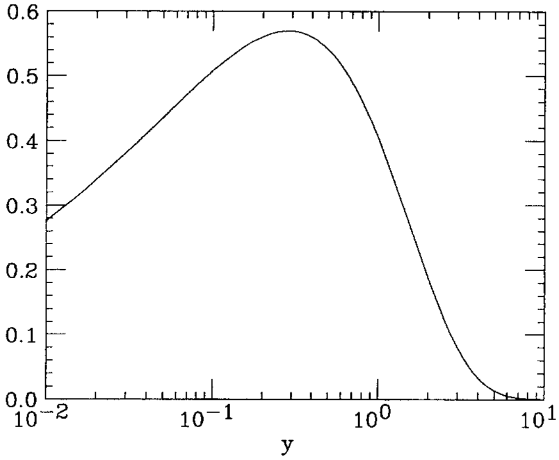


Fig. 1. Normalized synchrotron radiation spectrum $F(y)$.

In the limit $\gamma \gg 1$,

for $\omega \ll \omega_c$:

$$\frac{dI}{d(\hbar\omega)} \approx 3.3\alpha\,(\omega R/c)^{1/3}\ ;$$

and for $\omega \gtrsim 3\omega_c$:

$$\frac{dI}{d(\hbar\omega)} \approx \sqrt{\frac{3\pi}{2}}\,\alpha\,\gamma\left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c}\left[1 + \frac{55}{72}\frac{\omega_c}{\omega} + \ldots\right]\ .$$

The radiation is confined to angles $\lesssim 1/\gamma$ relative to the instantaneous direction of motion.

---

* Revised April 1990 by J.D. Jackson. See J.D. Jackson, *Classical Electrodynamics*, 2^{nd} edition (John Wiley & Sons, New York, 1975) for more formulae and details. (Prepared April 1974; revised April 1990.) Jackson uses a definition of ω_c twice as large as the customary definition given above.

CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND *d* FUNCTIONS

Note: A $\sqrt{\ }$ is to be understood over <u>every</u> coefficient; e.g., for -8/15 read $-\sqrt{8/15}$.

Notation:

		J	J	. . .
		M	M	. . .
m_1	m_2	Coefficients		
m_1	m_2			
.	.			
.	.			

1/2 × 1/2

		1
		+1
+1/2	+1/2	1

		1	0
		0	0
+1/2	-1/2	1/2	1/2
-1/2	+1/2	1/2	-1/2

		1
		-1
-1/2	-1/2	1

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\ \cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\ \sin\theta\ e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\ \cos^2\theta - \frac{1}{2}\right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\ \sin\theta\cos\theta\ e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\ \sin^2\theta\ e^{2i\phi}$$

2 × 1/2

		5/2
		+5/2
+2	1/2	1

		5/2	3/2
		3/2	+3/2
+2	-1/2	1/5	4/5
+1	+1/2	4/5	-1/5

		5/2	3/2
		+1/2	+1/2
+1	-1/2	2/5	3/5
0	+1/2	3/5	-2/5

		5/2	3/2
		-1/2	-1/2
0	-1/2	3/5	2/5
-1	+1/2	2/5	-3/5

		5/2	3/2
		-3/2	-3/2
-1	-1/2	4/5	1/5
-2	+1/2	1/5	-4/5

		5/2
		-5/2
-2	-1/2	1

1 × 1/2

		3/2
		+3/2
+1	+1/2	1

		3/2	1/2
		+1/2	+1/2
+1	-1/2	1/3	2/3
0	+1/2	2/3	-1/3

		3/2	1/2
		-1/2	-1/2
0	-1/2	2/3	1/3
-1	+1/2	1/3	-2/3

		3/2
		-3/2
-1	-1/2	1

3/2 × 1/2

		2
		+2
+3/2	+1/2	1

		2	1
		+1	+1
+3/2	-1/2	1/4	3/4
+1/2	+1/2	3/4	-1/4

		2	1
		0	0
+1/2	-1/2	1/2	1/2
-1/2	+1/2	1/2	-1/2

		2	1
		-1	-1
-1/2	-1/2	3/4	1/4
-3/2	+1/2	1/4	-3/4

		2
		-2
-3/2	-1/2	1

2 × 1

		3
		+3
+2	+1	1

		3	2
		+2	+2
+2	0	1/3	2/3
+1	+1	2/3	-1/3

		3	2	1
		+1	+1	+1
+2	-1	1/15	1/3	3/5
+1	0	8/15	1/6	-3/10
0	+1	6/15	-1/2	1/10

		3	2	1
		0	0	0
+1	-1	1/5	1/2	3/10
0	0	3/5	0	-2/5
-1	+1	1/5	-1/2	3/10

		3	2	1
		-1	-1	-1
0	-1	6/15	1/2	1/10
-1	0	8/15	-1/6	-3/10
-2	+1	1/15	-1/3	3/5

		3	2
		-2	-2
-1	-1	2/3	1/3
-2	0	1/3	-2/3

		3
		-3
-2	-1	1

3/2 × 1

		5/2
		+5/2
+3/2	+1	1

		5/2	3/2
		+3/2	+3/2
+3/2	0	2/5	3/5
+1/2	+1	3/5	-2/5

		5/2	3/2	1/2
		+1/2	+1/2	+1/2
+3/2	-1	1/10	2/5	1/2
+1/2	0	3/5	1/15	-1/3
-1/2	+1	3/10	-8/15	1/6

		5/2	3/2	1/2
		-1/2	-1/2	-1/2
+1/2	-1	3/10	8/15	1/6
-1/2	0	3/5	-1/15	-1/3
-3/2	+1	1/10	-2/5	1/2

		5/2	3/2
		-3/2	-3/2
-1/2	-1	3/5	2/5
-3/2	0	2/5	-3/5

		5/2
		-5/2
-3/2	-1	1

1 × 1

		2
		+2
+1	+1	1

		2	1
		+1	+1
+1	0	1/2	1/2
0	+1	1/2	-1/2

		2	1	0
		0	0	0
+1	-1	1/6	1/2	1/3
0	0	2/3	0	-1/3
-1	+1	1/6	-1/2	1/3

		2	1
		-1	-1
0	-1	1/2	1/2
-1	0	1/2	-1/2

		2
		-2
-1	-1	1

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^\ell_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\ Y_\ell^m e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

$$d^j_{m',m} = (-1)^{m-m'} d^j_{m,m'} = d^j_{-m,-m'}$$

$$d^{1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^{1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2}$$

$$d^1_{1,1} = \frac{1+\cos\theta}{2} \qquad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

$$d^1_{1,-1} = \frac{1-\cos\theta}{2} \qquad d^1_{0,0} = \cos\theta$$

3/2 × 3/2

		3
		+3
+3/2	+3/2	1

		3	2
		+2	+2
+3/2	+1/2	1/2	1/2
+1/2	+3/2	1/2	-1/2

		3	2	1
		+1	+1	+1
+3/2	-1/2	1/5	1/2	3/10
+1/2	+1/2	3/5	0	-2/5
-1/2	+3/2	1/5	-1/2	3/10

		3	2	1	0
		0	0	0	0
+3/2	-3/2	1/20	1/4	9/20	1/4
+1/2	-1/2	9/20	1/4	-1/20	-1/4
-1/2	+1/2	9/20	-1/4	-1/20	1/4
-3/2	+3/2	1/20	-1/4	9/20	-1/4

		3	2	1
		-1	-1	-1
+1/2	-3/2	1/5	1/2	3/10
-1/2	-1/2	3/5	0	-2/5
-3/2	+1/2	1/5	-1/2	3/10

		3	2
		-2	-2
-1/2	-3/2	1/2	1/2
-3/2	-1/2	1/2	-1/2

		3
		-3
-3/2	-3/2	1

2 × 3/2

		7/2
		+7/2
+2	+3/2	1

		7/2	5/2
		+5/2	+5/2
+2	+1/2	3/7	4/7
+1	+3/2	4/7	-3/7

		7/2	5/2	3/2
		+3/2	+3/2	+3/2
+2	-1/2	1/7	16/35	2/5
+1	1/2	4/7	1/35	-2/5
0	3/2	2/7	-18/35	1/5

		7/2	5/2	3/2	1/2
		+1/2	+1/2	+1/2	+1/2
+2	-3/2	1/35	6/35	2/5	2/5
+1	-1/2	12/35	5/14	0	-3/10
0	1/2	18/35	-3/35	-1/5	1/5
-1	3/2	4/35	-27/70	2/5	-1/10

		7/2	5/2	3/2	1/2
		-1/2	-1/2	-1/2	-1/2
+1	-3/2	4/35	27/70	2/5	1/10
0	-1/2	18/35	3/35	-1/5	-1/5
-1	1/2	12/35	-5/14	0	3/10
-2	3/2	1/35	-6/35	2/5	-2/5

		7/2	5/2	3/2
		-3/2	-3/2	-3/2
0	-3/2	2/7	18/35	1/5
-1	-1/2	4/7	-1/35	-2/5
-2	1/2	1/7	-16/35	2/5

		7/2	5/2
		-5/2	-5/2
-1	-3/2	4/7	3/7
-2	-1/2	3/7	-4/7

		7/2
		-7/2
-2	-3/2	1

2 × 2

		4
		4
+2	+2	1

		4	3
		+3	+3
+2	+1	1/2	1/2
+1	+2	1/2	-1/2

		4	3	2
		+2	+2	+2
+2	0	3/14	1/2	2/7
+1	1	4/7	0	-3/7
0	2	3/14	-1/2	2/7

		4	3	2	1
		+1	+1	+1	+1
+2	-1	1/14	3/10	3/7	1/5
+1	0	3/7	1/5	-1/14	-3/10
0	1	3/7	-1/5	-1/14	3/10
-1	2	1/14	-3/10	3/7	-1/5

		4	3	2	1	0
		0	0	0	0	0
+2	-2	1/70	1/10	2/7	2/5	1/5
+1	-1	8/35	2/5	1/14	-1/10	-1/5
0	0	18/35	0	-2/7	0	1/5
-1	1	8/35	-2/5	1/14	1/10	-1/5
-2	2	1/70	-1/10	2/7	-2/5	1/5

		4	3	2	1
		-1	-1	-1	-1
+1	-2	1/14	3/10	3/7	1/5
0	-1	3/7	1/5	-1/14	-3/10
-1	0	3/7	-1/5	-1/14	3/10
-2	1	1/14	-3/10	3/7	-1/5

		4	3	2
		-2	-2	-2
0	-2	3/14	1/2	2/7
-1	-1	4/7	0	-3/7
-2	0	3/14	-1/2	2/7

		4	3
		-3	-3
-1	-2	1/2	1/2
-2	-1	1/2	-1/2

		4
		-4
-2	-2	1

$$d^{3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,1/2} = -\sqrt{3}\ \frac{1+\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-1/2} = \sqrt{3}\ \frac{1-\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{1/2,1/2} = \frac{3\cos\theta-1}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{1/2,-1/2} = -\frac{3\cos\theta+1}{2}\sin\frac{\theta}{2}$$

$$d^2_{2,2} = \left(\frac{1+\cos\theta}{2}\right)^2$$

$$d^2_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta$$

$$d^2_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta$$

$$d^2_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta$$

$$d^2_{2,-2} = \left(\frac{1-\cos\theta}{2}\right)^2$$

$$d^2_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta-1)$$

$$d^2_{1,0} = -\sqrt{\frac{3}{2}}\ \sin\theta\ \cos\theta$$

$$d^2_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta+1)$$

$$d^2_{0,0} = \left(\frac{3}{2}\ \cos^2\theta - \frac{1}{2}\right)$$

Sign convention is that of Wigner (*Group Theory*, Academic Press, New York, 1959), also used by Condon and Shortley (*The Theory of Atomic Spectra*, Cambridge Univ. Press, New York, 1953), Rose (*Elementary Theory of Angular Momentum*, Wiley, New York, 1957), and Cohen (*Tables of the Clebsch-Gordan Coefficients*, North American Rockwell Science Center, Thousand Oaks, Calif., 1974). The signs and numbers in the current tables have been calculated by computer programs written independently by Cohen and at LBL. (Table extended April 1974.)

SU(3) ISOSCALAR FACTORS AND REPRESENTATION MATRICES

The most commonly used SU(3) isoscalar factors, corresponding to the singlet, octet, and decuplet content of $8 \otimes 8$ and $10 \otimes 8$, are shown at the right. The notation uses particle names to identify the coefficients, so that the pattern of relative couplings may be seen at a glance. We illustrate the use of the coefficients by example. See J.J de Swart, Rev. Mod. Phys. **35**, 916 (1963) for detailed explanations and phase conventions.

A $\sqrt{\ }$ is to be understood over every integer in the matrices; the exponent 1/2 on each matrix is a reminder of this. For example, the $\Xi \to \Omega K$ element of our $10 \to 10 \otimes 8$ matrix is $-\sqrt{6}/\sqrt{24} = -1/2$.

Intramultiplet relative decay strengths may be read directly from our matrices. Thus, the ratio of the partial widths for $\Omega^* \to \Xi\overline{K}$ and $\Delta \to N\pi$ is, from the $10 \to 8 \times 8$ matrix,

$$\frac{\Gamma\left(\Omega^* \to \Xi\overline{K}\right)}{\Gamma\left(\Delta \to N\pi\right)} = \frac{12}{6} \times \text{ (phase space factors) } .$$

Supplying isospin Clebsch-Gordan coefficients, we obtain, e.g.,

$$\frac{\Gamma(\Omega^{*-} \to \Xi^0 K^-)}{\Gamma(\Delta^+ \to p\pi^0)} = \frac{1/2}{2/3} \times \frac{12}{6} \times p.s.f. = \frac{3}{2} \times p.s.f.$$

Partial widths for $8 \to 8 \otimes 8$ involve a linear superposition of 8_1 (symmetric) and 8_2 (antisymmetric) couplings. For example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim \left(-\sqrt{\frac{9}{20}}\, g_1 + \sqrt{\frac{3}{12}}\, g_2\right)^2 .$$

The relations between g_1 and g_2 (with de Swart's normalization) and the standard D and F couplings that appear in the interaction Lagrangian,

$$\mathcal{L} = -\sqrt{2}\, D\, Tr\left([\overline{B}, B]_+ M\right) + \sqrt{2}\, F\, Tr\left([\overline{B}, B]_- M\right) ,$$

are

$$D = \frac{\sqrt{30}}{40}\, g_1 , \qquad F = \frac{\sqrt{6}}{24}\, g_2 .$$

Thus, for example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim (F - D)^2 \sim (1 - 2\alpha)^2 .$$

where $\alpha \equiv D/(D + F)$.

When acting upon a representation of dimension d, the generators of SU(3) transformations, λ_a ($a = 1, 8$), are $d \times d$ matrices that obey the following commutation and anticommutation relationships:

$$[\lambda_a, \lambda_b] = 2i f_{abc} \lambda_c$$

$$\{\lambda_a, \lambda_b\} = \frac{4}{3}\delta_{ab} I + 2 d_{abc} \lambda_c ,$$

where I is the $d \times d$ unit matrix. The f_{abc} are odd under the permutation of any pair of indices, while the d_{abc} are even. The nonzero elements are

$1 \to 8 \otimes 8$

$$(\Lambda) \to \left(N\overline{K} \quad \Sigma\pi \quad \Lambda\eta \quad \Xi K\right) = \frac{1}{\sqrt{8}} \left(2 \quad 3 \quad -1 \quad -2\right)^{1/2}$$

$8_1 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi & N\eta & \Sigma K & \Lambda K & \\ N\overline{K} & \Sigma\pi & \Lambda\pi & \Sigma\eta & \Xi K \\ N\overline{K} & \Sigma\pi & \Lambda\eta & \Xi K & \\ \Sigma\overline{K} & \Lambda\overline{K} & \Xi\pi & \Xi\eta & \end{pmatrix} = \frac{1}{\sqrt{20}} \begin{pmatrix} 9 & -1 & -9 & -1 & \\ -6 & 0 & 4 & 4 & -6 \\ 2 & -12 & -4 & -2 & \\ 9 & -1 & -9 & -1 & \end{pmatrix}^{1/2}$$

$8_2 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi & N\eta & \Sigma K & \Lambda K & \\ N\overline{K} & \Sigma\pi & \Lambda\pi & \Sigma\eta & \Xi K \\ N\overline{K} & \Sigma\pi & \Lambda\eta & \Xi K & \\ \Sigma\overline{K} & \Lambda\overline{K} & \Xi\pi & \Xi\eta & \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} 3 & 3 & 3 & -3 & \\ 2 & 8 & 0 & 0 & -2 \\ 6 & 0 & 0 & 6 & \\ 3 & 3 & 3 & -3 & \end{pmatrix}^{1/2}$$

$10 \to 8 \otimes 8$

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} & N\pi & N\eta & & \\ N\overline{K} & \Sigma\pi & \Lambda\pi & \Sigma\eta & \Xi K \\ \Sigma\overline{K} & \Lambda\overline{K} & \Xi\pi & \Xi\eta & \\ & & \Xi\overline{K} & & \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} & -6 & 6 & & \\ -2 & 2 & -3 & 3 & 2 \\ 3 & -3 & 3 & 3 & \\ & & 12 & & \end{pmatrix}^{1/2}$$

$8 \to 10 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} & \Delta\pi & \Sigma K & \\ \Delta\overline{K} & \Sigma\pi & \Sigma\eta & \Xi K \\ & \Sigma\pi & \Xi K & \\ \Sigma\overline{K} & \Xi\pi & \Xi\eta & \Omega K \end{pmatrix} = \frac{1}{\sqrt{15}} \begin{pmatrix} & -12 & 3 & \\ 8 & -2 & -3 & 2 \\ & -9 & 6 & \\ 3 & -3 & -3 & 6 \end{pmatrix}^{1/2}$$

$10 \to 10 \otimes 8$

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} \Delta\pi & \Delta\eta & \Sigma K & \\ \Delta\overline{K} & \Sigma\pi & \Sigma\eta & \Xi K \\ \Sigma\overline{K} & \Xi\pi & \Xi\eta & \Omega K \\ & \Xi\overline{K} & \Omega\eta & \end{pmatrix} = \frac{1}{\sqrt{24}} \begin{pmatrix} & 15 & 3 & -6 \\ 8 & 8 & 0 & -8 \\ 12 & 3 & -3 & -6 \\ & 12 & -12 & \end{pmatrix}^{1/2}$$

abc	f_{abc}	*abc*	d_{abc}	*abc*	d_{abc}
123	1	118	$1/\sqrt{3}$	355	$1/2$
147	$1/2$	146	$1/2$	366	$-1/2$
156	$-1/2$	157	$1/2$	377	$-1/2$
246	$1/2$	228	$1/\sqrt{3}$	448	$-1/(2\sqrt{3})$
257	$1/2$	247	$-1/2$	558	$-1/(2\sqrt{3})$
345	$1/2$	256	$1/2$	668	$-1/(2\sqrt{3})$
367	$-1/2$	338	$1/\sqrt{3}$	778	$-1/(2\sqrt{3})$
458	$\sqrt{3}/2$	344	$1/2$	888	$-1/\sqrt{3}$
678	$\sqrt{3}/2$				

In the fundamental 3-dimensional representation, the λ_a's are

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

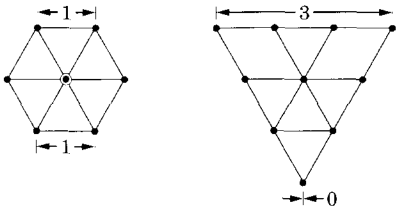
$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

SU(N) MULTIPLETS AND YOUNG DIAGRAMS

This note tells how SU(n) particle multiplets are identified or labeled, how to find the number of particles in a multiplet from its label, how to draw the Young diagram for a multiplet, and how to use Young diagrams to determine the overall multiplet structure of a composite system, such as a 3-quark or a meson-baryon system.

(1) Multiplet labels – An SU(n) multiplet is uniquely identified by a string of $(n-1)$ nonnegative integers: $(\alpha, \beta, \gamma, \ldots)$. Any such set of integers specifies a multiplet. For an SU(2) multiplet such as an isospin multiplet, the single integer α is the number of *steps* from one end of the multiplet to the other (i.e., it is one fewer than the number of particles in the multiplet). In SU(3), the two integers α and β are the numbers of steps across the top and bottom levels of the multiplet diagram. Thus the labels for the SU(3) octet and decuplet



are (1,1) and (3,0). For larger n, the interpretation of the integers in terms of the geometry of the multiplets, which exist in an $(n-1)$-dimensional space, is not so readily apparent.

The label for the SU(n) singlet is $(0, 0, \ldots, 0)$. In a flavor SU(n), the n quarks together form a $(1, 0, \ldots, 0)$ multiplet, and the n antiquarks belong to a $(0, \ldots, 0, 1)$ multiplet. These two multiplets are *conjugate* to one another, which means their labels are related by $(\alpha, \beta, \ldots) \leftrightarrow (\ldots, \beta, \alpha)$.

(2) Number of particles The number of particles in a multiplet, $N = N(\alpha, \beta, \ldots)$, is given as follows (note the pattern of the equations). In SU(2), $N = N(\alpha)$ is

$$N = \frac{(\alpha + 1)}{1} \; .$$

In SU(3), $N = N(\alpha, \beta)$ is

$$N = \frac{(\alpha + 1)}{1} \cdot \frac{(\beta + 1)}{1} \cdot \frac{(\alpha + \beta + 2)}{2} \; .$$

In SU(4), $N = N(\alpha, \beta, \gamma)$ is

$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \; .$$

Note that there is no factor with $(\alpha + \gamma + 2)$: only a *consecutive* sequence of the label integers appears in any factor. One more example should make the pattern clear for any SU(n). In SU(5), $N = N(\alpha, \beta, \gamma, \delta)$ is

$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\delta{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \times$$
$$\frac{(\gamma{+}\delta{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \cdot \frac{(\beta{+}\gamma{+}\delta{+}3)}{3} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}\delta{+}4)}{4} \; .$$

Multiplets that are conjugate to one another obviously have the same number of particles, but so can other multiplets. For example, the SU(4) multiplets (3,0,0) and (1,1,0) each have 20 particles.

(3) Young diagrams – A Young diagram consists of an array of boxes (or some other symbol) arranged in one or more *left-justified* rows, with each row being *at least as long* as the row beneath. The correspondence between a diagram and a multiplet label is: The top row juts out α boxes to the right past the end of the second row, the second row juts out β boxes to the right past the end of the third row, etc. A diagram in SU(n) has at most n rows. There can be any number of "completed" columns of n boxes buttressing the left of a diagram: these don't affect the label. Thus in SU(3) the diagrams

represent the multiplets (1,0), (0,1), (0,0), (1,1), and (3,0). In any SU(n), the quark multiplet is represented by a single box, the antiquark multiplet by a column of $(n-1)$ boxes, and a singlet by a completed column of n boxes.

(4) Coupling multiplets together – The following recipe tells how to find the multiplets that occur in coupling two multiplets together. To couple together more than two multiplets, first couple two, then couple the third with each of the multiplets obtained from the first two, etc.

First a definition: A sequence of the letters $a, b, c, \ldots$ is *admissible* if at any point in the sequence at least as many a's have occurred as b's, at least as many b's have occurred as c's, etc. Thus *abcd* and *aabcb* are admissible sequences and *abb* and *acb* are not. Now the recipe:

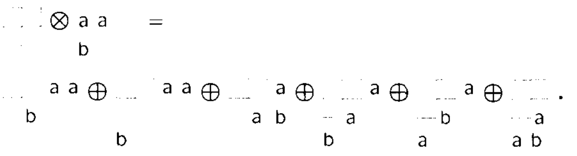
(a) Draw the Young diagrams for the two multiplets, but in one of the diagrams replace the boxes in the first row with a's, the boxes in the second row with b's, etc. The unlettered diagram forms the *upper left-hand corner* of all the enlarged diagrams constructed below.

(b) Add the a's from the lettered diagram to the unlettered diagram to form all possible legitimate Young diagrams that have no more than one a per column. (All the a's appear in each new diagram.)

(c) Use the b's to further enlarge the diagrams already obtained, subject to the same rules. Throw away any diagram in which the sequence of letters formed by reading *right to left* in the first row, then the second row, etc., is not admissible.

(d) Proceed as in (c) with the c's, etc.

Thus, for example, the calculation to find the multiplets that can occur in a system made up of two SU(3) octets (one might be the π-meson octet, the other the N-baryon octet) is as follows:



Here only the diagrams with admissible sequences and with fewer than four rows (since $n = 3$) have been kept. In terms of multiplet labels, the above may be written

$$(1,1) \otimes (1,1) = (2,2) \oplus (3,0) \oplus (0,3) \oplus (1,1) \oplus (1,1) \oplus (0,0) \; ,$$

or in terms of numbers of particles,

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} \; .$$

The product of the numbers on the left is equal to the sum on the right. (See the section on the Quark Model for results for 3-quark systems.)

C.M. ENERGY AND MOMENTUM VS. BEAM MOMENTUM

(for scattering on a fixed proton target)

(Formulae are given in Section B of the Kinematics section; this table may be dropped in future editions.)

$$E_{\text{cm}}\,dE_{\text{cm}} = m_p\,dT_{\text{beam}} = m_p\,\beta_{\text{beam}}\,dp_{\text{beam}}$$

p_{beam} (GeV/c)	E_{cm} (GeV) $\gamma p, \nu p$ $\approx ep$	πp	Kp	pp	Momentum in c.m. (GeV/c) $\gamma p, \nu p$ $\approx ep$	πp	Kp	pp
0.00	.938	1.078	1.432	1.877	.000	.000	.000	.000
0.02	.958	1.079	1.432	1.877	.020	.017	.013	.010
0.04	.977	1.083	1.433	1.877	.038	.035	.026	.020
0.06	.996	1.089	1.434	1.878	.056	.052	.039	.030
0.08	1.015	1.096	1.436	1.878	.074	.068	.052	.040
0.10	1.033	1.105	1.439	1.879	.091	.085	.065	.050
0.12	1.051	1.116	1.441	1.880	.107	.101	.078	.060
0.14	1.069	1.127	1.445	1.882	.123	.117	.091	.070
0.16	1.087	1.139	1.448	1.883	.138	.132	.104	.080
0.18	1.104	1.152	1.453	1.885	.153	.147	.116	.090
0.20	1.121	1.165	1.457	1.887	.167	.161	.129	.099
0.22	1.137	1.178	1.462	1.889	.182	.175	.141	.109
0.24	1.154	1.192	1.468	1.892	.195	.189	.153	.119
0.26	1.170	1.206	1.473	1.894	.209	.202	.166	.129
0.28	1.186	1.219	1.480	1.897	.222	.215	.178	.138
0.30	1.201	1.233	1.486	1.900	.234	.228	.189	.148
0.32	1.217	1.247	1.493	1.903	.247	.241	.201	.158
0.34	1.232	1.261	1.500	1.906	.259	.253	.213	.167
0.36	1.247	1.275	1.507	1.910	.271	.265	.224	.177
0.38	1.262	1.288	1.514	1.913	.282	.277	.235	.186
0.40	1.277	1.302	1.522	1.917	.294	.288	.247	.196
0.42	1.292	1.315	1.530	1.921	.305	.300	.258	.205
0.44	1.306	1.329	1.538	1.925	.316	.311	.268	.214
0.46	1.320	1.342	1.546	1.929	.327	.322	.279	.224
0.48	1.335	1.356	1.554	1.934	.337	.332	.290	.233
0.50	1.349	1.369	1.563	1.938	.348	.343	.300	.242
0.52	1.362	1.382	1.571	1.943	.358	.353	.310	.251
0.54	1.376	1.395	1.580	1.947	.368	.363	.321	.260
0.56	1.390	1.408	1.589	1.952	.378	.373	.331	.269
0.58	1.403	1.421	1.598	1.957	.388	.383	.341	.278
0.60	1.416	1.434	1.607	1.962	.397	.393	.350	.287
0.62	1.430	1.447	1.616	1.968	.407	.402	.360	.296
0.64	1.443	1.459	1.625	1.973	.416	.412	.370	.304
0.66	1.456	1.472	1.634	1.978	.425	.421	.379	.313
0.68	1.468	1.484	1.643	1.984	.434	.430	.388	.322
0.70	1.481	1.496	1.653	1.989	.443	.439	.397	.330
0.72	1.494	1.509	1.662	1.995	.452	.448	.406	.339
0.74	1.506	1.521	1.671	2.001	.461	.457	.415	.347
0.76	1.519	1.533	1.681	2.007	.470	.465	.424	.355
0.78	1.531	1.545	1.690	2.013	.478	.474	.433	.364
0.80	1.543	1.557	1.699	2.019	.486	.482	.442	.372
0.82	1.555	1.569	1.709	2.025	.495	.490	.450	.380
0.84	1.567	1.580	1.718	2.031	.503	.499	.459	.388
0.86	1.579	1.592	1.728	2.037	.511	.507	.467	.396
0.88	1.591	1.604	1.737	2.043	.519	.515	.475	.404
0.90	1.603	1.615	1.747	2.050	.527	.523	.484	.412
0.92	1.615	1.627	1.756	2.056	.535	.531	.492	.420
0.94	1.626	1.638	1.765	2.062	.542	.538	.500	.428
0.96	1.638	1.649	1.775	2.069	.550	.546	.508	.435
0.98	1.649	1.661	1.784	2.075	.558	.554	.515	.443
1.00	1.660	1.672	1.794	2.082	.565	.561	.523	.451
1.02	1.672	1.683	1.803	2.088	.573	.569	.531	.458
1.04	1.683	1.694	1.812	2.095	.580	.576	.538	.466
1.06	1.694	1.705	1.822	2.102	.587	.583	.546	.473
1.08	1.705	1.716	1.831	2.108	.594	.591	.553	.481
1.10	1.716	1.726	1.840	2.115	.601	.598	.561	.488
1.12	1.727	1.737	1.850	2.122	.609	.605	.568	.495
1.14	1.738	1.748	1.859	2.129	.616	.612	.575	.502
1.16	1.748	1.759	1.868	2.136	.622	.619	.583	.510
1.18	1.759	1.769	1.877	2.142	.629	.626	.590	.517
1.20	1.770	1.780	1.887	2.149	.636	.633	.597	.524
1.22	1.780	1.790	1.896	2.156	.643	.639	.604	.531
1.24	1.791	1.800	1.905	2.163	.650	.646	.611	.538
1.26	1.801	1.811	1.914	2.170	.656	.653	.618	.545
1.28	1.812	1.821	1.923	2.177	.663	.660	.624	.552
1.30	1.822	1.831	1.932	2.184	.669	.666	.631	.559
1.32	1.832	1.841	1.941	2.191	.676	.673	.638	.565
1.34	1.843	1.851	1.950	2.198	.682	.679	.645	.572
1.36	1.853	1.862	1.959	2.205	.689	.685	.651	.579
1.38	1.863	1.872	1.968	2.212	.695	.692	.658	.585
1.40	1.873	1.882	1.977	2.219	.701	.698	.664	.592
1.42	1.883	1.891	1.986	2.226	.708	.704	.671	.599
1.44	1.893	1.901	1.995	2.233	.714	.711	.677	.605
1.46	1.903	1.911	2.004	2.240	.720	.717	.684	.612
1.48	1.913	1.921	2.013	2.247	.726	.723	.690	.618
1.50	1.922	1.931	2.022	2.254	.732	.729	.696	.624
1.52	1.932	1.940	2.031	2.261	.738	.735	.702	.631
1.54	1.942	1.950	2.039	2.268	.744	.741	.709	.637
1.56	1.951	1.959	2.048	2.275	.750	.747	.715	.643
1.58	1.961	1.969	2.057	2.282	.756	.753	.721	.650
1.60	1.970	1.978	2.065	2.289	.762	.759	.727	.656
1.62	1.980	1.988	2.074	2.296	.768	.765	.733	.662
1.64	1.989	1.997	2.083	2.304	.773	.770	.739	.668
1.66	1.999	2.006	2.091	2.311	.779	.776	.745	.674
1.68	2.008	2.016	2.100	2.318	.785	.782	.751	.680

p_{beam} (GeV/c)	E_{cm} (GeV) $\gamma p, \nu p$ $\approx ep$	πp	Kp	pp	Momentum in c.m. (GeV/c) $\gamma p, \nu p$ $\approx ep$	πp	Kp	pp
1.70	2.018	2.025	2.109	2.325	.791	.788	.756	.686
1.72	2.027	2.034	2.117	2.332	.796	.793	.762	.692
1.74	2.036	2.043	2.126	2.339	.802	.799	.768	.698
1.76	2.045	2.053	2.134	2.346	.807	.805	.774	.704
1.78	2.054	2.062	2.143	2.353	.813	.810	.780	.710
1.80	2.064	2.071	2.151	2.360	.818	.816	.785	.716
1.82	2.073	2.080	2.159	2.367	.824	.821	.791	.721
1.84	2.082	2.089	2.168	2.374	.829	.827	.796	.727
1.86	2.091	2.098	2.176	2.381	.835	.832	.802	.733
1.88	2.100	2.107	2.184	2.388	.840	.837	.808	.739
1.90	2.109	2.115	2.193	2.395	.845	.843	.813	.744
1.92	2.117	2.124	2.201	2.402	.851	.848	.819	.750
1.94	2.126	2.133	2.209	2.409	.856	.853	.824	.756
1.96	2.135	2.142	2.217	2.416	.861	.859	.829	.761
1.98	2.144	2.151	2.226	2.423	.867	.864	.835	.767
2.0	2.153	2.159	2.234	2.430	.872	.869	.840	.772
2.1	2.196	2.202	2.274	2.465	.897	.895	.866	.799
2.2	2.238	2.244	2.314	2.500	.922	.920	.892	.826
2.3	2.280	2.286	2.353	2.534	.947	.944	.917	.852
2.4	2.320	2.326	2.392	2.568	.970	.968	.941	.877
2.5	2.360	2.366	2.430	2.602	.994	.991	.965	.901
2.6	2.400	2.405	2.468	2.636	1.02	1.01	.989	.926
2.7	2.439	2.444	2.505	2.669	1.04	1.04	1.01	.949
2.8	2.477	2.482	2.542	2.702	1.06	1.06	1.03	.972
2.9	2.514	2.520	2.578	2.735	1.08	1.08	1.06	.995
3.0	2.551	2.556	2.613	2.768	1.10	1.10	1.08	1.02
3.1	2.588	2.593	2.649	2.800	1.12	1.12	1.10	1.04
3.2	2.624	2.629	2.683	2.832	1.14	1.14	1.12	1.06
3.3	2.660	2.664	2.718	2.863	1.16	1.16	1.14	1.08
3.4	2.695	2.699	2.752	2.895	1.18	1.18	1.16	1.10
3.5	2.729	2.734	2.785	2.926	1.20	1.20	1.18	1.12
3.6	2.763	2.768	2.818	2.957	1.22	1.22	1.20	1.14
3.7	2.797	2.801	2.851	2.987	1.24	1.24	1.22	1.16
3.8	2.830	2.835	2.884	3.018	1.26	1.26	1.24	1.18
3.9	2.863	2.868	2.916	3.048	1.28	1.28	1.26	1.20
4.0	2.896	2.900	2.947	3.077	1.30	1.29	1.27	1.22
4.1	2.928	2.932	2.979	3.107	1.31	1.31	1.29	1.24
4.2	2.960	2.964	3.010	3.136	1.33	1.33	1.31	1.26
4.3	2.992	2.996	3.041	3.165	1.35	1.35	1.33	1.27
4.4	3.023	3.027	3.071	3.194	1.37	1.36	1.34	1.29
4.5	3.054	3.058	3.101	3.223	1.38	1.38	1.36	1.31
4.6	3.084	3.088	3.131	3.251	1.40	1.40	1.38	1.33
4.7	3.115	3.118	3.161	3.279	1.42	1.41	1.40	1.34
4.8	3.144	3.148	3.190	3.307	1.43	1.43	1.41	1.36
4.9	3.174	3.178	3.220	3.335	1.45	1.45	1.43	1.38
5.0	3.204	3.207	3.248	3.363	1.46	1.46	1.44	1.40
5.2	3.262	3.265	3.305	3.417	1.50	1.49	1.48	1.43
5.4	3.319	3.322	3.362	3.471	1.53	1.53	1.51	1.46
5.6	3.375	3.378	3.417	3.524	1.56	1.56	1.54	1.49
5.8	3.430	3.433	3.471	3.576	1.59	1.59	1.57	1.52
6.0	3.484	3.487	3.524	3.627	1.62	1.61	1.60	1.55
6.2	3.538	3.541	3.577	3.678	1.64	1.64	1.63	1.58
6.4	3.590	3.593	3.629	3.728	1.67	1.67	1.65	1.61
6.6	3.642	3.645	3.680	3.778	1.70	1.70	1.68	1.64
6.8	3.693	3.696	3.731	3.827	1.73	1.73	1.71	1.67
7.0	3.744	3.747	3.781	3.875	1.75	1.75	1.74	1.70
7.2	3.794	3.797	3.830	3.923	1.78	1.78	1.76	1.72
7.4	3.843	3.846	3.878	3.970	1.81	1.81	1.79	1.75
7.6	3.891	3.894	3.926	4.016	1.83	1.83	1.82	1.78
7.8	3.939	3.942	3.974	4.062	1.86	1.86	1.84	1.80
8.0	3.987	3.989	4.021	4.108	1.88	1.88	1.87	1.83
8.2	4.033	4.036	4.067	4.153	1.91	1.91	1.89	1.85
8.4	4.080	4.082	4.113	4.198	1.93	1.93	1.92	1.88
8.6	4.125	4.128	4.158	4.242	1.96	1.95	1.94	1.90
8.8	4.171	4.173	4.203	4.286	1.98	1.98	1.96	1.93
9.0	4.215	4.218	4.247	4.329	2.00	2.00	1.99	1.95
9.2	4.260	4.262	4.291	4.372	2.03	2.03	2.01	1.97
9.4	4.303	4.306	4.335	4.415	2.05	2.05	2.03	2.00
9.6	4.347	4.349	4.378	4.457	2.07	2.07	2.06	2.02
9.8	4.390	4.392	4.420	4.498	2.09	2.09	2.08	2.04
10.0	4.432	4.435	4.462	4.540	2.12	2.12	2.10	2.07
10.5	4.537	4.539	4.566	4.641	2.17	2.17	2.16	2.12
11.0	4.639	4.642	4.668	4.741	2.22	2.22	2.21	2.18
11.5	4.739	4.742	4.767	4.839	2.28	2.28	2.26	2.23
12.0	4.837	4.839	4.864	4.934	2.33	2.33	2.31	2.28
12.5	4.933	4.935	4.960	5.028	2.38	2.38	2.36	2.33
13.0	5.027	5.030	5.053	5.120	2.43	2.43	2.41	2.38
13.5	5.120	5.122	5.145	5.211	2.47	2.47	2.46	2.43
14.0	5.211	5.213	5.236	5.300	2.52	2.52	2.51	2.48
14.5	5.300	5.302	5.324	5.388	2.57	2.57	2.56	2.53
15.0	5.388	5.390	5.412	5.474	2.61	2.61	2.60	2.57
15.5	5.474	5.476	5.498	5.559	2.66	2.66	2.65	2.62
16.0	5.559	5.561	5.582	5.642	2.70	2.70	2.69	2.66
16.5	5.643	5.645	5.666	5.725	2.74	2.74	2.73	2.70
17.0	5.726	5.727	5.748	5.806	2.79	2.79	2.78	2.75

p_{beam} (GeV/c)	E_{cm} (GeV) $\gamma p, \nu p$ $\approx ep$	πp	Kp	pp	Momentum in c.m. (GeV/c) $\gamma p, \nu p$ $\approx ep$	πp	Kp	pp
17.5	5.807	5.809	5.829	5.886	2.83	2.83	2.82	2.79
18.0	5.887	5.889	5.909	5.965	2.87	2.87	2.86	2.83
18.5	5.966	5.968	5.988	6.043	2.91	2.91	2.90	2.87
19.0	6.044	6.046	6.066	6.120	2.95	2.95	2.94	2.91
19.5	6.122	6.123	6.142	6.196	2.99	2.99	2.98	2.95
20	6.198	6.199	6.218	6.272	3.03	3.03	3.02	2.99
21	6.347	6.349	6.367	6.419	3.10	3.10	3.09	3.07
22	6.493	6.495	6.513	6.564	3.18	3.18	3.17	3.14
23	6.636	6.638	6.655	6.705	3.25	3.25	3.24	3.22
24	6.776	6.778	6.795	6.843	3.32	3.32	3.31	3.29
25	6.913	6.915	6.932	6.979	3.39	3.39	3.38	3.36
26	7.048	7.049	7.066	7.112	3.46	3.46	3.45	3.43
27	7.180	7.181	7.197	7.243	3.53	3.53	3.52	3.50
28	7.309	7.311	7.326	7.371	3.59	3.59	3.59	3.56
29	7.436	7.438	7.453	7.497	3.66	3.66	3.65	3.63
30	7.562	7.563	7.578	7.621	3.72	3.72	3.71	3.69
31	7.685	7.686	7.701	7.743	3.79	3.78	3.78	3.76
32	7.806	7.807	7.822	7.864	3.85	3.85	3.84	3.82
33	7.925	7.926	7.941	7.982	3.91	3.91	3.90	3.88
34	8.043	8.044	8.058	8.099	3.97	3.97	3.96	3.94
35	8.158	8.160	8.174	8.214	4.03	4.02	4.02	4.00
36	8.273	8.274	8.288	8.327	4.08	4.08	4.08	4.06
37	8.385	8.386	8.400	8.439	4.14	4.14	4.13	4.11
38	8.496	8.498	8.511	8.549	4.20	4.20	4.19	4.17
39	8.606	8.607	8.621	8.658	4.25	4.25	4.24	4.23
40	8.715	8.716	8.729	8.766	4.31	4.31	4.30	4.28
41	8.822	8.823	8.836	8.872	4.36	4.36	4.35	4.34
42	8.927	8.928	8.941	8.978	4.41	4.41	4.41	4.39
43	9.032	9.033	9.046	9.081	4.47	4.47	4.46	4.44
44	9.135	9.136	9.149	9.184	4.52	4.52	4.51	4.50
45	9.237	9.238	9.251	9.286	4.57	4.57	4.56	4.55
46	9.338	9.339	9.352	9.386	4.62	4.62	4.62	4.60
47	9.438	9.439	9.451	9.486	4.67	4.67	4.67	4.65
48	9.537	9.538	9.550	9.584	4.72	4.72	4.72	4.70
49	9.635	9.636	9.648	9.681	4.77	4.77	4.77	4.75
50	9.732	9.733	9.745	9.778	4.82	4.82	4.81	4.80
52	9.923	9.924	9.935	9.968	4.92	4.92	4.91	4.89
54	10.11	10.11	10.12	10.15	5.01	5.01	5.01	4.99
56	10.29	10.30	10.31	10.34	5.10	5.10	5.10	5.08
58	10.47	10.48	10.49	10.52	5.20	5.19	5.19	5.17
60	10.65	10.65	10.66	10.69	5.28	5.28	5.28	5.26
62	10.83	10.83	10.84	10.87	5.37	5.37	5.37	5.35
64	11.00	11.00	11.01	11.04	5.46	5.46	5.45	5.44
66	11.17	11.17	11.18	11.21	5.54	5.54	5.54	5.53
68	11.34	11.34	11.35	11.37	5.63	5.63	5.62	5.61
70	11.50	11.50	11.51	11.54	5.71	5.71	5.71	5.69
72	11.66	11.66	11.67	11.70	5.79	5.79	5.79	5.77
74	11.82	11.82	11.83	11.86	5.87	5.87	5.87	5.85
76	11.98	11.98	11.99	12.02	5.95	5.95	5.95	5.93
78	12.13	12.14	12.14	12.17	6.03	6.03	6.03	6.01
80	12.29	12.29	12.30	12.32	6.11	6.11	6.10	6.09
82	12.44	12.44	12.45	12.48	6.18	6.18	6.18	6.17
84	12.59	12.59	12.60	12.63	6.26	6.26	6.26	6.24
86	12.74	12.74	12.75	12.77	6.33	6.33	6.33	6.32
88	12.88	12.89	12.89	12.92	6.41	6.41	6.40	6.39
90	13.03	13.03	13.04	13.06	6.48	6.48	6.48	6.46
92	13.17	13.17	13.18	13.21	6.55	6.55	6.55	6.54
94	13.31	13.32	13.32	13.35	6.62	6.62	6.62	6.61
96	13.45	13.46	13.46	13.49	6.69	6.69	6.69	6.68
98	13.59	13.59	13.60	13.63	6.76	6.76	6.76	6.75
100	13.73	13.73	13.74	13.76	6.83	6.83	6.83	6.82
150	16.80	16.80	16.81	16.83	8.38	8.38	8.37	8.36
200	19.40	19.40	19.40	19.42	9.68	9.67	9.67	9.66
250	21.68	21.68	21.69	21.70	10.8	10.8	10.8	10.8
300	23.75	23.75	23.75	23.76	11.9	11.9	11.9	11.8
350	25.65	25.65	25.65	25.66	12.8	12.8	12.8	12.8
400	27.41	27.41	27.42	27.43	13.7	13.7	13.7	13.7
450	29.07	29.07	29.08	29.09	14.5	14.5	14.5	14.5
500	30.65	30.65	30.65	30.66	15.3	15.3	15.3	15.3
550	32.14	32.14	32.14	32.15	16.1	16.1	16.1	16.0
600	33.57	33.57	33.57	33.58	16.8	16.8	16.8	16.8
650	34.94	34.94	34.94	34.95	17.5	17.5	17.5	17.4
700	36.26	36.26	36.26	36.27	18.1	18.1	18.1	18.1
800	38.76	38.76	38.76	38.77	19.4	19.4	19.4	19.4
900	41.11	41.11	41.11	41.12	20.5	20.5	20.5	20.5
1000	43.33	43.33	43.33	43.34	21.7	21.7	21.7	21.6
2000	61.27	61.27	61.27	61.28	30.6	30.6	30.6	30.6
5000	96.87	96.87	96.87	96.87	48.4	48.4	48.4	48.4
10000	137.0	137.0	137.0	137.0	68.5	68.5	68.5	68.5
20000	193.7	193.7	193.7	193.7	96.9	96.9	96.9	96.9
50000	306.3	306.3	306.3	306.3	153	153	153	153
1×10^5	433.2	433.2	433.2	433.2	217	217	217	217
2×10^5	612.6	612.6	612.6	612.6	306	306	306	306
5×10^5	968.6	968.6	968.6	968.6	484	484	484	484
1×10^6	1370	1370	1370	1370	685	685	685	685

KINEMATICS*

Throughout this section units are used in which $\hbar = c = 1$. The following conversions are useful: $\hbar c = 197.3$ MeV fermi, $(\hbar c)^2 = 0.3894\ (\text{GeV})^2$ mb.

A. LORENTZ TRANSFORMATIONS

The energy E and 3-momentum $\vec{p}$ of a particle of mass m form a 4-vector $p = (E, \vec{p})$ whose square $p^2 \equiv E^2 - |\vec{p}|^2 = m^2$. The velocity of the particle is $\vec{\beta} = \vec{p}/E$. The energy and momentum $(E^*, \vec{p}^{\,*})$ viewed from a frame moving with velocity $\vec{\beta}_f$ are given by

$$\begin{pmatrix} E^* \\ p_\parallel^* \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f\beta_f \\ -\gamma_f\beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_\parallel \end{pmatrix} , \quad p_\perp^* = p_\perp , \tag{A.1}$$

where $\gamma_f = (1 - \beta_f^2)^{-1/2}$ and $p_\perp$ $(p_\parallel)$ are the components of $\vec{p}$ perpendicular (parallel) to $\vec{\beta}_f$. The scalar product of two 4-vectors $p_1 \cdot p_2 = E_1E_2 - \vec{p}_1 \cdot \vec{p}_2$ is invariant (frame independent).

In the collision of two particles of masses m_1 and m_2 the total center-of-mass energy is

$$E_{\text{cm}} = (p_1 + p_2)^{1/2} = \left[(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2\right]^{1/2} ,$$
$$= \left[m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta)\right]^{1/2} , \tag{A.2}$$

where θ is the angle between the particles. In the frame where one particle (of mass m_2) is at rest (lab frame),

$$E_{\text{cm}} = (m_1^2 + m_2^2 + 2E_{1\,\text{lab}}\, m_2)^{1/2} . \tag{A.3}$$

The velocity in the lab of the center-of-mass frame is

$$\vec{\beta}_{\text{cm}} = \vec{p}_{1\,\text{lab}}/(E_{1\,\text{lab}} + m_2) , \tag{A.4}$$

and

$$\gamma_{\text{cm}} = (E_{1\,\text{lab}} + m_2)/E_{\text{cm}} .$$

B. CENTER OF MASS ENERGY AND MOMENTUM

A beam of particles with mass m and momentum p_{beam} is incident on a fixed target consisting of particles with mass M. The energy of the beam particles E_{beam}, the center-of-mass energy E_{cm}, and center of mass momentum of one of the particles p_{cm} are given by

$$E_{\text{beam}} = \sqrt{p_{\text{beam}}^2 + m^2}$$
$$E_{\text{cm}} = \sqrt{m^2 + 2E_{\text{beam}}M + M^2}$$
$$p_{\text{cm}} = p_{\text{beam}}\frac{M}{E_{\text{cm}}} .$$

For example, if a 0.80 GeV/c kaon beam is incident on a proton target, the center of mass energy is 1.699 GeV and the center of mass momentum of either particle is 0.442 GeV/c. It is also useful to note that

$$E_{\text{cm}}\, dE_{\text{cm}} = M\, dE_{\text{beam}} = M\,\beta_{\text{beam}}\, dp_{\text{beam}} .$$

C. LORENTZ INVARIANT AMPLITUDES

The invariant amplitude $-i\mathcal{M}$ for a scattering or decay process is determined in perturbation theory by a set of Feynman diagrams. The convention of Bjorken and Drell is used except that fermion spinors are normalized so that $u\bar{u} = 2m$. As an example, the S-matrix for $2 \to 2$ scattering is related to $\mathcal{M}$ by

$$\langle p_1'p_2'\,|S|\,p_1p_2\rangle = I - i(2\pi)^4\,\delta^4(p_1 + p_2 - p_1' - p_2')$$
$$\times \frac{\mathcal{M}(p_1,\, p_2;\, p_1',\, p_2')}{(2E_1)^{1/2}\,(2E_2)^{1/2}\,(2E_1')^{1/2}\,(2E_2')^{1/2}} . \tag{C.1}$$

The state normalization is such that

$$\langle p'|p\rangle = (2\pi)^3\delta^3(\vec{p} - \vec{p}\,') . \tag{C.2}$$

D. PARTICLE DECAYS

The partial decay rate of a particle of mass M into n bodies in its rest frame is given in terms of the Lorentz invariant matrix element $\mathcal{M}$ by

$$d\Gamma = \frac{(2\pi)^4}{2M}\,|\mathcal{M}|^2\, d\Phi_n\,(P;\, p_1,\, \ldots,\, p_n), \tag{D.1}$$

where $d\Phi_n$ is an element of n-body phase space given by

$$d\Phi_n(P;\, p_1,\, \ldots,\, p_n) = \delta^4\,(P - \sum_{i=1}^{n} p_i)\,\prod_{i=1}^{n}\frac{d^3p_i}{(2\pi)^3 2E_i} . \tag{D.2}$$

This phase space can be generated recursively, viz.

$$d\Phi_n(P;\, p_1,\, \ldots,\, p_n) = d\Phi_j(q;\, p_1,\, \ldots,\, p_j) \tag{D.3}$$
$$\times\ d\Phi_{n-j+1}\,(P;\, q,\, p_{i+1},\, \ldots,\, p_n)(2\pi)^3 dq^2 ,$$

where $q^2 = (\sum_{i=j+1}^{n} E_i)^2 - \left|\sum_{i=j+1}^{n} \vec{p}_i\right|^2$. This form is particularly useful in the case where a particle decays into another particle which subsequently decays.

D.1 Survival probability:

If a particle of mass M has mean proper lifetime τ $(= 1/\Gamma)$ and has momentum $(E, \vec{p})$, then the probability that it lives for a time t_0 or greater before decaying is given by

$$P(t_0) = e^{-t_0\,\Gamma/\gamma} = e^{-Mt_0\,\Gamma/E} , \tag{D.4}$$

and the probability that it travels a distance x_0 or greater is

$$P(x_0) = e^{-Mx_0\,\Gamma/|\vec{p}|} . \tag{D.5}$$

D.2 Two-body decays:

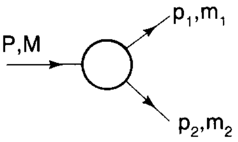


Fig. 1. Variable definitions for two-body decays.

In the rest frame of a particle of mass M, decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} ,$$
$$|\vec{p}_1| = |\vec{p}_2| \tag{D.6}$$
$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M} ,$$

and

$$d\Gamma = \frac{1}{32\pi^2}\,|\mathcal{M}|^2\,\frac{|\vec{p}_1|}{M^2}\,d\Omega , \tag{D.7}$$

where $d\Omega = d\phi_1 d(\cos\theta_1)$ is the solid angle of particle 1.

D.3 Three-body decays:

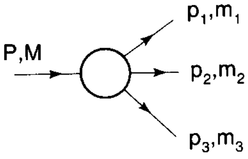


Fig. 2. Variable definitions for three-body decays.

Defining $p_{ij} = p_i + p_j$, $m_{ij}^2 = p_{ij}^2$, then $m_{12}^2 + m_{23}^2 + m_{13}^2 = M^2 + m_1^2 + m_2^2 + m_3^2$ and $m_{12}^2 = (P - p_3)^2 = M^2 + m_3^2 - 2ME_3$. The relative orientation of the three final-state particles is fixed if their energies are known. Their momenta can therefore be specified by giving three Euler angles (α, β, γ) which specify the orientation of the final system relative to the initial particle. Then

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M} \, |\mathcal{M}|^2 \, dE_1 \, dE_2 \, d\alpha \, d\cos\beta \, d\gamma \ . \tag{D.8}$$

Alternatively

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M^2} \, |\mathcal{M}|^2 \, |\vec{p}_1^{\,*}| \, |\vec{p}_3| \, dm_{12} \, d\Omega_1^* \, d\Omega_3 \ , \tag{D.9}$$

where $(|\vec{p}_1^{\,*}|, \Omega_1^*)$ is the momentum of particle 1 in the rest frame of 1 and 2, and Ω_3 is the angle of particle 3 in the rest frame of the decaying particle. $|\vec{p}_1^{\,*}|$ and $|\vec{p}_3|$ are given by

$$|\vec{p}_1^{\,*}| = \frac{\left[\left(m_{12}^2 - (m_1 + m_2)^2\right)\left(m_{12}^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2m_{12}} \ ,$$

and

$$|\vec{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M} \ . \tag{D.10}$$

[Compare with Eq. (D.6).]

Integrating over the angles in Eq. (D.8) (this is only possible if the decaying particle is a scalar or we average over its spin states; otherwise $\mathcal{M}$ depends on α, β, and γ) gives

$$\begin{aligned} d\Gamma &= \frac{1}{(2\pi)^3} \frac{1}{8M} \, |\mathcal{M}|^2 \, dE_1 \, dE_2 \\ &= \frac{1}{(2\pi)^3} \frac{1}{32M^3} \, |\mathcal{M}|^2 \, dm_{12}^2 \, dm_{23}^2 \ . \end{aligned} \tag{D.11}$$

This is the standard form for the Dalitz plot.

D.3.1 Dalitz plot:

If m_{12}^2 is fixed then the range of m_{13}^2 is determined by its values when $\vec{p}_1$ is parallel or antiparallel to $\vec{p}_3$.

$$(m_{13}^2)_{\max} = (E_1^* + E_3^*)^2 - \left(\sqrt{E_1^{*2} - m_1^2} - \sqrt{E_3^{*2} - m_3^2}\right)^2 \ .$$

$$(m_{13}^2)_{\min} = (E_1^* + E_3^*)^2 - \left(\sqrt{E_1^{*2} - m_1^2} + \sqrt{E_3^{*2} - m_3^2}\right)^2 \ .$$

where $E_3^* = (M^2 - m_{12}^2 - m_3^2)/(2m_{12})$ and $E_1^* = (m_{12}^2 + m_1^2 - m_2^2)/(2m_{12})$. The scatter plot in m_{12}^2 and m_{13}^2 has uniform phase space density [see Eq. (D.11)] and is called a Dalitz plot.

A nonuniformity in the plot gives immediate information on $|\mathcal{M}|^2$. For example, in the case of $D \to K\pi\pi$, bands appear when $m_{(K\pi)} = m_{K^*(892)}$, reflecting the appearance of the decay chain $D \to K^*(892)\pi \to K\pi\pi$.

D.4 Kinematic limits:

In a three-body decay the maximum of $|\vec{p}_3|$, [given by Eq. (D.10)], is achieved when $m_{12} = m_1 + m_2$, i.e., particles 1 and 2 have the same vector velocity in the rest frame of the decaying particle. If, in addition, $m_3 > m_1, m_2$, then $|\vec{p}_3|_{\max} > |\vec{p}_1|_{\max}$, $|\vec{p}_2|_{\max}$.

D.5 Multibody decays:

The above results may be generalized to final states containing any number of particles by combining some of the particles into "effective particles" and treating the final states as 2 or 3 "effective particle" states. Thus, if $p_{ijk\ldots} = p_i + p_j + p_k + \ldots$, then

$$m_{ijk\ldots} = \sqrt{p^2{}_{ijk\ldots}} \ ,$$

and $m_{ijk\ldots}$ may be used in place of e.g., m_{12} in the relations in Sec. D.3 or D.3.1 above.

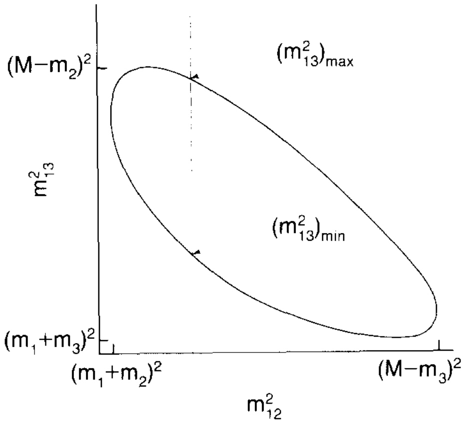


Fig. 3. Dalitz plot for a three-body final state. Four-momentum conservation restricts events to the interior of the closed curve.

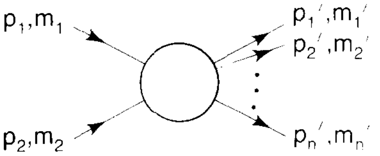


Fig. 4. Variable definitions for production of an n-body final state.

E. CROSS SECTIONS

The differential cross section is given by

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2;\, p_3, \ldots, p_{n+2}) \ . \tag{E.1}$$

[See Eq. (D.2).] In the rest frame of m_2(lab),

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = m_2 p_{1\,\text{lab}} \ ;$$

while in the center-of-mass frame

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = p_{1\text{cm}} \sqrt{s} \ .$$

E.1 Two-body reactions:

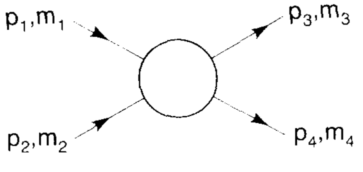


Fig. 5. Variable definitions for a two-body final state.

Two particles of momenta p_1 and p_2 and masses m_1 and m_2 scatter to particles of momenta p_3 and p_4 and masses m_3 and m_4; the Lorentz

KINEMATICS (Cont'd)

invariant Mandelstam variables are defined by

$$\begin{aligned} s &= (p_1 + p_2)^2 = (p_3 + p_4)^2 \\ &= m_1^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2 + m_2^2 \ , \\ t &= (p_1 - p_3)^2 = (p_2 - p_4)^2 \\ &= m_1^2 - 2E_1E_3 + 2\vec{p}_1 \cdot \vec{p}_3 + m_3^2 \ , \\ u &= (p_1 - p_4)^2 = (p_2 - p_3)^2 \\ &= m_1^2 - 2E_1E_4 + 2\vec{p}_1 \cdot \vec{p}_4 + m_4^2 \ , \end{aligned} \tag{E.2}$$

and they satisfy

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2 \ .$$

The two-body cross section may be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{p}_{1\text{cm}}|^2} |\mathcal{M}|^2 \ . \tag{E.3}$$

In the center-of-mass frame

$$\begin{aligned} t &= (E_{1\text{cm}} - E_{3\text{cm}})^2 - (p_{1\text{cm}} - p_{3\text{cm}})^2 \\ &\quad -4p_{1\text{cm}}\, p_{3\text{cm}} \sin^2(\theta_{\text{cm}}/2) \\ &= t_0 - 4p_{1\text{cm}}\, p_{3\text{cm}} \sin^2(\theta_{\text{cm}}/2) \ , \end{aligned} \tag{E.4}$$

where θ_{cm} is the angle between particle 1 and 3.

$$\begin{aligned} t_{\mp} = {} & \left[\frac{m_1^2 - m_3^2 - m_2^2 + m_4^2}{2\sqrt{s}}\right]^2 \\ & - \left\{ \left[\left(\frac{s + m_1^2 - m_2^2}{2\sqrt{s}}\right)^2 - m_1^2\right]^{1/2} \right. \\ & \left. \mp \left[\left(\frac{s + m_3^2 - m_4^2}{2\sqrt{s}}\right)^2 - m_3^2\right]^{1/2} \right\}^2 \ . \end{aligned} \tag{E.5}$$

Note that t_- (t_+) is the largest (smallest) value of t for 2 → 2 scattering processes and that t_+ is always negative. In the literature the notation t_{min} (t_{max}) for t_- (t_+) is sometimes used. This usage should be discouraged since $t_- > t_+$. The center-of-mass energies and momenta of the incoming particles are

$$E_{\text{cm}} = \frac{s + m_1^2 - m_2^2}{2\sqrt{s}} \ , \tag{E.6}$$

$$\begin{aligned} p_{\text{cm}} &= \frac{\left[\left(s - (m_1 + m_2)^2\right)\left(s - (m_1 - m_2)^2\right)\right]^{1/2}}{2\sqrt{s}} \\ &= \frac{p_{1\,\text{lab}} m_2}{\sqrt{s}} \ , \end{aligned} \tag{E.7}$$

Here the subscript lab refers to the frame where particle 2 is at rest. [For other relations see Eqs. (A2–A4).]

E.2 Inclusive reactions:

Choose some direction (usually the beam direction) for the z-axis; then the energy and momentum of a particle can be written as

$$E = m_\perp \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_\perp \sinh y \ ,$$

where $m_\perp$ is the transverse mass

$$m_\perp^2 = m^2 + p_x^2 + p_y^2 \ ,$$

and the rapidity y is defined by

$$\begin{aligned} y &= \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z}\right) \\ &= \ln \left(\frac{E + p_z}{m_\perp}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right) \ . \end{aligned} \tag{E.8}$$

Under a boost in the z-direction to a frame with velocity β, $y \to y + \tanh^{-1}\beta$. Hence the shape of the rapidity distribution dN/dy is invariant. The invariant cross section may also be rewritten

$$E\frac{d^3\sigma}{dp^3} = \frac{d^3\sigma}{dy\, dp_\perp^2} \ .$$

Feynman's x variable is given by

$$x = \frac{p_z}{p_{z\text{max}}} \approx \left(\frac{E + p_z}{(E + p_z)_{\text{max}}}\right) \ ;$$

in the center-of-mass frame,

$$x \approx \frac{2p_{z\text{cm}}}{\sqrt{s}} \approx \frac{2m_\perp \sinh y_{\text{cm}}}{\sqrt{s}} \ . \tag{E.9}$$

For y_{cm} such that $e^{-2y_{\text{cm}}} \ll 1$,

$$x \approx \frac{m_\perp}{\sqrt{s}} e^{y_{\text{cm}}}$$

and

$$(y_{\text{cm}})_{\text{max}} = \ln\left(\sqrt{s}/m\right) \ .$$

The definition of rapidity [Eq. (E.8)] may be expanded to obtain

$$\begin{aligned} y &= \frac{1}{2} \ln \frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots} \\ &\approx -\ln \tan(\theta/2) \equiv \eta \end{aligned} \tag{E.10}$$

if the particle has zenith angle θ. The pseudorapidity η defined by the second line is approximately equal to the rapidity y for $m \gg p$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

$$\begin{aligned} &\sinh \eta = \cot \theta \\ &\cosh \eta = 1/\sin \theta \\ &\tanh \eta = \cos \theta \ . \end{aligned}$$

E.3 Partial waves:

The amplitude in the center of mass for elastic scattering of spinless particles may be expanded in Legendre polynomials

$$f(k, \theta) = \frac{1}{k} \sum_\ell (2\ell + 1) a_\ell P_\ell(\cos \theta) \ , \tag{E.11}$$

where k is the c.m. momentum, θ is the c.m. scattering angle, $a_\ell = (\eta_\ell e^{2i\delta_\ell} - 1)/2i$, $0 \le \eta_\ell \le 1$, and δ_ℓ is the phase shift of the ℓ^{th} partial wave. For purely elastic scattering, $\eta_\ell = 1$. The differential cross section is

$$\frac{d\sigma}{d\Omega} = |f(k, \theta)|^2 \ .$$

The optical theorem states that

$$\sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im}\, f(k, 0) \ , \tag{E.12}$$

and the cross section in the ℓ^{th} partial wave is therefore bounded:

$$\sigma_\ell = \frac{4\pi}{k^2}(2\ell + 1)|a_\ell|^2 \le \frac{4\pi(2\ell + 1)}{k^2} \ . \tag{E.13}$$

The partial-wave amplitude a_ℓ can be displayed in an Argand plot.

The usual Lorentz invariant matrix element $\mathcal{M}$ (see Sec. C above) for the elastic process is related to $f(k, \theta)$ by

$$\mathcal{M} = -8\pi\sqrt{s}\, f(k, \theta) \ ,$$

so

$$\sigma_{\text{tot}} = -\frac{1}{2k\sqrt{s}} \text{Im}\, \mathcal{M}(t = 0) \ , \tag{E.14}$$

where s and t are the center-of-mass energy squared and momentum transfer squared, respectively (see Sec. D.1).

KINEMATICS (Cont'd)

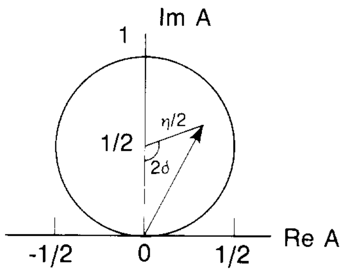


Fig. 6. Argand plot for the display of a partial-wave amplitude as a function of energy.

E.3.1 Resonances:

The Breit-Wigner form for a_ℓ with a resonance at c.m. energy E_R, elastic width $\Gamma_{\rm el}$, and total width $\Gamma_{\rm tot}$ is

$$a_\ell = \frac{\Gamma_{\rm el}/2}{E_R - E - i\Gamma_{\rm tot}/2}\ , \tag{E.15}$$

where E is the c.m. energy. This gives a circle in the Argand plot with center $ix_{\rm el}/2$ and radius $x_{\rm el}/2$, where the elasticity $x_{\rm el} = \Gamma_{\rm el}/\Gamma_{\rm tot}$. The amplitude has a pole at $E = E_R - i\Gamma_{\rm tot}/2$.

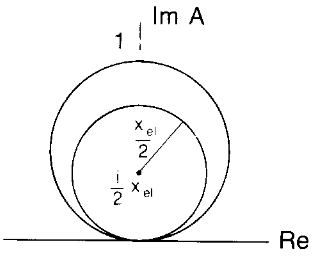


Fig. 7. Argand plot for a resonance.

The Breit-Wigner cross section for a spin-J resonance produced in the collision of particles of spin S_1 and S_2 is

$$\sigma_{BW}(E) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)}\,\frac{\pi}{k^2}\,\frac{B_{\rm in}B_{\rm out}\Gamma^2_{\rm tot}}{(E-E_R)^2+\Gamma^2_{\rm tot}/4}\ ,$$

where k is the c.m. momentum, E is the c.m. energy, and $B_{\rm in}$ and $B_{\rm out}$ are the branching fractions of the resonance into the entrance and exit channels. The $2S+1$ factors are the multiplicities of the incident spin states, so they are replaced by 2 for photons, etc. This expression is valid only for a particle of narrow width. If the width is not small, $\Gamma_{\rm tot}$ cannot be treated as a constant independent of E. There are many other forms for σ_{BW}, all of which are equivalent to the one given here in the narrow-width case. Some of these forms may be more appropriate if the resonance is broad.

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* Revised April 1990 with the assistance of K. Kajantie.

CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES

A. LEPTOPRODUCTION

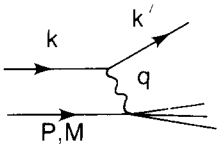

Fig. 1. Kinematic quantities for description of lepton-nucleon scattering. k and k' are the four-momenta of incoming and outgoing leptons, P is the four-momentum of a nucleon with mass M. The exchanged particle is a γ, $W^\pm$, or Z^0; it transfers four-momentum $q = k - k'$ to the target.

Invariant quantities:

$\nu = \dfrac{q\cdot P}{M} = E - E'$ is the lepton's energy loss in the lab (in earlier literature sometimes $\nu = q\cdot P$). Here, E and E' are the initial and final lepton energies in the lab.

$Q^2 = -q^2 = 2(EE' - \vec{k}\cdot\vec{k}{}') - m_\ell^2 - m_{\ell'}^2$ where $m_\ell(m_{\ell'})$ is the initial (final) lepton mass. If $EE'\sin^2(\theta/2) \gg m_\ell^2,\ m_{\ell'}^2$, then

$\approx 4EE'\sin^2(\theta/2)$, where θ is the lepton's scattering angle in the lab.

$x = \dfrac{Q^2}{2M\nu}$ In the parton model, x is the fraction of the target nucleon's momentum carried by the struck quark. See section on QCD.

$y = \dfrac{q\cdot P}{k\cdot P} = \dfrac{\nu}{E}$ is the fraction of the lepton's energy lost in the lab.

$W^2 = (P+q)^2 = M^2 + 2M\nu - Q^2$ is the mass squared of the system recoiling against the lepton.

$s = (k+P)^2 = \dfrac{Q^2}{xy} + M^2$

A.1 Leptoproduction cross sections:

$$\frac{d^2\sigma}{dx\,dy} = \nu\,(s-M^2)\,\frac{d^2\sigma}{d\nu\,dQ^2} = \frac{2\pi\,M\nu}{E'}\,\frac{d^2\sigma}{d\Omega_{\rm lab}\,dE'}$$

$$= x(s-M^2)\,\frac{d^2\sigma}{dx\,dQ^2}\ .$$

A.2 Electroproduction structure functions:

The neutral-current process, $eN \to eX$, is parity conserving at low Q^2 and can be written in terms of two structure functions $F_1^{\rm NC}(x,Q^2)$ and $F_2^{\rm NC}(x,Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{4\pi\,\alpha^2(s-M^2)}{Q^4}\left[(1-y)\,F_2^{\rm NC} + y^2\,xF_1^{\rm NC} - \frac{M^2}{(s-M^2)}\,xy\,F_2^{\rm NC}\right]\ .$$

The charged-current processes, $e^-N \to \nu X$, $\nu N \to e^-X$, and $\overline{\nu}N \to e^+X$, are parity violating and can be written in terms of three structure functions $F_1^{\rm CC}(x,Q^2)$, $F_2^{\rm CC}(x,Q^2)$, and $F_3^{\rm CC}(x,Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi}\,\frac{M_W^4}{(Q^2+M_W^2)^2} \tag{A.1}$$

$$\times\left\{\left[1-y-\frac{M^2}{(s-M^2)}\right]F_2^{\rm CC} + \frac{y^2}{2}\,2x\,F_1^{\rm CC} + (y-\frac{y^2}{2})\,x\,F_3^{\rm CC}\right\}\ .$$

CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES (Cont'd)

A.3 The QCD parton model:

In the QCD parton model, the structure functions defined above can be expressed in terms of parton distribution functions. The quantity $f_i(x, Q^2)dx$ is the probability that a parton of type i (quark, antiquark, or gluon), carries a momentum fraction between x and $x + dx$ of the nucleon's momentum in a frame where the nucleon's momentum is large. For the cross section corresponding to the ***neutral-current process*** $ep \to eX$, we have for $s \gg M^2$ (in the case where the incoming electron is either left- (L) or right- (R) handed):

$$\frac{d^2\sigma}{dx\,dy} = \frac{\pi\alpha^2}{sx^2\,y^2}\left[\sum_q (x\,f_q\,(x,\,Q^2) + x\,f_{\overline{q}}\,(x,\,Q^2)\right]$$

$$\times\left[A_q + (1-y)^2\,B_q\right]\,.$$

Here the index q refers to a quark flavor (i.e., u, d, s, c, b, or t), and

$$A_q = \left(-q_q + g_{Lq}\,g_{Le}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 + \left(-q_q + g_{Rq}\,g_{Re}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 ,$$

$$B_q = \left(-q_q + g_{Rq}\,g_{Le}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 + \left(-q_q + g_{Lq}\,g_{Re}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 .$$

Here q_q is the charge of flavor q. For a left-handed electron, $g_{Re} = 0$ and $g_{Le} = (-1/2 + \sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, while for a right-handed one, $g_{Le} = 0$ and $g_{Re} = (\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$. For the quarks, $g_{Lq} = (T_3 - q_q\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, and $g_{Rq} = (-q_q\sin^2\theta_W)\,/\,(\sin\theta_W\cos\theta_W)$.

For neutral-current ***neutrino*** (***antineutrino***) ***scattering***, the same formula applies with g_{Le} replaced by $g_{L\nu} = 1/(2\sin\theta_W\cos\theta_W)$ ($g_{L\overline{\nu}} = 0$) and g_{Re} replaced by $g_{R\nu} = 0$ [$g_{R\overline{\nu}} = -1/(2\sin\theta_W\cos\theta_W)$].

In the case of the ***charged-current processes*** $e_L^- p \to \nu X$ and $\overline{\nu}p \to e^+X$, Eq. (A.1) applies with

$$F_2 = 2xF_1 = 2x\Big[f_u(x,Q^2) + f_c(x,Q^2)$$

$$+ f_t(x,Q^2) + f_{\overline{d}}\,(x,Q^2) + f_{\overline{s}}\,(x,Q^2) + f_{\overline{b}}\,(x,Q^2)\Big]\,,$$

$$F_3 = 2x\Big[f_u(x,Q^2) + f_c(x,Q^2)$$

$$+ f_t(x,Q^2) - f_{\overline{d}}\,(x,Q^2) - f_{\overline{s}}\,(x,Q^2) - f_{\overline{b}}\,(x,Q^2)\Big]\,.$$

For the process $\nu p \to e^-X$:

$$F_2 = 2xF_1 = 2x\Big[f_d(x,Q^2) + f_s(x,Q^2)$$

$$+ f_b(x,Q^2) + f_{\overline{u}}\,(x,Q^2) + f_{\overline{c}}\,(x,Q^2) + f_{\overline{t}}\,(x,Q^2)\Big]\,,$$

$$F_3 = 2x\Big[f_d(x,Q^2) + f_s(x,Q^2)$$

$$+ f_b(x,Q^2) - f_{\overline{u}}\,(x,Q^2) - f_{\overline{c}}\,(x,Q^2) - f_{\overline{t}}\,(x,Q^2)\Big]\,.$$

B. e^+e^- ANNIHILATION

For pointlike spin-1/2 fermions in the c.m., the differential cross section for $e^+e^- \to f\overline{f}$ via single photon annihilation is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,\beta\,\left[1 + \cos^2\theta + (1-\beta^2)\sin^2\theta\right]Q_f^2\,.$$

where β is the velocity of the final state fermion in the center of mass and Q_f is the charge of the fermion in units of the proton charge. For $\beta \to 1$,

$$\sigma = \frac{4\pi\alpha^2}{3s}\,Q_f^2 = \frac{86.8\,Q_f^2\,nb}{s(\mathrm{GeV}^2)}\,.$$

At higher energies the Z^0 (mass M_Z and width Γ_Z) must be included, and the differential cross section for $e^+e^- \to f\overline{f}$ becomes

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,\beta\,\Bigg[Q_f^2[1 + \cos^2\theta + (1-\beta^2)\sin^2\theta]$$

$$-2Q_f\,\chi_1\Big\{VV_f\,[1 + \cos^2\theta + (1-\beta^2)\sin^2\theta] - 2a_f\,\beta\cos\theta\Big\}$$

$$+\chi_2\Big\{V_f^2\,(1+V^2)\,[1 + \cos^2\theta + (1-\beta^2)\sin^2\theta]$$

$$+\beta^2\,a_f^2(1+V^2)\,[1+\cos^2\theta] - 8\beta\,VV_f\,a_f\cos\theta\Big\}\Bigg]\,,$$

$$\chi_1 = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\,\frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + \Gamma_Z^2M_Z^2}\,,$$

$$\chi_2 = \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\,\frac{s^2}{(s-M_Z^2)^2 + \Gamma_Z^2M_Z^2}\,.$$

$$V = -1 + 4\sin^2\theta_W\,,$$

$$a_f = 2T_{3f}\,,$$

$$V_f = 2T_{3f} - 4Q_f\sin^2\theta_W\,,$$

where the subscript f refers to the particular fermion and

$T_3 = +1/2$ for ν_e, ν_μ, ν_τ, u, c, t.

$T_3 = -1/2$ for e^-, μ^-, τ^-, d, s, b.

C. e^+e^- TWO-PHOTON PROCESS

In the equivalent photon approximation, the cross section for $e^+e^- \to e^+e^-X$ is related to the cross section for $\gamma\gamma \to X$ by

$$d\sigma_{e^+e^-\to e^+e^-X}\,(s) = \eta^2\int_0^1 d\omega\,f(\omega)\,d\sigma_{\gamma\gamma\to X}\,(\omega s)\,,$$

where

$$\eta \approx \frac{\alpha}{2\pi}\,\ln\left(\frac{s}{4m_e^2}\right)$$

and

$$f(\omega) = \frac{1}{\omega}\left[(2+\omega)^2\,\ln\frac{1}{\omega} - 2(1-\omega)(3+\omega)\right]\,.$$

The factor η arises from integrating over the mass squared of the virtual photon. For the production of a resonance, form factors suppress contributions from very virtual photons, so in the standard formula for production of a resonance of mass m_R and spin $J \neq 1$, namely,

$$\sigma(e^+e^- \to e^+e^-R) = \eta^2\,\frac{(2J+1)\,8\pi^2\,\Gamma(R\to\gamma\gamma)}{sm_R}\,f(\frac{m_R^2}{s})\,,$$

it would be better to use

$$\eta \approx \frac{\alpha}{2\pi}\,\ln\left(\frac{m_V^2}{4m_e^2}\right)\,,$$

where m_V is the mass of the vector (ρ, ϕ, $\cdots$) that enters into the form factor.

D. INCLUSIVE HADRONIC REACTIONS

One-particle inclusive cross sections $E(d^3\sigma)/(d^3p_i)$ for the production of a particle of momentum p_i are conveniently expressed in terms of rapidity (see above) and the momentum $p_\perp$ transverse to the beam direction (defined in the center-of-mass frame)

$$\frac{d^3\sigma}{dy\,d^2p_\perp} = E\,\frac{d^3\sigma}{d^3p}\,.$$

In the case of processes where $p_\perp$ is large or the mass of the produced particle is large (here large means greater than 10 GeV), the parton model can be used to calculate the rate. Symbolically

$$\sigma_{\text{hadronic}} = \sum_{ij}\int f_i(x_1,\,Q^2)\,f_j(x_2,\,Q^2)\,dx_1\,dx_2\,\widehat{\sigma}_{\text{partonic}}\,,$$

where $f_i(x,\,Q^2)$ is the parton distribution introduced above and Q is a typical momentum transfer in the partonic process and $\widehat{\sigma}$ is the partonic cross section. Two examples will help to clarify. The production of a W^+ in pp reactions at rapidity y in the center-of-mass frame is given by

$$\begin{aligned}\frac{d\sigma}{dy} &= \frac{G_F\,\pi\sqrt{2}}{3}\\ &\times \tau\Big[\cos^2\theta_c\Big(u(x_1\,,\,M_W^2)\,\overline{d}\,(x_2,M_W^2)\\ &\quad + u(x_2\,.\,M_W^2)\,\overline{d}\,(x_1,M_W^2)\Big)\\ &\quad + \sin^2\theta_c\Big(u(x_1\,,\,M_W^2)\,\overline{s}\,(x_2\,.\,M_W^2)\\ &\quad + s(x_2,M_W^2)\,\overline{u}\,(x_1,M_W^2)\Big)\Big]\ .\end{aligned}$$

where $x_1 = \sqrt{\tau}\,e^y$, $x_2 = \sqrt{\tau}\,e^{-y}$, and $\tau = M_W^2/s$. Similarly the production of a jet in pp (or $p\overline{p}$) collisions is given by

$$\begin{aligned}\frac{d^3\sigma}{d^2p_\perp\,dy} &= \sum_{ij}\int f_i(x_1\,.\,p_\perp^2)\,f_j(x_2,p_\perp^2)\\ &\times\ \left[\widehat{s}\,\frac{d\widehat{\sigma}}{d\,\widehat{t}}\right]_{ij} dx_1\,dx_2\,\delta(\,\widehat{s}+\,\widehat{t}+\widehat{u})\ ,\end{aligned}\qquad\text{(D.1)}$$

where the summation is over quarks, gluons, and antiquarks. Here

$$\begin{aligned}s &= (p_1+p_2)^2\ ,\\ t &= (p_1-p_{\rm jet})^2\ ,\\ u &= (p_2-p_{\rm jet})^2\ .\end{aligned}$$

p_1 and p_2 are the momenta of the incoming p and p (or $\overline{p}$) and $\widehat{s}$, $\widehat{t}$, and $\widehat{u}$ are s, t, and u with $p_1 \to x_1p_1$ and $p_2 \to x_2p_2$. The partonic cross section $\widehat{s}\,[\,(d\widehat{\sigma})/(d\,\widehat{t}\,)\,]$ can be found in Ref. 1. Example: for the process $gg \to q\overline{q}$.

$$\widehat{s}\,\frac{d\sigma}{dt} = 3\alpha_s^2\,\frac{(\,\widehat{t}^{\,2}+\widehat{u}^2)}{8\widehat{s}}\,\left[\frac{4}{9\,\widehat{t}\,\widehat{u}} - \frac{1}{\widehat{s}^{\,2}}\right]\ .$$

The prediction of Eq. (D.1) is compared to data from the UA1 and UA2 collaborations in a figure labeled "Jet Production in pp and $\overline{p}p$ Interactions" in the Plots of Cross Sections and Related Quantities section.

E. ONE-PARTICLE INCLUSIVE DISTRIBUTIONS

In order to describe one-particle inclusive production in e^+e^- annihilation or deep inelastic scattering, it is convenient to introduce a fragmentation function $D_i^h\,(z,Q^2)/z$ which is the probability that a parton of type i and momentum p will fragment into a hadron of type h and momentum zp. The Q^2 evolution is predicted by QCD and is similar to that of the parton distribution functions (see section on Quantum Chromodynamics). The $D_i^h(z,Q^2)$ are normalized so that

$$\sum_h\int D_i^h\,(z,Q^2)dz = 1\ .$$

If the contributions of the Z boson and three-jet events are neglected, the cross section for producing a hadron h in e^+e^- annihilation is given by

$$\frac{1}{\sigma_{\rm had}}\,\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\,D_i^h\,(z,Q^2)}{\sum_i e_i^2}\ .$$

where e_i is the charge of quark-type i, $\sigma_{\rm had}$ is the total hadronic cross section, and the momentum of the hadron is $zE_{\rm cm}/2$.

In the case of deep inelastic muon scattering, the cross section for producing a hadron of energy E_h is given by

$$\frac{1}{\sigma_{\rm tot}}\,\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\,q_i(x,Q^2)\,D_i^h(z,Q^2)}{\sum_i e_i^2\,q_i(x,Q^2)}\ .$$

where $E_h = \nu z$. (For the kinematics of deep inelastic scattering, see section D.2 of the Kinematics section of this Review.) The fragmentation functions for light and heavy quarks have a different z dependence; the former peak near $z = 0$. They are illustrated in a figure in the section on Plots of Cross Sections and Related Quantities.

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1. G.F. Owens, F. Reya, and M. Glück, Phys. Rev. **D18**, 1501 (1978).

QUANTUM CHROMODYNAMICS*

A. THE QCD LAGRANGIAN

Quantum Chromodynamics (QCD), the gauge field theory which describes the interactions of colored quarks and gluons, is one of the components of the SU(3)×SU(2)×U(1) Standard Model. The Lagrangian is (up to gauge-fixing terms)

$$\begin{aligned}L_{\rm QCD} &= -\frac{1}{4}F_{\mu\nu}^{(a)}\,F^{(a)\mu\nu} + i\sum_q \overline{\psi}_q^i\,\gamma^\mu\,(D_\mu)_{ij}\,\psi_q^j\\ &\quad -\sum_q m_q\,\overline{\psi}_q^i\,\psi_{qi}\ ,\\ F_{\mu\nu}^{(a)} &= \partial_\mu\,A_\nu^a - \partial_\nu\,A_\mu^a + g_s\,f_{abc}\,A_\mu^b\,A_\nu^c\ .\\ (D_\mu)_{ij} &= \delta_{ij}\,\partial_\mu - ig_s\,\sum_a\frac{\lambda_{i,j}^a}{2}A_\mu^a\ .\end{aligned}\qquad\text{(A.1)}$$

where g_s is the QCD coupling constant, and the f_{abc} are the structure constants of the SU(3) algebra (the λ matrices and values for f_{abc} can be found in "SU(3) Isoscalar Factors and Representation Matrices"). The $\psi_q^i(x)$ are the 4-component Dirac spinors associated with each quark field of color i and flavor q and the $A_\mu^a(x)$ are the (8) Yang-Mills (gluon) fields. A complete list of the Feynman rules which derive from this Lagrangian, together with some useful color-algebra identities, can be found in Ref. 1.

The principle of "asymptotic freedom" (see below) determines that the renormalized QCD coupling is small only at high energies, and it is only in this domain that high-precision tests similar to those in QED can be performed using perturbation theory. Nonetheless, there has in recent years been much progress in understanding and quantifying the predictions of QCD in the nonperturbative domain, for example in soft hadronic processes and on the lattice.[2] This short review will concentrate on QCD at short distances (large momentum transfers), where perturbation theory is the standard tool.

B. THE QCD COUPLING AND RENORMALIZATION SCHEME

The renormalization scale dependence of the effective QCD coupling $\alpha_s = g_s^2/4\pi$ is controlled by the β-function:

$$\begin{aligned}\mu\frac{\partial\alpha_s}{\partial\mu} &= -\frac{\beta_0}{2\pi}\,\alpha_s^2 - \frac{\beta_1}{8\pi^2}\,\alpha_s^3 - \cdots\ ,\\ \beta_0 &= 11 - \frac{2}{3}n_f\ ,\\ \beta_1 &= 102 - \frac{38}{3}n_f\ .\end{aligned}\qquad\text{(B.1)}$$

and n_f is the number of quarks with mass less than the energy scale μ. In solving this differential equation for α_s, a constant of integration is introduced. This constant is the one fundamental constant of QCD which must be determined from experiment. The most sensible choice for this constant is the value of α_s at a fixed reference scale μ_0, but it is more conventional to introduce the dimensional parameter Λ. The definition of Λ is arbitrary. One way to define it (adopted here) is to write a solution of Eq. (B.1) as an expansion in inverse powers of $\ln(\mu^2)$:

$$\alpha_s(\mu) = \frac{12\pi}{(33-2n_f)\ \ln(\mu^2/\Lambda^2)} \times \left[1 - \frac{6(153-19n_f)}{(33-2n_f)^2}\ \frac{\ln\left[\ln(\mu^2/\Lambda^2)\right]}{\ln(\mu^2/\Lambda^2)}\right] + \cdots \ . \tag{B.2}$$

The next term in this expansion is

$$\mathcal{O}\left(\frac{\ln^2\left[\ln(\mu^2/\Lambda^2)\right]}{\ln^3(\mu^2/\Lambda^2)}\right) .$$

This solution illustrates the ***asymptotic freedom*** property: $\alpha_s \to 0$ as $\mu \to \infty$. Alternative definitions of Λ are possible. For example, the solution of Eq. (B.1) with the β-function truncated at the second order:

$$\frac{1}{\alpha_s} + b_1 \ \ln\left(\frac{b_1\,\alpha_s}{1+b_1\,\alpha_s}\right) = b_0\ \ln\frac{\mu}{\Lambda} ,$$
$$b_0 = \frac{\beta_0}{2\pi} , \qquad b_1 = \frac{\beta_1}{4\pi\beta_0} \tag{B.3}$$

can be used.[3] For a given value of $\alpha_s(\mu = 5$ GeV) one finds that (Λ[Eq. (B.2)] − Λ[Eq. (B.3)]) varies by 5 to 22 MeV as Λ goes from 120 to 350 MeV, while for $\alpha_s(\mu = 30$ GeV) it varies by 3 to 11 MeV over the same Λ range.

In the above discussion we have ignored quark-mass effects, i.e., we have assumed an idealized situation where quarks of mass greater than μ are neglected completely. In this picture, the β-function coefficients change by discrete amounts as flavor thresholds are crossed when integrating the differential equation for α_s. It follows that, for a relationship such as Eq. (B.2) to remain valid for all values of μ, Λ must also change discretely through flavor thresholds. This leads to the concept of a different Λ for each range of μ corresponding to an effective number of massless quarks: $\Lambda \to \Lambda^{(n_f)}$. This is the standard convention. It follows that when comparing measured Λ values, account must be taken of the effective number of quark flavors in each experiment. In practice, it is straightforward to relate the different $\Lambda^{(n_f)}$ using the above expressions. For example, one finds[4] (the meaning of $\overline{\text{MS}}$ will be explained below)

$$\Lambda^{(4)}_{\overline{\text{MS}}} \approx \Lambda^{(5)}_{\overline{\text{MS}}} \left[\frac{m_b}{\Lambda^{(5)}_{\overline{\text{MS}}}}\right]^{2/25} \left[2\ \ln\left(\frac{m_b}{\Lambda^{(5)}_{\overline{\text{MS}}}}\right)\right]^{963/14375}$$
$$\Lambda^{(4)}_{\overline{\text{MS}}} \approx \Lambda^{(3)}_{\overline{\text{MS}}} \left[\frac{\Lambda^{(3)}_{\overline{\text{MS}}}}{m_c}\right]^{2/25} \left[2\ \ln\left(\frac{m_c}{\Lambda^{(3)}_{\overline{\text{MS}}}}\right)\right]^{-107/1875} . \tag{B.4}$$

Note that these differences are numerically very significant; for example, if $\Lambda^{(5)}_{\overline{\text{MS}}} = 200$ MeV, the corresponding $\Lambda^{(4)}_{\overline{\text{MS}}} = 293$ MeV. Most data from PEP/PETRA quote a value of $\Lambda^{(5)}_{\overline{\text{MS}}}$. We have converted it to $\Lambda^{(4)}_{\overline{\text{MS}}}$ as required.

All this confusion could be avoided by ignoring Λ altogether, but old habits die hard. The confusion can be minimized by adopting $\Lambda^{(4)}_{\overline{\text{MS}}}$ defined through Eq. (B.2) as the standard. This is done for all values of Λ quoted in this summary. In a given experiment where 1.5 GeV$< \mu <$ 5 GeV, $\Lambda^{(4)}$ is obtained from Eq. (B.2) with $n_f = 4$. For 5 GeV$< \mu < m_t$ GeV (m_t is the top-quark mass), $\Lambda^{(5)}$ is obtained from Eq. (B.2) with $n_f = 5$. Eq. (B.4) is then used to convert to $\Lambda^{(4)}$.

We turn now to a discussion of renormalization-scheme dependence in QCD. Although necessarily rather technical, this discussion is vital to understanding how Λ values can be measured and compared. See the review by Duke and Roberts[5] for further details.

Consider a "typical" QCD cross section which, when calculated perturbatively, starts at $\mathcal{O}(\alpha_s)$:

$$\sigma = A_1\,\alpha_s + A_2\,\alpha_s^2 + \cdots \ . \tag{B.5}$$

The coefficients A_1, A_2 come from calculating the appropriate Feynman diagrams. In performing such calculations various divergences arise, and these must be regulated in a consistent way. This requires a particular renormalization scheme (RS). The most commonly used one is the modified minimal subtraction ($\overline{\text{MS}}$) scheme.[6] This involves continuing momentum integrals from 4 to 4-2ϵ dimensions and then subtracting off the resulting $1/\epsilon$ poles and also ($\ln 4\pi - \gamma_E$), which is another artifact of continuing the dimension. (Here γ_E is the Euler-Mascheroni constant.) To preserve the dimensionless nature of the coupling, a mass scale μ must also be introduced: $g \to \mu^\epsilon g$. The finite coefficients A_i thus obtained depend implicitly on the renormalization convention used and explicitly on the scale μ.

The first two coefficients (β_0, β_1) in Eq. (B.1) are independent of the choice of RS's. In contrast, the coefficients of terms proportional to α_s^n for $n > 3$ ***are*** RS-dependent. Although the value of Λ, defined as above, does depend on the convention, it is straightforward to relate the different Λ's corresponding to different RS's. It has become conventional to use the $\overline{\text{MS}}$ scheme for calculating QCD cross sections beyond leading order.

The fundamental theorem of RS dependence is straightforward. Physical quantities, in particular the cross section, calculated to all orders in perturbation theory, do not depend on the RS. It follows that a truncated series ***does*** exhibit RS dependence. In practice all QCD cross sections are known either to leading or to next-to-leading order, and it is only the latter, which has reduced RS dependence, that are useful for precision tests. At second order the RS dependence is completely given by one condition which can be taken to be the value of the renormalization scale μ. One therefore has to address the question of what is the "best" choice for μ. There is no definite answer to this question—higher order corrections do not "fix" the scale, rather they render the theoretical predictions less sensitive to its variation.

There has been much discussion as to what constitutes the best choice of scheme. One could imagine that choosing a scale μ characteristic of the typical energy scale in the process would be most appropriate. More sophisticated choices are the scale for which the next-to-leading-order correction vanishes ("Fastest Apparent Convergence"[7]) or the scale for which the next-to-leading-order prediction is stationary.[3]

An important corollary is that if the higher order corrections are naturally small, then the additional uncertainties introduced by the RS dependence are likely to be less than the experimental measurement errors. There are some processes, however, for which the choice of scheme (i.e. the value of μ) ***can*** influence the extracted value of $\Lambda_{\overline{\text{MS}}}$. There is no resolution to this problem other than to try to calculate even more terms in the perturbation series.[†]

In the cases where the higher order corrections to a process are known and are large, some caution should be exercised when quoting the value of α_s. In what follows we will, where possible, indicate the size of the correction and will assign a theoretical uncertainty to α_s which corresponds to the size of this higher order correction. We estimate this error by comparing the value of $\alpha_s(\mu)$ obtained by fitting data using the QCD formula to highest known order in α_s, and then comparing it with the value obtained using the next-to-highest-order formula (μ is chosen as the typical energy scale in the process). The corresponding Λ's are then obtained by evolving $\alpha_s(\mu)$ to $\mu = 5$ GeV using Eq. (B.1) to the same order in α_s as the fit, and then converting to $\Lambda^{(4)}$ using Eq. (B.4).

C. QCD IN DEEP INELASTIC SCATTERING

The original and still one of the most powerful quantitative tests of perturbative QCD is the breaking of Bjorken scaling in deep inelastic lepton-hadron scattering. In the leading-logarithm approximation the measured structure functions $F_i(x, Q^2)$ are related to the quark distribution functions $q_i(x, Q^2)$ according to the naive parton model by the formulae in "Cross-Section Formulae for Specific Processes" (in that section, q_i is denoted by the notation f_q). In describing the way in which scaling is broken in QCD, it is convenient to define nonsinglet and singlet quark distributions:

$$F^{NS} = q_i - q_j \qquad F^S = \sum_i (q_i + \bar{q}_i) \ . \tag{C.1}$$

The nonsinglet structure functions have nonzero values of flavor quantum numbers such as isospin or baryon number. The variation with Q^2 of these is described by the so-called Altarelli-Parisi equations[8]:

$$\begin{aligned} Q^2 \frac{\partial F^{NS}}{\partial Q^2} &= \frac{\alpha_s(|Q|)}{2\pi} P^{qq} * F^{NS} \\ Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} F^S \\ G \end{pmatrix} &= \frac{\alpha_s(|Q|)}{2\pi} \begin{pmatrix} P^{qq} & 2n_f P^{qg} \\ P^{gq} & P^{gg} \end{pmatrix} * \begin{pmatrix} F^S \\ G \end{pmatrix} \end{aligned} \tag{C.2}$$

where $*$ denotes a convolution integral:

$$f * g = \int_x^1 \frac{dy}{y} \, f(y) \, g\left(\frac{x}{y}\right) \ . \tag{C.3}$$

The leading-order Altarelli-Parisi splitting functions are

$$\begin{aligned} P^{qq} &= \frac{4}{3} \left[\frac{1+x^2}{1-x} \right]_+ + 2\delta(1-x) \ , \\ P^{qg} &= \frac{1}{2} \left[x^2 + (1-x)^2 \right] \ , \\ P^{gq} &= \frac{4}{3} \left[\frac{1+(1-x)^2}{x} \right] \ , \\ P^{gg} &= 6 \left[\frac{1-x}{x} + x(1-x) + \left(\frac{x}{1-x} \right)_+ + \frac{11}{12}\delta(1-x) \right] \\ &\quad - \frac{n_f}{3}\delta(1-x) \ . \end{aligned} \tag{C.4}$$

Here the gluon distribution $G(x, Q^2)$ has been introduced and $1/(1-x)_+$ means

$$\int_0^1 dx \frac{f(x)}{(1-x)_+} = \int_0^1 dx \ \frac{f(x) - f(1)}{(1-x)} \ .$$

The precision of contemporary experimental data demands that higher order corrections also be included.[9] The above results are for massless quarks. Algorithms exist for the inclusion of nonzero quark masses.[10] At low Q^2 values there are also important "higher-twist" contributions of the form:

$$F_i(x, Q^2) = F_i^{(LT)}(x, Q^2) + \frac{F_i^{(HT)}(x, Q^2)}{Q^2} + \cdots \ . \tag{C.5}$$

These corrections are numerically important only for $Q^2 < \mathcal{O}(10 \text{ GeV}^2)$ except for x very close to 1.

A detailed review of the current status of the experimental data can be found, for example, in Ref. 11, and only a brief summary will be presented here. From Eq. (C.2), it is clear that a nonsinglet structure function offers in principle the most precise test of the theory since the Q^2 evolution is independent of the unmeasured gluon distribution. In practice, however, such a measurement involves forming differences between cross sections (e.g., F_3 in neutrino scattering). Until recently this has meant that the most accurate measurements, involving singlet-dominated structure functions such as F_2, have resulted in strongly correlated measurements of $\Lambda_{\overline{\text{MS}}}$ and the gluon distribution. The most accurate data currently available are from the BCDMS collaboration. By utilizing high-statistics data at large x (> 0.25) and large Q^2, the impact of the gluon distribution on the evolution and hence on the measured value of $\Lambda_{\overline{\text{MS}}}$ is much reduced. The result obtained is,[12]

$$\Lambda^{(4)}_{\overline{\text{MS}}} = 230 \pm 20(\text{stat.}) \pm 60(\text{sys.}) \text{ MeV} \ , \tag{C.6}$$

which is consistent with earlier measurements. A summary of published $\Lambda_{\overline{\text{MS}}}$ values from various experiments is displayed in Fig. 1. In Fig. 2 we have indicated the average value of $\Lambda^{(4)}_{\overline{\text{MS}}}$ (238 ± 43 MeV, statistical and systematic uncertainty added in quadrature) from the deep inelastic experiments shown in Fig. 1.

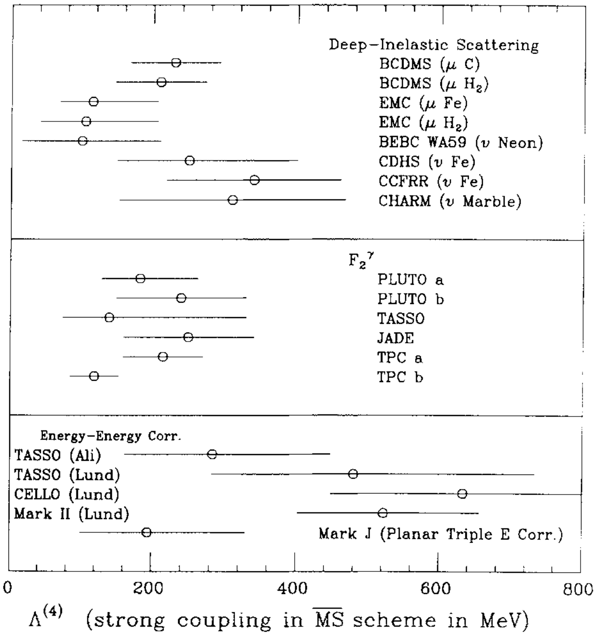

Fig. 1. Values of $\Lambda^{(4)}_{\overline{\text{MS}}}$ as determined by various experiments. The results on deep inelastic scattering are from BCDMS,[12,13] EMC,[14] BEBC,[15] CDHS,[16] CCFRR,[17] and CHARM.[18] The photon structure function results are from PLUTO[19] and TPC,[20] who quote two values of Λ arising from different assumptions about the hadronic part of the structure function, and from TASSO[21] and JADE.[22] The Energy-Energy correlation results are from TASSO,[23] CELLO,[24] and Mark II.[25] The Planar Triple Energy correlation result is due to MARK-J.[26]

The impact on the measurement of α_s of the higher order corrections can be estimated as follows. BCDMS used the evolution Eqs. (C.2) to leading order in α_s, and defined Λ_{LO} from $\alpha_s(Q^2) = 12\pi/[(33 - 2n_f) \ln(Q^2/\Lambda^2_{\text{LO}})]$. They then obtained $\Lambda_{\text{LO}} = 215$ MeV. This corresponds to $\alpha_s(5 \text{ GeV}) = 0.240$, whereas their next-to-leading-order fit corresponds to $\alpha_s(5 \text{ GeV}) = 0.191$. We have used this to estimate the theoretical uncertainty shown on Fig. 2.

Typically, Λ is extracted from the data by parametrizing the parton densities in a simple analytic way at some Q_0^2, evolving to higher Q^2 using the next-to-leading-order evolution equations, and fitting globally to the measured structure functions to obtain $\Lambda_{\overline{\text{MS}}}$. Thus an important by-product of such studies is the extraction of parton densities at a fixed reference value of Q_0^2. These can then be evolved in Q^2 and used as input for phenomenological studies in hadron-hadron collisions (see below). To avoid having to evolve from the starting Q_0^2 value each time, a parton density is required; it is useful to have available a simple analytic approximation to the densities valid over a range of x and Q^2 values. Such parametrizations are available in the literature.[27]

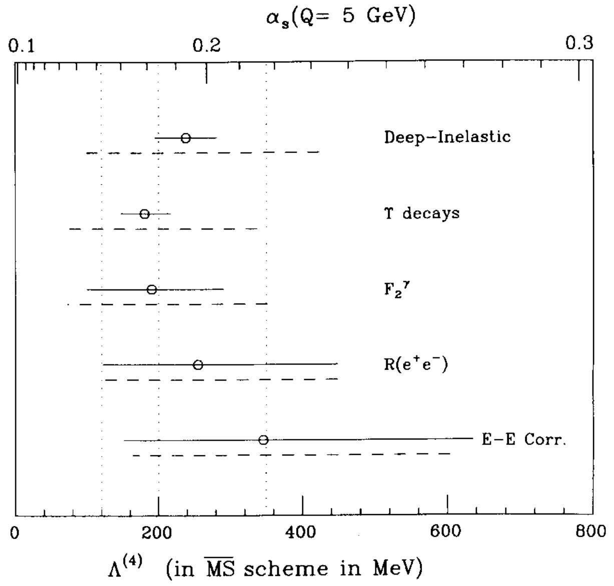

Fig. 2. Summary of the values of $\Lambda^{(4)}_{\overline{\rm MS}}$ from various processes. The deep inelastic value is an average of those shown in Fig. 1. The Υ result is from[28] an average of measurements.[29,30,31] The two-photon value is the allowed range from the results of Fig. 1 and takes into account the systematic error from the different models for the nonperturbative component of the structure function. The value from R is the average[32] of the compilation of Ref. 24. The result for the energy-energy correlations[33] is a range of allowed values and includes the systematic errors due to different fragmentation models. The dashed lines give our estimate of the possible uncertainty due to higher order QCD corrections; see text. For convenience, the top scale gives the value of α_s(5 GeV) corresponding to the values of $\Lambda^{(4)}_{\overline{\rm MS}}$. The vertical dotted lines indicate our allowed range and central value for Λ.

D. QCD IN HIGH ENERGY HADRON COLLISIONS

There are many ways in which perturbative QCD can be tested in high energy hadron colliders. The most precise of these is the production of single large-transverse-momentum photons. The leading-order QCD subprocesses are $q\overline{q} \to \gamma g$ and $qg \to \gamma q$. Explicit expressions for the corresponding scattering amplitudes can be found, for example, in Ref. 34. If the parton distributions are taken from other processes and a value of $\Lambda_{\overline{\rm MS}}$ assumed, then an absolute prediction is obtained. Conversely, the data can be used to extract information on quark and gluon distributions and the value of $\Lambda_{\overline{\rm MS}}$. This is also one of the few hard scattering processes for which the next-to-leading-order corrections are known,[35] and so a precision test is possible in principle. In practice, however, the residual uncertainties on the (most accurate) experimental data and in the theoretical prediction are on the order of 20–30%, and this is sufficiently large to limit the accuracy of an α_s measurement. Nevertheless a value for $\Lambda_{\overline{\rm MS}}$ in the range 100–300 MeV gives very satisfactory agreement with a wide range of data.[36]

The production of hadrons with large transverse momentum in hadron-hadron collisions provides a direct probe of the scattering of quarks and gluons: $qq \to qq$, $qg \to qg$, $gg \to gg$, etc. The present generation of $p\overline{p}$ colliders provide center-of-mass energies which are sufficiently high that these processes can be unambiguously identified in two-jet production at large transverse momentum. Corrected inclusive jet cross sections can be directly compared to the corresponding parton cross sections, and the agreement is impressive. As an example, the figure on "Jet Production in pp and $p\overline{p}$ Interactions" in "Plots of Cross Sections and Related Quantities" shows the inclusive jet cross section at zero pseudorapidity as a function of the jet transverse momentum for $p\overline{p}$ collisions. The QCD prediction combines the parton distributions with the leading-order $2 \to 2$ parton scattering amplitudes. Data are also available on the angular distribution of jets; these are also in agreement with QCD expectations.[37]

QCD corrections to Drell-Yan type cross sections (i.e., the production in hadron collisions by quark-antiquark annihilation of lepton pairs of invariant mass Q from virtual photons, or of real W or Z bosons) are known.[38] These $\mathcal{O}(\alpha_s)$ QCD corrections are sizable and approximately constant over the lepton-pair mass range probed by experiments. Thus

$$\sigma_{DY} \approx \sigma^{(0)}_{DY} \left[1 + \frac{\alpha_s(Q^2)}{2\pi} C + \cdots \right] . \tag{D.1}$$

It is interesting to note that the corresponding correction to W and Z production, as measured at $p\overline{p}$ colliders, has essentially the same theoretical form and is of order 30%. Total W and Z production cross sections soon will be measured accurately enough to be sensitive to such 30% effects and can in principle offer a test of the theory. The key ingredient which is missing at present is the complete $\mathcal{O}(\alpha_s^2)$ QCD correction which is potentially important in view of the large $\mathcal{O}(\alpha_s)$ term. QCD effects are also observable in the production of W and Z bosons with large transverse momentum.[39] There is good qualitative agreement, although the statistics are rather poor at present.[40]

E. QCD IN HEAVY QUARKONIUM DECAY

Under the assumption that the hadronic and leptonic decay widths of heavy $Q\overline{Q}$ resonances can be factorized into a nonperturbative part—dependent on the confining potential—and a calculable perturbative part, the ratios of partial decay widths allow measurements of α_s at the heavy quark mass scale. The most precise data come from the decay widths of the 1^{--} J/ψ and Υ resonances. Potential model dependences cancel from the ratios of decay widths. Important examples of such ratios are

$$\frac{\Gamma(1^{--} \to ggg)}{\Gamma(1^{--} \to \mu^+\mu^-)} , \; \frac{\Gamma(1^{--} \to \gamma gg)}{\Gamma(1^{--} \to ggg)} . \tag{E.1}$$

The perturbative corrections to these ratios are rather large.[41] They change the predictions by a factor of 1.64 and 0.77 respectively in the case of Υ decay. The corrections in the J/ψ case are much larger. Relativistic corrections are unknown and could be substantial for the J/ψ case. We will therefore assign a 20% uncertainty to the value of α_s obtained from Υ decays.

A recent analysis[28] of bottomonium decay-width ratios from CUSB, CLEO, and ARGUS[29,30,31] finds

$$\alpha_s(m_b) = 0.179 \pm 0.009 \tag{E.2}$$

if the theoretical uncertainties are ignored. These uncertainties are indicated in Fig. 2.

F. PERTURBATIVE QCD IN e^+e^- COLLISIONS

The total cross section for $e^+e^- \to$ hadrons is obtained by multiplying the muon-pair cross section by the factor $R = 3\Sigma_q e_q^2$. The higher order QCD corrections to this quantity have been calculated, and the results can be expressed in terms of the factor:

$$R = R^{(0)} \left[1 + \frac{\alpha_s}{\pi} + C_2 \left(\frac{\alpha_s}{\pi}\right)^2 + C_3 \left(\frac{\alpha_s}{\pi}\right)^3 + \cdots \right] ,$$

$$C_2^{\overline{\rm MS}} = \left(\frac{2}{3}\zeta(3) - \frac{11}{12} \right) n_f + \frac{365}{24} - 11\zeta(3) . \tag{F.1}$$

$R^{(0)}$ can be obtained from the formula for $d\sigma/d\Omega$ for $e^+e^- \to f\overline{f}$ by integrating over Ω. The formula is given in "Cross-Section Formulae for Specific Processes," Section B. Numerically $C_2^{\overline{\rm MS}} = 1.41$. Recently C_3 has been computed;[42] numerically (for $n_f = 5$) $C_3^{\overline{\rm MS}} = 64.7$. This result is strictly only correct in the zero-quark-mass limit. The $\mathcal{O}(\alpha_s)$ corrections are also known for massive quarks.[43]

At the highest energies currently accessible (PETRA-PEP-TRISTAN), the corrections from QCD and Z exchange are comparable. A comparison of the theoretical prediction of Eq. (F.1) (corrected for the b-quark mass) with all the available data (including those from TRISTAN at $\sqrt{s} = 50$ GeV) has been performed by the CELLO collaboration.[24] The result is a correlated measurement of α_s and $\sin^2\theta_W$. Fixing $\sin^2\theta_W$ at the world-average value of 0.23 then gives:[32]

$$\alpha_s(34\ \text{GeV}) = 0.132 \pm 0.016\ . \tag{F.2}$$

The corresponding value of $\Lambda_{\overline{\text{MS}}}$ is shown in Fig. 2. Two comments are in order. First, the principal advantage of determining α_s from R in e^+e^- annihilation is that there is no dependence on fragmentation models, jet algorithms, etc. Second, the order α_s^3 term in Eq. (F.1) is numerically twice as large as the order α_s^2 term. The accuracy of the QCD prediction is therefore suspect. To take account of this we have given in Fig. 2 a theoretical uncertainty which corresponds to the difference of the values of α_s with and without the α_s^3 term (12% of α_s).

The traditional method of determining α_s in e^+e^- annihilation is from measuring quantities which are sensitive to the relative rate of two- and three-jet events.[44] There are many possible choices of such "shape variables": thrust,[45] energy-energy correlations,[46] planar triple-energy correlations,[47] average jet mass, etc. All of these are infrared safe, which means they can be reliably calculated in perturbation theory. The starting point for all these quantities is the simple "three-jet" cross section for $e^+e^- \to q\bar{q}g$:

$$\frac{1}{\sigma}\,\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\,\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}\ , \tag{F.3}$$

where

$$x_i = \frac{2E_i}{\sqrt{s}}$$

are the center-of-mass energy fractions of the final-state (massless) quarks. A distribution in a "three-jet" variable, such as those listed above, is obtained by integrating this differential cross section over an appropriate phase space region for a fixed value of the variable.

See Fig. 1 for a compilation of the more recent data on Λ from the energy-energy correlation. Three comments must be made concerning these determinations of α_s. First, there are theoretical ambiguities in the way that the second-order matrix elements are combined with parton fragmentation. These have been a source of some confusion and have accounted for some of the differences in the results obtained from different analyses. Fortunately, there appears to now be some consensus and the different approaches have converged.[48] A more serious source of uncertainty concerns the effect of using different hadronization models which are used to describe the evolution of a parton jet into a hadron jet.[49,50,51] These dynamics are controlled by QCD effects which we cannot yet calculate. Some experimental groups continue to quote separate α_s values according to the fragmentation model used, while others combine the uncertainty with other systematic errors. For example the TASSO collaboration[23] uses the energy-energy correlation and quotes α_s (44 GeV) $= 0.143 \pm 0.014$ for the Lund fragmentation model[49] and α_s (44 GeV) $= 0.129 \pm 0.012$ for the Ali model,[50] after the fragmentation models have been fitted to the data at $\sqrt{s} = 44$ GeV.

Third, numerically the order α_s^2 terms produce corrections of order 13%.[52] We will therefore assign a theoretical uncertainty of this size to the value of α_s extracted (see Fig. 2).

A compilation of all the available data and a complete list of references can be found in Ref. 53. A "world-average" is[33]

$$\alpha_s(34\ \text{GeV}) = 0.14 \pm 0.02\ , \tag{F.4}$$

with the error being the spread between the different experiments including the fragmentation uncertainty, but not that due to the size of the higher order corrections, which from our estimate above is somewhat larger than this error. Notice that this value of α_s is in agreement with the value obtained from the measurement of R described above. Since these results are essentially completely independent, the associated $\Lambda_{\overline{\text{MS}}}$ values are displayed separately in Fig. 2.

There are many other ways in which QCD can be tested in electron-positron collisions. Mention should be made in particular of the interesting and important results from "two-photon" processes. For a comprehensive review of the data, see Ref. 54. Paramount among these is the measurement of the photon structure function in collisions involving a highly virtual and an almost real photon.

In contrast to hadronic structure functions, the photon structure function increases linearly with $\log Q^2$,[55] and a measurement of the absolute size at large Q^2 provides information about Λ. However, the exact situation is complicated and somewhat controversial. The difficulty arises when the higher order QCD corrections[56] are included. These appear to introduce a negative singularity in the structure function at $x = 0$.[57] A more complete treatment then reveals that these singularities are in fact compensated by the nonperturbative hadronic component (the solution of the homogeneous part of the Altarelli-Parisi equations). This appears to reduce the usefulness of the photon structure function to that of hadronic structure functions, in that only the evolution can be unambiguously predicted in QCD, and the sensitivity to Λ is much reduced. Furthermore, fits to the data involve the determination of parameters which fix the nonperturbative components as well as Λ.[58] The TPC/2-gamma collaboration[20] quotes two values of $\Lambda_{\overline{\text{MS}}} = 215 \pm 55$ and 119 ± 34 MeV, depending upon how the nonperturbative component is parametrized. Systematic errors from this parametrization dominate statistical errors and the situation is somewhat similar to that for the energy-energy correlations discussed above. All the data on the photon structure function (see Fig. 1) are consistent with[59]

$$\Lambda_{\overline{\text{MS}}} = 180^{+100}_{-90}\ \text{MeV}\ . \tag{F.5}$$

This value is shown in Fig. 2. The higher order QCD corrections correspond approximately to a shift of 20% in the photon structure function and hence in α_s.[56] The corresponding uncertainty is indicated on Fig. 2.

G. CONCLUSIONS

In this short review we have focused on those high energy processes which currently offer the most quantitative tests of perturbative QCD. The precision measurements of $\Lambda_{\overline{\text{MS}}}$ come from those processes which involve real or virtual photons and for which the next-to-leading corrections are known. From Fig. 2 we see that all measurements are consistent and point to a value of $\Lambda_{\overline{\text{MS}}}$ for $n_f = 4$ of order 200^{+150}_{-80} MeV. The remarks in Sec. B concerning different Λ's for different effective n_f values should be remembered. It is interesting to note that the measurements are not yet precise enough to reveal the expected differences from different processes. Jet production data from high energy hadron collisions, while not yet in the precision measurement class, demonstrate in a very clear way the scattering of quarks and gluons over many orders of magnitude in cross section.

The need for brevity has meant that many other important topics in QCD phenomenology have had to be omitted from this review. One should mention in particular the study of exclusive processes (form factors, elastic scattering, ...), the behavior of quarks and gluons in nuclei, the spin properties of the theory and the importance of polarized scattering data, the interface of soft and hard QCD as manifest, for example, by minijet production and hard diffractive processes and QCD effects in hadron spectroscopy. While we can be confident that QCD ***is*** the strong interaction field theory, there are still many important tests to be made.

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[*] Prepared April 1988 by R.M. Barnett, I. Hinchliffe, and W.J. Stirling; minor changes in September 1989.

[†] Since the perturbation expansion is an asymptotic series, eventually the computation of additional terms is of no value.

[‡] This fit includes the C_3 term. If this term is not included, the fit gives α_s (34 GeV) $= 0.145 \pm 0.019$.[24]

QUANTUM CHROMODYNAMICS (Cont'd)

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STANDARD MODEL OF ELECTROWEAK INTERACTIONS*

The standard electroweak model is based on the gauge group[1] SU(2) × U(1), with gauge bosons W_μ^i, $i = 1,2,3$, and B_μ for the SU(2) and U(1) factors, respectively, and the corresponding gauge coupling constants g and g'. The left-handed fermion fields $\psi_i = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}$ and $\begin{pmatrix} u_i \\ d_i' \end{pmatrix}$ of the i^{th} fermion family transform as doublets under SU(2), where $d_i' \equiv \sum_j V_{ij}\, d_j$, and V is the Cabibbo-Kobayashi-Maskawa mixing matrix.** The right-handed fields are SU(2) singlets. In the minimal model there are three fermion families and a single complex Higgs doublet $\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$.

After spontaneous symmetry breaking the Lagrangian is

$$\mathcal{L}_F = \sum_i \overline{\psi}_i \left(i \not\partial - m_i - \frac{g m_i H}{2M_W} \right) \psi_i$$

$$- \frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i \, \gamma^\mu \, (1-\gamma^5)(T^+ \, W_\mu^+ + T^- \, W_\mu^-) \, \psi_i$$

$$- e \sum_i q_i \, \overline{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu - \frac{g}{2\cos\theta_W} \times$$

$$\sum_i \overline{\psi}_i \, \gamma^\mu (V^i - A^i \gamma^5) \, \psi_i \, Z_\mu \, . \tag{1}$$

$\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle; $e = g \sin\theta_W$ is the positron electric charge; and $A \equiv B\cos\theta_W + W^3 \sin\theta_W$ is the (massless) photon field. $W^\pm \equiv (W^1 \mp i W^2)/\sqrt{2}$ and $Z \equiv -B\sin\theta_W + W^3\cos\theta_W$ are the massive charged and neutral weak boson fields, respectively. T^+ and T^- are the weak isospin raising and lowering operators. The vector and axial couplings are

$$V^i \equiv t_{3L}(i) - 2q_i \sin^2\theta_W$$

$$A^i \equiv t_{3L}(i) \, , \tag{2}$$

where $t_{3L}(i)$ is the weak isospin of fermion i ($+1/2$ for u_i and ν_i; $-1/2$ for d_i and e_i) and q_i is the charge of ψ_i in units of e.

The second term in $\mathcal{L}_F$ represents the charged-current weak interaction.[2] For example, the coupling of a W to an electron and a neutrino is

$$-\frac{e}{2\sqrt{2}\sin\theta_W} \left[W_\mu^- \, \overline{e} \, \gamma^\mu (1-\gamma^5)\nu + W_\mu^+ \, \overline{\nu} \, \gamma^\mu \, (1-\gamma^5) e \right] \, . \tag{3}$$

For momenta small compared to M_W, the second term gives rise to the effective four-fermion interaction with the Fermi constant given (at tree level, i.e., lowest order in perturbation theory) by $G_F/\sqrt{2} = g^2/8M_W^2$. CP violation is incorporated in the Standard Model by a single observable phase in V_{ij}. The third term in $\mathcal{L}_F$ describes electromagnetic interactions (QED), and the last is the weak neutral-current interaction.

In Eq. (1), m_i is the mass of the i^{th} fermion ψ_i. For the quarks these are the current masses. For the light quarks, a typical estimate[3] gives $m_u \approx 5.6 \pm 1.1$ MeV, $m_d \approx 9.9 \pm 1.1$ MeV, $m_s \approx 199 \pm 33$ MeV, and $m_c \approx 1.35 \pm 0.05$ GeV (these are running masses evaluated at 1 GeV). For the heavier quarks $m_b \approx 5$ GeV (the "pole" mass), and $m_t > \mathcal{O}(80)$ GeV.

H is the physical neutral Higgs scalar which is the only remaining part of ϕ after spontaneous symmetry breaking. The Yukawa coupling of H to ψ_i, which is flavor diagonal in the minimal model, is $g m_i / 2M_W$. The H mass is not predicted by the model. Experimental limits are given in the Higgs section. In nonminimal models there are additional charged and neutral scalar Higgs particles[4].

Renormalization and radiative corrections: The Standard Model has three parameters (not counting M_H and the fermion masses and mixings). A particularly useful set is: (a) the fine structure constant $\alpha = 1/137.036$,† determined from the electron magnetic moment anomaly ($g-2$), (b) the Fermi constant, $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}, determined from the muon lifetime formula (to which one must add lepton mass and $\mathcal{O}(\alpha)$ radiative corrections):

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} \, , \tag{4}$$

and (c) $\sin^2\theta_W$, determined from neutral-current processes[5] and the W and Z masses. The value of $\sin^2\theta_W$ depends on the renormalization prescription. A very useful scheme[6] is to take the tree-level formula $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ as the definition of the renormalized $\sin^2\theta_W$ to all orders in perturbation theory.‡ Alternatively, one can take M_Z rather than $\sin^2\theta_W$ as the third fundamental parameter.

Experiments are now at such a level of precision that complete $\mathcal{O}(\alpha)$ radiative corrections must be applied. These corrections are conveniently divided into two classes:

1. QED diagrams involving the emission of real photons or the exchange of virtual photons in loops, but not including vacuum polarization diagrams. These graphs yield finite and gauge-invariant contributions to observable processes. However, they are dependent on energies, experimental cuts, etc., and must be calculated individually for each experiment.
2. Electroweak corrections, including $\gamma\gamma$, γZ, ZZ, and WW vacuum polarization diagrams, as well as vertex corrections, box graphs, etc., involving virtual W's and Z's. Many of these corrections are absorbed into the renormalized Fermi constant defined in Eq. (4). Others modify the tree-level expressions for neutral-current amplitudes in several ways.[5]

In addition, the tree-level expressions for M_W and M_Z are modified:

$$M_W = \frac{A_0}{\sin\theta_W (1-\Delta r)^{1/2}}$$

$$M_Z = \frac{M_W}{\cos\theta_W} \tag{5}$$

where $A_0 = (\pi\alpha/\sqrt{2}G_F)^{1/2} = 37.281$ GeV. The radiative correction parameter Δr is predicted to be 0.0574 ± 0.0013 for $m_t = 100$ GeV and 0.0217 for $m_t = 200$ GeV (both for $M_H = 100$ GeV). If M_Z is regarded as fundamental, then

$$\sin^2\theta_W = \tfrac{1}{2}\left[1 - \left(1 - \frac{4A_0^2}{M_Z^2(1-\Delta r)} \right)^{1/2} \right] \tag{6}$$

is a derived parameter, and $M_W = M_Z \cos\theta_W$.

Cross section and asymmetry formulas: It is convenient to write the four-fermion interactions relevant to ν-hadron, νe, and parity-violating e-hadron neutral-current processes in a form that is valid in an arbitrary gauge theory (assuming massless left-handed neutrinos). One has

$$-\mathcal{L}^{\nu\mathrm{Hadron}} = \frac{G_F}{\sqrt{2}} \, \overline{\nu} \, \gamma^\mu \, (1-\gamma^5)\nu$$

$$\times \sum_i \left[\epsilon_L(i) \, \overline{q}_i \, \gamma_\mu (1-\gamma^5) q_i + \epsilon_R(i) \, \overline{q}_i \, \gamma_\mu (1+\gamma^5) q_i \right] \, , \tag{7}$$

$$-\mathcal{L}^{\nu e} = \frac{G_F}{\sqrt{2}} \, \overline{\nu}_\mu \, \gamma^\mu (1-\gamma^5) \nu_\mu \, \overline{e} \, \gamma_\mu (g_V^e - g_A^e \gamma^5) e \tag{8}$$

(for $\nu_e e$ or $\overline{\nu}_e e$, the charged-current contribution must be included), and

$$-\mathcal{L}^{e\mathrm{Hadron}} = -\frac{G_F}{\sqrt{2}}$$

$$\times \sum_i \left[C_{1i} \, \overline{e} \, \gamma_\mu \, \gamma^5 \, e \, \overline{q}_i \, \gamma^\mu \, q_i + C_{2i} \, \overline{e} \, \gamma_\mu \, e \, \overline{q}_i \, \gamma^\mu \, \gamma^5 \, q_i \right] \, . \tag{9}$$

(One must add the parity-conserving QED contribution.)

The Standard Model expressions for $\epsilon_{L,R}(i)$, $g_{V,A}^e$, and C_{ij} are given in Table 1.

A precise determination of $\sin^2\theta_W$, which depends only very weakly on m_t and M_H, is obtained from deep inelastic neutrino scattering from (approximately) isoscalar targets. The ratio $R_\nu \equiv \sigma_{\nu N}^{NC}/\sigma_{\nu N}^{CC}$ of neutral- to charged-current cross sections has been measured to 1% accuracy by the CDHS[7] and CHARM[8] collaborations, so it is important to obtain theoretical expressions for R_ν and $R_{\overline{\nu}} \equiv \sigma_{\overline{\nu}N}^{NC}/\sigma_{\overline{\nu}N}^{CC}$ (as functions of $\sin^2\theta_W$) to comparable accuracy. Fortunately, most of the uncertainties from the strong interactions and neutrino spectra cancel in the ratio.

STANDARD MODEL OF ELECTROWEAK INTERACTIONS (Cont'd)

Table 1. Standard model expressions for the neutral-current parameters for ν-hadron, νe, and e-hadron processes. If radiative corrections are ignored, $\rho = \kappa = 1$, $\lambda = 0$. At $\mathcal{O}(\alpha)$, $\rho_{\nu N}^{NC} = 1.0032$, $\kappa_{\nu N} = 1.0078$, $\lambda_{u_L} = -0.0031$, $\lambda_{d_L} = -0.0026$, and $\lambda_{u_R} = 1/2\,\lambda_{d_R} = 3.5 \times 10^{-5}$ for $m_t = 100$ GeV, $M_H = 100$ GeV, $\sin^2\theta_W = 0.23$, and $\langle Q^2 \rangle = 20$ GeV^2. For νe scattering, $\kappa_{\nu e} = 1.0074$ and $\rho_{\nu e} = 1.0079$ (at $\langle Q^2 \rangle = 0.$). For atomic parity violation, $\rho'_{eq} = 0.9818$ and $\kappa'_{eq} = 1.012$. For the SLAC polarized electron experiment, $\rho'_{eq} = 0.972$, $\kappa'_{eq} = 1.011$, $\rho_{eq} = 0.995$, and $\kappa_{eq} = 1.05$ after incorporating additional QED corrections. For $m_t = 200$ GeV the $\rho(\kappa)$ values should be increased by 0.0094 (0.0402).

Quantity	Standard Model Expression
$\epsilon_L(u)$	$\rho_{\nu N}^{NC}\left(\frac{1}{2} - \frac{2}{3}\kappa_{\nu N}\ \sin^2\theta_W + \lambda_{uL}\right)$
$\epsilon_L(d)$	$\rho_{\nu N}^{NC}\left(-\frac{1}{2} + \frac{1}{3}\kappa_{\nu N}\ \sin^2\theta_W + \lambda_{dL}\right)$
$\epsilon_R(u)$	$\rho_{\nu N}^{NC}\left(-\frac{2}{3}\kappa_{\nu N}\ \sin^2\theta_W + \lambda_{uR}\right)$
$\epsilon_R(d)$	$\rho_{\nu N}^{NC}\left(\frac{1}{3}\kappa_{\nu N}\ \sin^2\theta_W + \lambda_{dR}\right)$
g_V^e	$\rho_{\nu e}\left(-\frac{1}{2} + 2\kappa_{\nu e}\ \sin^2\theta_W\right)$
g_A^e	$\rho_{\nu e}\left(-\frac{1}{2}\right)$
C_{1u}	$\rho'_{eq}\left(-\frac{1}{2} + \frac{4}{3}\kappa'_{eq}\ \sin^2\theta_W\right)$
C_{1d}	$\rho'_{eq}\left(\frac{1}{2} - \frac{2}{3}\kappa'_{eq}\ \sin^2\theta_W\right)$
C_{2u}	$\rho_{eq}\left(-\frac{1}{2} + 2\kappa_{eq}\ \sin^2\theta_W\right)$
C_{2d}	$-C_{2u}$

A simple zeroth-order approximation is

$$R_\nu = g_L^2 + g_R^2 r$$

$$R_{\overline{\nu}} = g_L^2 + \frac{g_R^2}{r}\ , \tag{10}$$

where

$$g_L^2 \equiv \epsilon_L\,(u)^2 + \epsilon_L\,(d)^2 \approx \tfrac{1}{2} - \sin^2\theta_W + \tfrac{5}{9}\sin^4\theta_W$$

$$g_R^2 \equiv \epsilon_R\,(u)^2 + \epsilon_R\,(d)^2 \approx \tfrac{5}{9}\sin^4\theta_W\ , \tag{11}$$

and $r \equiv \sigma_{\overline{\nu}N}^{CC}/\sigma_{\nu N}^{CC}$ is the ratio of $\overline{\nu}$ and ν charged-current cross sections, which can be measured directly. [In the simple parton model, ignoring hadron energy cuts, $r \approx (\frac{1}{3} + \epsilon)/(1 + \frac{1}{3}\epsilon)$, where $\epsilon \sim 0.125$ is the ratio of the fraction of the nucleon's momentum carried by antiquarks to that carried by quarks.] In practice, Eq. (10) must be corrected for quark mixing, the s and c seas, c-quark threshold effects, nonisoscalar target effects, W-Z propagator differences, and radiative corrections (which lower the extracted value of $\sin^2\theta_W$ by $\sim$ 0.009). Details of the neutrino spectra, experimental cuts, x and Q^2 dependence of structure functions, and longitudinal structure functions enter only at the level of these corrections and therefore lead to very small uncertainties. The largest theoretical uncertainty is associated with the c threshold, which mainly affects σ^{CC}. Using the slow rescaling prescription[5] the central value of $\sin^2\theta_W$ varies as 0.013 [m_c(GeV)-1.5], where m_c is the effective mass. For $m_c = 1.5 \pm 0.3$ GeV (determined from ν-induced dimuon production) this contributes ± 0.004 to the total theoretical uncertainty $\Delta\sin^2\theta_W \sim \pm 0.005$. This would be very hard to improve in the future. (The experimental uncertainty is ± 0.003).

The laboratory cross section for $\nu_\mu e \rightarrow \nu_\mu e$ or $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ elastic scattering is

$$\frac{d\sigma_{\nu_\mu,\overline{\nu}_\mu}}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} \times$$

$$\left[(g_V^e \pm g_A^e)^2 + (g_V^e \mp g_A^e)^2(1-y)^2 - (g_V^{e2} - g_A^{e2})\frac{y\,m_e}{E_\nu}\right]\ , \tag{12}$$

where the upper (lower) sign refers to $\nu_\mu(\overline{\nu}_\mu)$, and $y \equiv E_e/E_\nu$ [which runs from 0 to $(1 + m_e/2E_\nu)^{-1}$] is the ratio of the kinetic energy of the recoil electron to the incident ν or $\overline{\nu}$ energy. For $E_\nu \gg m_e$ this yields a total cross section

$$\sigma = \frac{G_F^2\ m_e\ E_\nu}{2\pi}\left[(g_V^e \pm g_A^e)^2 + \tfrac{1}{3}(g_V^e \mp g_A^e)^2\right]\ . \tag{13}$$

The most accurate leptonic measurements[9–11] of $\sin^2\theta_W$ are from the ratio $R \equiv \sigma_{\nu_\mu e}/\sigma_{\overline{\nu}_\mu e}$ in which many of the systematic uncertainties cancel. Radiative corrections (other than m_t effects) are small compared to the precision of present experiments and have negligible effect on the extracted $\sin^2\theta_W$. The cross sections for $\nu_e e$ and $\overline{\nu}_e e$ may be obtained from Eq. (12) by replacing $g_{V,A}^e$ by $g_{V,A}^e + 1$, where the 1 is due to the charged-current contribution.

The SLAC polarized-electron experiment[12] measured the parity-violating asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}\ , \tag{14}$$

where $\sigma_{R,L}$ is the cross section for the deep-inelastic scattering of a right- or left-handed electron: $e_{R,L}N \rightarrow eX$. In the quark parton model

$$\frac{A}{Q^2} = a_1 + a_2\,\frac{1-(1-y)^2}{1+(1-y)^2}\ , \tag{15}$$

where $Q^2 > 0$ is the momentum transfer and y is the fractional energy transfer from the electron to the hadrons. For the deuteron or other isoscalar target, one has, neglecting the s quark and antiquarks,

$$a_1 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{1u} - \tfrac{1}{2}C_{1d}\right) \approx \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(-\tfrac{3}{4} + \tfrac{5}{3}\sin^2\theta_W\right)$$

$$a_2 = \frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{2u} - \tfrac{1}{2}C_{2d}\right) \approx \frac{9G_F}{5\sqrt{2}\pi\alpha}\left(\sin^2\theta_W - \tfrac{1}{4}\right)\ . \tag{16}$$

Radiative corrections (other than m_t effects) lower the extracted value of $\sin^2\theta_W$ by $\sim$ 0.005.

Experiments measuring atomic parity violation[13] are now quite precise, and the uncertainties associated with atomic wave functions are relatively small (especially for cesium). For heavy atoms one determines the "weak charge"

$$\begin{aligned} Q_W &= -2\left[C_{1u}\,(2Z + N) + C_{1d}(Z + 2N)\right] \\ &\approx Z(1 - 4\sin^2\theta_W) - N\ . \end{aligned} \tag{17}$$

Radiative corrections increase the extracted $\sin^2\theta_W$ by $\sim$ 0.008.

The forward-backward asymmetry for $e^+e^- \rightarrow \ell\overline{\ell}$, $\ell = \mu$ or τ, is defined as

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}\ , \tag{18}$$

where $\sigma_F(\sigma_B)$ is the cross section for ℓ^- to travel forward (backward) with respect to the e^- direction. A_{FB} and R, the total cross section relative to pure QED, are given by

$$R = F_1$$

$$A_{FB} = 3F_2/4F_1\ , \tag{19}$$

where

$$F_1 = 1 - 2\chi_0\ V^e\ V^\ell\ \cos\delta_R + \chi_0^2\left(V^{e2} + A^{e2}\right)\left(V^{\ell 2} + A^{\ell 2}\right)$$

$$F_2 = -2\chi_0\ A^e\ A^\ell\ \cos\delta_R + 4\chi_0^2\ A^e\ A^\ell\ V^e\ V^\ell\ , \tag{20}$$

STANDARD MODEL OF ELECTROWEAK INTERACTIONS (Cont'd)

where

$$\tan\delta_R = \frac{M_Z\Gamma_Z}{M_Z^2 - s}$$

$$\chi_0 = \frac{G_F}{2\sqrt{2}\pi\alpha}\frac{sM_Z^2}{\left[(m_Z^2 - s)^2 + m_Z^2\Gamma_Z^2\right]^{1/2}} \tag{21}$$

and $\sqrt{s}$ is the CM energy. Eq. (20) is valid at tree level. If the data are radiatively corrected for QED effects (as described above), then the remaining electroweak corrections can be incorporated[14] (in an approximation adequate for existing PEP, PETRA, and TRISTAN data) by replacing χ_0 by $\chi(s) \equiv \chi_0(s)\alpha/\widehat{\alpha}(s)$, where $\widehat{\alpha}(s)$ is the running QED coupling. Numerically, $\alpha/\widehat{\alpha}(s) \sim 1 - \Delta r$ if Δr is evaluated for $m_t < 100$ GeV. Formulas for $e^+e^- \to$ *hadrons* may be found in Ref. 15.

At SLC and LEP, A_{FB} for $e^+e^- \to \overline{f}f$ at the Z pole will be measured to high precision for $f = \mu, \tau, s, c, b$. Similarly, the left-right asymmetry

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} , \tag{22}$$

where $\sigma_L(\sigma_R)$ is the cross section for a left- (right)-handed incident electron, will be measured very precisely at SLC and possibly at LEP. At tree level and neglecting terms of order $(\Gamma_Z/M_Z)^2$, one has

$$A_{FB} \approx 3\eta_f \frac{\eta_e + 1/2(P_e)}{1 + 2P_e\eta_e}$$

$$A_{LR} \approx 2\eta_e , \tag{23}$$

where P_e is the initial e^- polarization and

$$\eta_f \equiv \frac{V^f A^f}{V^{f2} + A^{f2}} . \tag{24}$$

Unlike A_{FB}, A_{LR} is especially sensitive to $\sin^2\theta_W$, and is insensitive to radiative corrections. Precise measurements of the τ polarization $P_\tau = \eta_\tau$ should also be obtained.

Neutral-current experimental results: $\sin^2\theta_W$ and, equivalently, M_Z have been determined from the W and Z masses and from a variety of neutral-current processes spanning a very wide Q^2 range. The results,[5,7–13,15–25] shown in Table 2, are in impressive agreement with each other, indicating the quantitative success of the Standard Model. The best fit to all data yields $\sin^2\theta_W = 0.2305 \pm 0.0005$ for m_t = 100 GeV and 0.2189 ± 0.0004 for $m_t = 200$ GeV, where the errors (as well as those given below for other neutral-current parameters) include full statistical, systematic, and theoretical uncertainties. When m_t is allowed to be totally arbitrary, the fits to all data yield $\sin^2\theta_W = 0.2259 \pm 0.0046$.

The most precise results are from M_Z. However, the derived $\sin^2\theta_W$ is sensitive to the isospin breaking[5,26] associated with a large m_t, as can be seen in Fig. 1. Consistency of the $\sin^2\theta_W$ values derived from the various reactions requires[5] $m_t < 186$ GeV at 90% CL ($m_t < 198$ GeV at 95% CL) for $M_H \leq 100$ GeV, with a slightly weaker limit for larger M_H. (Similar limits hold for the mass splittings between fourth-generation quarks or leptons.) It has been emphasized[27] that the $\overline{\text{MS}}$ quantity $\sin^2\widehat{\theta}_W(M_Z)$ is less sensitive to m_t. A fit to all data yields $\sin^2\widehat{\theta}_W(M_Z) = 0.2334 \pm 0.0005$ (0.2307 ± 0.0005) for $m_t = 100$ (200) GeV, and 0.2324 ± 0.0011 for arbitrary m_t.

The measured values of M_W and M_Z are given in Table 3. They are in agreement with the predictions of the Standard Model when full radiative corrections (to both the W and Z mass formulas and to deep inelastic scattering) are included, but disagree significantly when the corrections are excluded. From a fit to all data one obtains [see Eq. (5)] $\Delta r = 0.047 \pm 0.011$ (0.036 ± 0.011) for $m_t = 100$ (200) GeV, and $\Delta r = 0.044 \pm 0.014$ for arbitrary m_t.

W and Z decays: The partial decay width for gauge bosons to decay into massless fermions $f_1\overline{f}_2$ is

$$\Gamma(W^- \to e^+\nu_e) = \frac{G_F M_W^3}{6\sqrt{2}\pi} \approx 229 \pm 3 \text{ MeV}$$

Table 2. Determination of $\sin^2\theta_W$ and M_Z (in GeV) from various reactions. The central values of all fits assume M_H = 100 GeV in the radiative corrections. Where two errors are shown, the first is experimental and the second (in square brackets) is theoretical, computed assuming 3 fermion families and $M_H < 1$ TeV. Z production refers to the individual M_Z measurements, while M_W/M_Z refers to the ratio obtained in $p\overline{p}$ experiments. At PEP, PETRA, and TRISTAN energies the asymmetries are nearly an absolute prediction of the model (almost independent of $\sin^2\theta_W$ and m_t). The total cross sections only constrain $\sin^2\theta_W$ (via the vector couplings) weakly. The stronger $\sin^2\theta_W$ constraint from the energy dependence of the propagator[15] is included in the M_Z constraint. The top line is for m_t = 100 GeV; the bottom line (in parentheses) shows the central value for m_t = 200 GeV. (The results extrapolate roughly linearly in this range.)

Reaction	$\sin^2\theta_W$	M_Z
Z production	$0.2306 \pm 0.0002 \pm [0.0004]$ (0.2188)	91.161 ± 0.031
Deep inelastic (isocalar)	$0.233 \pm 0.003 \pm [0.005]$ (0.230)	$90.8 \pm 0.4 \pm [0.7]$ (89.6)
$\nu_\mu(\overline{\nu}_\mu)p \to \nu_\mu(\overline{\nu}_\mu)p$	0.207 ± 0.032 (0.201)	94.8 ± 4.7 (94.0)
$\nu_\mu(\overline{\nu}_\mu)e \to \nu_\mu(\overline{\nu}_\mu)e$	0.222 ± 0.011 (0.214)	92.4 ± 1.5 (91.9)
M_W/M_Z	0.219 ± 0.009 (0.219)	92.9 ± 1.3 (91.2)
Atomic parity violation	$0.215 \pm 0.007 \pm [0.017]$ (0.204)	$93.5 \pm 1.1 \pm [2.5]$ (93.5)
SLAC eD	$0.217 \pm 0.015 \pm [0.013]$ (0.211)	$93.1 \pm 2.2 \pm [1.9]$ (92.4)
All data	$0.2305 \pm 0.0002 \pm [0.0004]$ (0.2189)	91.16 ± 0.03

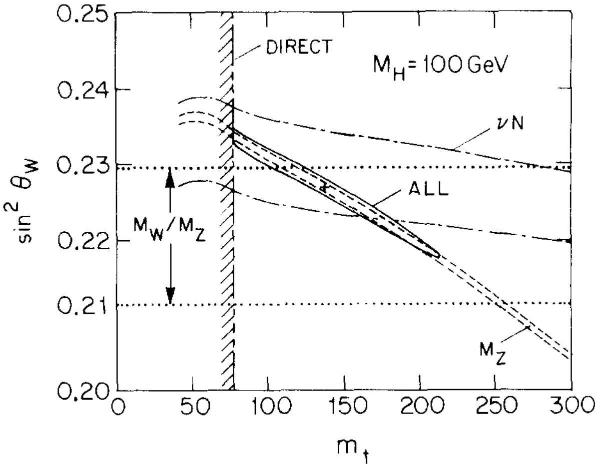

Fig. 1. One standard deviation uncertainties in $\sin^2\theta_W$ as a function of m_t, the direct constraint $m_t > 77$ GeV, and the 90% CL region in $\sin^2\theta_W - m_t$ allowed by all data.

$$\Gamma(W^+ \to u_i\overline{d}_i) = \frac{CG_F M_W^3}{6\sqrt{2}\pi}|V_{ij}|^2 \approx (714 \pm 11)|V_{ij}|^2 \text{ MeV} \tag{25}$$

Table 3. The W and Z masses (in GeV). The first uncertainties are mainly statistical and the second are energy calibration uncertainties that are 100% correlated between M_W and M_Z for each group. There is an additional LEP machine energy uncertainty $\Delta M_Z = 0.030$ which is common to the 4 LEP experiments. The combined fit is from the Listings for the W and Z in the full-sized edition of the Review of Particle Properties. The last two rows are predictions of the Standard Model, using $\sin^2\theta_W$ determined from deep inelastic scattering, with and without radiative corrections, respectively.

Group	M_W	M_Z
UA2 (Ref. 16)	$80.79 \pm 0.37 \pm 0.81$	$91.49 \pm 0.37 \pm 0.92$
UA1 (Ref. 17)(e modes)	$82.7 \pm 1.0 \pm 2.7$	$93.1 \pm 1.0 \pm 3.1$
MARK II (Ref. 18)	—	91.14 ± 0.12
ALEPH (Ref. 19)	—	91.182 ± 0.026
DELPHI (Ref. 20)	—	91.171 ± 0.030
L3 (Ref. 21)	—	91.160 ± 0.024
OPAL (Ref. 22)	—	91.154 ± 0.021
CDF (Ref. 23)	$80.0 \pm 3.3 \pm 2.4$	$90.9 \pm 0.3 \pm 0.2$
e^+e^- E< 90 GeV (Ref. 24)	—	$88.6\ ^{+2.0}_{-1.8}$
Combined fit	80.6 ± 0.4	91.161 ± 0.031
Prediction with radiative corrections	$79.6 \pm 0.9^*$ (78.6)	$90.8 \pm 0.7^*$ (89.6)
Prediction without radiative corrections	75.9 ± 0.9	87.1 ± 0.7

*The first value is for $m_t = 100$ GeV; the second (in parentheses) is for 200 GeV.

$$\Gamma(Z \to \psi_i\bar{\psi}_i) = \frac{CG_F M_Z^3}{6\sqrt{2}\pi}\left[V^{i2} + A^{i2}\right]$$

$$\approx \begin{cases} 166.2 \pm 0.2\ (167.8)\ \text{MeV}\ (\nu\bar{\nu}),\ 83.4 \pm 0.1\ (84.2)\ \text{MeV}\ (e^+e^-), \\ 296.1 \pm 0.4\ (300.6)\ \text{MeV}\ (u\bar{u}),\ 382.3 \pm 0.5\ (387.7)\ \text{MeV}\ (d\bar{d}), \end{cases}$$

where the first (second) values are for $m_t = 100$ (200) GeV and the quoted errors are from $M_{W,Z}$. For leptons $C = 1$, while for quarks $C = 3(1 + \alpha_s(M_V)/\pi)$, where the 3 is due to color and the factor in parentheses is a QCD correction, which introduces an additional uncertainty of ~ 1% in the hadronic widths.[6,28] Corrections to Eq. (25) for massive fermions are given in Refs. 6 and 28. Here the numerical values assume $M_W = 80.6 \pm 0.4$ GeV, $M_Z = 91.161 \pm 0.031$ GeV, and $\alpha_s \approx 0.12 \pm 0.02$. Expressing the widths in terms of $G_F M^3_{W,Z}$ incorporates the bulk of the electroweak radiative corrections.[6,28] The remaining corrections introduce a small m_t dependence, which is included in the numbers.

For 3-fermion families the total widths are

$$\Gamma_Z \approx 2.482 \pm 0.003\ (2.507)\ \text{GeV}$$

$$\Gamma_W \approx 2.11 \pm 0.03\ \text{GeV}\ . \tag{26}$$

for $m_t = 100$ (200) GeV. QCD introduces an additional uncertainty of ≈ 11 MeV in Γ_Z. (Fermion masses have been included in Γ_Z). This is to be compared with the experimental results:[18–22] $\Gamma_Z = 2.534 \pm 0.027$ GeV and $\Gamma_W = 2.25 \pm 0.14$ GeV.

Deviations from the Standard Model: The W and Z masses and neutral-current data can be used to search for and set limits on deviations from the Standard Model. For example, the relation in Eq. (5) between M_W and M_Z is modified if there are Higgs multiplets with weak isospin > 1/2 with significant vacuum expectation values. In order to calculate to higher orders in such theories one must define a set of four fundamental renormalized parameters. It is convenient to take these as α, G_F, M_Z, and M_W, since M_W and M_Z are directly measurable. Then $\sin^2\theta_W$ and ρ can be considered dependent parameters defined by

$$\sin^2\theta_W \equiv A_0^2/M_W^2(1 - \Delta r) \tag{27}$$

and

$$\rho \equiv M_W^2/(M_Z^2\cos^2\theta_W)\ . \tag{28}$$

Provided that the new physics which yields $\rho \neq 1$ is a small perturbation which does not significantly affect the radiative corrections, ρ can be regarded as a phenomenological parameter which multiplies G_F in Eqs. (7)–(9), (21), and Γ_Z in Eq. (25). (Also, the expression for M_Z in Eq. (5) is divided by $\sqrt{\rho}$; the M_W formula is unchanged.) The allowed regions in the $\rho - \sin^2\theta_W$ plane are shown in Fig. 2, and a global fit to all data yields[5]

$$\sin^2\theta_W = 0.230 \pm 0.0013\ (0.221 \pm 0.0013)$$

$$\rho = 1.003 \pm 0.004\ (0.993 \pm 0.004)\ , \tag{29}$$

for $m_t = 100$ (200) GeV, which is remarkably close to unity (justifying the neglect of $\rho - 1$ in the radiative corrections). The effects of $\rho < 1$ can compensate a large m_t, leading to the much weaker limit $m_t < 400$ GeV.

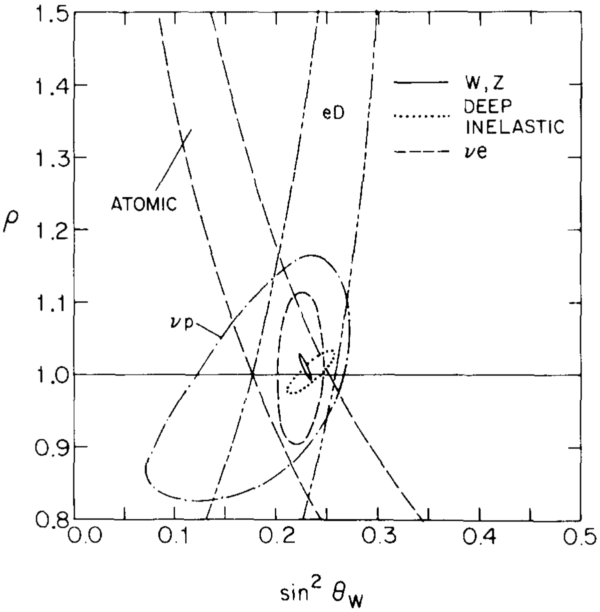

Fig. 2. The allowed regions in $\sin^2\theta_W - \rho$ at 90% CL for various reactions for $m_t = 100$ GeV.

Most of the parameters relevant to ν-hadron, νe, e-hadron, and e^+e^- processes are now determined uniquely and precisely from the data in "model independent" fits (i.e., fits which allow for an arbitrary electroweak gauge theory). The values for the parameters defined in Eqs. (7)–(9)are given in Table 4 along with the predictions of the Standard Model. The agreement is excellent. The e^+e^- results are difficult to present in a model-independent way because Z-propagator effects are non-negligible at TRISTAN, PETRA, and PEP energies. However, assuming e-μ-τ universality, the lepton asymmetries imply[15] $4(A^e)^2 = 0.99 \pm 0.05$, in good agreement with the Standard Model prediction +1. Similarly, $2A^c = 1.12 \pm 0.20$ and $2A^b = -1.07 \pm 0.25$ compared with the predictions of +1 and −1 respectively.[15] The vector couplings are in agreement with the Standard Model, but with much larger errors.

STANDARD MODEL OF ELECTROWEAK INTERACTIONS (Cont'd)

Table 4. Values of the model-independent neutral-current parameters, compared with the Standard Model prediction using the global best fit value of $\sin^2\theta_W$ for m_t = 100 (200) GeV. There is a second $g^e_{V,A}$ solution, given approximately by $g^e_V \leftrightarrow g^e_A$, which is eliminated by e^+e^- data under the assumption that the neutral current is dominated by the exchange of a single Z. θ_i, $i = L$ or R, is defined as $\tan^{-1}[\epsilon_i(u)/\epsilon_i(d)]$.

Quantity	Experimental Value	Standard Model Prediction	Correlation
$\epsilon_L(u)$	0.328 ±0.016	0.343 (0.348)	
$\epsilon_L(d)$	−0.436 ±0.011	−0.427 (−0.431)	non-
$\epsilon_R(u)$	−0.177 ±0.009	−0.155 (−0.155)	Gaussian
$\epsilon_R(d)$	$-0.023\ ^{+0.077}_{-0.048}$	0.078 (0.078)	
g^2_L	0.2977±0.0042	0.300 (0.307)	
g^2_R	0.0317±0.0034	0.030 (0.030)	small
θ_L	2.50 ±0.03	2.46 (2.46)	
θ_R	$4.59\ ^{+0.44}_{-0.27}$	5.18 (5.18)	
g^e_A	−0.513 ±0.025	−0.504 (−0.509)	−0.05
g^e_V	−0.045 ±0.022	−0.036 (−0.042)	
C_{1u}	−0.253 ±0.071	−0.185 (−0.191)	−0.99 − 0.88
C_{1d}	0.391 ±0.064	0.338 (0.343)	0.88
$C_{2u} - \frac{1}{2}C_{2d}$	0.22 ±0.36	−0.025 (−0.036)	

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[*] This section prepared June 1989 by P. Langacker.

[**] Constraints on V are discussed in the section on the Cabibbo-Kobayashi-Maskawa mixing matrix.

[†] α is dependent upon the energy scale of the process in which it is measured. This value is appropriate for low energy. At energies of order M_W the value 1/128 is applicable.

[‡] An alternative is to use the modified minimal subtraction ($\overline{\text{MS}}$) quantity $\sin^2\widehat{\theta}_W(\mu)$, where μ is conveniently chosen to be M_Z for electroweak processes. The two definitions are related by $\sin^2\widehat{\theta}_W(M_Z) = C(m_t, M_H)\sin^2\theta_W$, where C = 1.013 (1.054) for m_t = 100 (200) GeV, M_H = 100 GeV.

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THE CABIBBO-KOBAYASHI-MASKAWA MIXING MATRIX*

In the standard model with SU(2) × U(1) as the gauge group of electroweak interactions, both the quarks and leptons are assigned to be left-handed doublets and right-handed singlets. The quark mass eigenstates are not the same as the weak eigenstates, and the matrix relating these bases was defined for six quarks and given an explicit parametrization by Kobayashi and Maskawa[1] in 1973. It generalizes the four-quark case, where the matrix is parametrized by a single angle, the Cabibbo angle.[2]

By convention, the three charge 2/3 quarks (u, c, and t) are unmixed, and all the mixing is expressed in terms of a 3×3 unitary matrix V operating on the charge $-1/3$ quarks (d, s, b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \tag{1}$$

The values of individual matrix elements can in principle all be determined from weak decays of the relevant quarks, or, in some cases, from deep inelastic neutrino scattering. Using the constraints discussed below together with unitarity, and assuming only three generations, the 90% confidence limits on the magnitude of the elements of the complete matrix are:

$$\begin{pmatrix} 0.9747 \text{ to } 0.9759 & 0.218 \text{ to } 0.224 & 0.001 \text{ to } 0.007 \\ 0.218 \text{ to } 0.224 & 0.9734 \text{ to } 0.9752 & 0.030 \text{ to } 0.058 \\ 0.003 \text{ to } 0.019 & 0.029 \text{ to } 0.058 & 0.9983 \text{ to } 0.9996 \end{pmatrix} . \tag{2}$$

The ranges shown are for the individual matrix elements. The constraints of unitarity connect different elements, so choosing a specific value for one element restricts the range of the others.

There are several parametrizations of the Cabibbo-Kobayashi-Maskawa matrix. In view of the need for a "standard" parametrization in the literature, we advocate:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \tag{3}$$

proposed by Chau and Keung.[3] The choice of rotation angles follows earlier work of Maiani,[4] and the placement of the phase follows that of Wolfenstein.[5] The notation used is that of Harari and Leurer[6] who, along with Fritzsch and Plankl,[7] proposed this parametrization as a particular case of a form generalizable to an arbitrary number of "generations." The general form was also put forward by Botella and Chau.[8] Here $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$, with i and j being "generation" labels, $\{i, j = 1, 2, 3\}$. In the limit $\theta_{23} = \theta_{13} = 0$ the third generation decouples, and the situation reduces to the usual Cabibbo mixing of the first two generations with θ_{12} identified with the Cabibbo angle.[2] The real angles θ_{12}, θ_{23}, θ_{13} can all be made to lie in the first quadrant by an appropriate redefinition of quark field phases. Then all s_{ij} and c_{ij} are positive, $|V_{us}| = s_{12}c_{13}$, $|V_{ub}| = s_{13}$, and $|V_{cb}| = s_{23}c_{13}$. As c_{13} is known to deviate from unity only in the fifth decimal place, $|V_{us}| = s_{12}$, $|V_{ub}| = s_{13}$, and $|V_{cb}| = s_{23}$ to an excellent approximation. The phase δ_{13} lies in the range $0 \leq \delta_{13} < 2\pi$, with non-zero values generally breaking CP invariance for the weak interactions. The generalization to the n generation case contains $n(n-1)/2$ angles and $(n-1)(n-2)/2$ phases.[6,7,8] The range of matrix elements in Eq. (2) corresponds to 90% CL limits on the angles of $s_{12} = 0.218$–$0.224, s_{23} = 0.030$–0.058, and $s_{13} = 0.001$–0.007.

Kobayashi and Maskawa[1] originally chose a parametrization involving the four angles, θ_1, θ_2, θ_3, δ:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3+c_2s_3e^{i\delta} & c_1s_2s_3-c_2c_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} , \tag{4}$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ for $i = 1, 2, 3$. In the limit $\theta_2 = \theta_3 = 0$, this reduces to the usual Cabibbo mixing with θ_1 identified (up to a sign) with the Cabibbo angle.[2] Slightly different forms of the Kobayashi-Maskawa parametrization are found in the literature. The C-K-M matrix used in the 1982 Review of Particle Properties is obtained by letting $s_1 \to -s_1$ and $\delta \to \delta + \pi$ in the matrix given above. An alternative is to change Eq. (4) by $s_1 \to -s_1$ but leave δ unchanged. With this change in s_1, the angle θ_1 becomes the usual Cabibbo angle, with the "correct" sign (i.e. $d' = d\cos\theta_1 + s\sin\theta_1$) in the limit $\theta_2 = \theta_3 = 0$. The angles θ_1, θ_2, θ_3 can, as before, all be taken to lie in the first quadrant by adjusting quark field phases. Since all these parametrizations are referred to as "the" Kobayashi-Maskawa form, some care about which one is being used is needed when the quadrant in which δ lies is under discussion.

Other parametrizations, mentioned above, are due to Maiani[4] and to Wolfenstein.[5] The latter emphasizes the relative sizes of the matrix elements by expressing them in powers of the Cabibbo angle. Still other parametrizations[9] have come into the literature in connection with attempts to define "maximal CP violation". No physics can depend on which of the above parametrizations (or any other) is used as long as a single one is used consistently and care is taken to be sure that no other choice of phases is in conflict.

Our present knowledge of the matrix elements comes from the following sources:

(1) Nuclear beta decay, when compared to muon decay, gives[13]

$$|V_{ud}| = 0.9744 \pm 0.0010 . \tag{5}$$

This includes refinements in the analysis of the radiative corrections, especially the order $Z\alpha^2$ effects, which have brought the ft-values from low and high Z Fermi transitions into good agreement.

(2) Analysis of K_{e3} decays yields[14]

$$|V_{us}| = 0.2196 \pm 0.0023 . \tag{6}$$

The isospin violation between K^+_{e3} and K^0_{e3} decays has been taken into account, bringing the values of $|V_{us}|$ extracted from these two decays into agreement at the 1% level of accuracy. The analysis of hyperon decay data has larger theoretical uncertainties because of first order SU(3) symmetry breaking effects in the axial-vector couplings, but due account of symmetry breaking[15] applied to the WA2 data[16] gives a corrected value[17] of 0.222 ± 0.003. We average these two results to obtain:

$$|V_{us}| = 0.2205 \pm 0.0018 . \tag{7}$$

(3) The magnitude of $|V_{cd}|$ may be deduced from neutrino and antineutrino production of charm off valence d quarks. The dimuon production cross sections of the CDHS group[18] yield $\overline{B}_c\,|V_{cd}|^2 = 0.41 \pm 0.07 \times 10^{-2}$, where $\overline{B}_c$ is the semileptonic branching fraction of the charmed hadrons produced. The corresponding preliminary value from a recent Tevatron experiment[19] is $\overline{B}_c\,|V_{cd}|^2 = 0.534^{+0.052}_{-0.078} \times 10^{-2}$. Averaging these two results gives $\overline{B}_c\,|V_{cd}|^2 = 0.47 \pm 0.05 \times 10^{-2}$. Supplementing this with measurements of the semileptonic branching fractions of charmed mesons,[20] weighted by a production ratio of $D^0/D^+ = (60 \pm 10)/(40 \mp 10)$, to give $\overline{B}_c = 0.113 \pm 0.015$, yields

$$|V_{cd}| = 0.204 \pm 0.017 \tag{8}$$

(4) Values of $|V_{cs}|$ from neutrino production of charm are dependent on assumptions about the strange quark density in the parton-sea. The most conservative assumption, that the strange-quark sea does not exceed the value corresponding to an SU(3) symmetric sea, leads to a lower bound,[18] $|V_{cs}| > 0.59$. It is more advantageous to proceed analogously to the method used for extracting $|V_{us}|$ from K_{e3} decay; namely, we compare the experimental value for the width of D_{e3} decay with the expression[21] that follows from the standard weak interaction amplitude:

$$\Gamma(D \to \overline{K}e^+\nu_e) = |f_+^D(0)|^2\,|V_{cs}|^2\,(1.54 \times 10^{11}\ \mathrm{s}^{-1}) . \tag{9}$$

Here $f_+^D(q^2)$, with $q = p_D - p_K$, is the form factor relevant to D_{e3} decay; its variation has been taken into account with the parametrization $f_+^D(t)/f_+^D(0) = M^2/(M^2 - t)$ and $M = 2.1$ GeV/c^2, a form and mass consistent with Mark III and E691 measurements.[23] Combining data on branching ratios for $D_{\ell 3}$ decays[22,23] with accurate values[24] for τ_{D^+} and τ_{D^0}, gives the value $0.78 \pm 0.11 \times 10^{11}$ s^{-1} for $\Gamma(D \to \overline{K} e^+ \nu_e)$. Therefore

$$|f_+^D(0)|^2 \, |V_{cs}|^2 = 0.51 \pm 0.07 \; . \tag{10}$$

A very conservative assumption is that $|f_+^D(0)| < 1$, from which it follows that $|V_{cs}| > 0.66$. Calculations of the form factor either performed[26] directly at $q^2 = 0$, or done[27] at the maximum value of $q^2 = (m_D - m_K)^2$ and interpreted at $q^2 = 0$ using the measured q^2 dependence, yield $f_+^D(0) = 0.7 \pm 0.1$. It follows that

$$|V_{cs}| = 1.02 \pm 0.18 \; . \tag{11}$$

The constraint of unitarity when there are only three generations gives a much tighter bound (see below).

(5) The ratio $|V_{ub}/V_{cb}|$ can be obtained from the semileptonic decay of B mesons by fitting to the lepton energy spectrum as a sum of contributions involving $b \to u$ and $b \to c$. The relative overall phase space factor between the two processes is calculated from the usual four-fermion interaction with one massive fermion (c quark or u quark) in the final state. The value of this factor depends on the quark masses, but is roughly one-half (in suppressing $b \to c$ compared to $b \to u$). Both the CLEO[28] and ARGUS[29] collaborations have reported evidence for $b \to u$ transitions in semileptonic B decays. The interpretation of the result in terms of $|V_{ub}/V_{cb}|$ depends fairly strongly on the theoretical model used to generate the lepton energy spectrum, especially for $b \to u$ transitions.[26,27,30] Combining the experimental and theoretical uncertainties, we quote

$$|V_{ub}/V_{cb}| = 0.09 \pm 0.04 \; . \tag{12}$$

(6) The magnitude of V_{cb} itself can be determined if the measured semileptonic bottom hadron partial width is assumed to be that of a b quark decaying through the usual $V - A$ interaction:

$$\Gamma(b \to c \ell \overline{\nu}_\ell) = \frac{\mathrm{BF}(b \to c \ell \overline{\nu}_\ell)}{\tau_b} = \frac{G_F^2 \, m_b^5}{192\pi^3} F(m_c/m_b) \, |V_{cb}|^2 \; . \tag{13}$$

where τ_b is the b lifetime and $F(m_c/m_b)$ is the phase space factor noted above as approximately one-half. Most of the error on $|V_{cb}|$ derived from Eq. (13) is not from the experimental uncertainties, but in the theoretical uncertainties in choosing a value of m_b and in the use of the quark model to represent inclusively semileptonic decays which, at least for the B meson, are dominated by a few exclusive channels. Instead we quote the value derived from $B_{\ell 3}$ decay, $\overline{B} \to D \ell \overline{\nu}_\ell$, by comparing the observed rate with the theoretical expression that involves a form factor, $f_+^B(q^2)$. This is analogous to what gives the most accurate values for $|V_{us}|$ (from K_{e3} decay) and $|V_{cs}|$ (from $D_{\ell 3}$ decay). It avoids all questions of what masses to use, and the heavy quarks in both the initial and final states give more confidence in the accuracy of the theoretical calculations of the form factor. With account of a number of models of the form factor, the data[31] yield

$$|V_{cb}| = 0.044 \pm 0.009 \; . \tag{14}$$

The central value and the error are now comparable to what is obtained from the inclusive semileptonic decays, but ultimately, with more data and more confidence in the calculation of the form factor, exclusive semileptonic decays should provide the most accurate value of $|V_{cb}|$.

The results for three generations of quarks, from Eqs. (5), (7), (8), (11), (12), and (14) plus unitarity, are summarized in the matrix in Eq. (2). The ranges given there are different from those given in Eqs. (5)–(14) (because of the inclusion of unitarity), but are consistent with the one standard deviation errors on the input matrix elements.

The data do not preclude there being more than three generations. Moreover, the entries deduced from unitarity might be altered when the C-K-M matrix is expanded to accommodate more generations. Conversely, the known entries restrict the possible values of additional elements if the matrix is expanded to account for additional generations. For example, unitarity and the known elements of the first row require that any additional element in the first row have a magnitude $|V_{ub'}| < 0.07$. When there are more than three generations the allowed ranges (at 90% CL) of the matrix elements connecting the first three generations are

$$\begin{pmatrix} 0.9728 \text{ to } 0.9757 & 0.218 \text{ to } 0.224 & 0.001 \text{ to } 0.007 & \ldots \\ 0.182 \text{ to } 0.227 & 0.865 \text{ to } 0.975 & 0.030 \text{ to } 0.058 & \ldots \\ 0 \text{ to } 0.13 & 0 \text{ to } 0.45 & 0 \text{ to } 0.9995 & \ldots \\ \vdots & \vdots & \vdots & \end{pmatrix} ;$$

where we have used unitarity (for the expanded matrix) and Eqs. (5), (7), (8), (11), (12), and (14).

Further information on the angles requires theoretical assumptions. For example, $B_d - \overline{B}_d$ mixing, if it originates from short distance contributions to ΔM_B dominated by box diagrams involving virtual t quarks, gives information on $V_{tb} V_{td}^*$ once hadronic matrix elements and the t quark mass are known. A similar comment holds for $V_{tb} V_{ts}^*$ and $B_s - \overline{B}_s$ mixing.

Direct and indirect information on the C-K-M matrix is neatly summarized in terms of the "unitarity triangle." The name arises since unitarity of the 3×3 C-K-M matrix applied to the first and third columns yields

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \; . \tag{15}$$

In the parametrization adopted above, V_{cb} is real and V_{cd} is real to a very good approximation. Setting cosines of small angles to unity, Eq. (15) becomes

$$V_{ub}^* + V_{td} = |V_{cd} V_{cb}| \; . \tag{16}$$

The unitarity triangle is just a geometrical presentation of this equation in the complex plane.[32]

CP-violating processes will involve the phase in the C-K-M matrix, assuming that the observed CP violation is solely related to a nonzero value of this phase. This allows additional constraints to be imposed. More specifically, a necessary and sufficient condition for CP violation with three generations can be formulated in a parametrization-independent manner in terms of the non-vanishing of the determinant of the commutator of the mass matrices for the charge $2e/3$ and charge $-e/3$ quarks.[33] CP violating amplitudes or differences of rates all are proportional to the C-K-M factor in this quantity. This is the product of factors $s_{12} s_{13} s_{23} c_{12} c_{13}^2 c_{23} s_{\delta_{13}}$ in the parametrization adopted above, and is $s_1^2 s_2 s_3 c_1 c_2 c_3 s_\delta$ in that of Ref. 1. With the approximation of setting cosines to unity, this is just twice the area of the unitarity triangle. While hadronic matrix elements whose values are imprecisely known generally now enter, the constraints from CP violation in the neutral kaon system are tight enough to very much restrict the range of angles and the phase of the C-K-M matrix. For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry in a given decay and $\sin 2\phi$, where ϕ is an appropriate angle of the unitarity triangle.[32] The combination of all the direct and indirect information can be used to find the overall constraints on the C-K-M matrix and thence the implications for future measurements of CP violation in the B system.[34]

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QUARK MODEL

A. QUANTUM NUMBERS

Each quark has spin 1/2. The additive quantum numbers (other than baryon number = 1/3) of the quarks known or presumed to exist are shown in Table 1. With the conventions used in Table 1, any flavor carried by a charged meson has the same sign as the charge; e.g., the strangeness of the K^+ is +1 and the bottomness of the B^+ is +1.

Table 1. Additive quantum numbers of the three generations of quarks.

	Quark type (flavor)					
Quantum number	d	u	s	c	b	t
Q electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I_z isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

B. MESONS

Nearly all known mesons can be understood as bound states of a quark q and an antiquark $\overline{q}'$ (the flavors of q and q' may be different). If the orbital angular momentum of the $q\overline{q}'$ state is L, then the parity $P = (-1)^{L+1}$. A state $q\overline{q}$ of a quark and its own antiquark is also an eigenstate of charge conjugation with $C = (-1)^{L+S}$, where the spin $S = 0$ or 1. The $L = 0$ states are the pseudoscalars, $J^P = 0^-$, and the vectors, $J^P = 1^-$. Assignments for some known $q\overline{q}'$ states are given in Table 2. States in the "normal" spin-parity series, $P = (-1)^J$, must, according to the above, have $S = 1$ and hence $CP = +1$. Thus mesons with normal spin-parity and $CP = -1$ are forbidden in the $q\overline{q}'$ quark model. The $J^{PC} = 0^{--}$ state is forbidden as well. Mesons with such J^{PC} may exist, but would lie outside the $q\overline{q}'$ model.

The nine possible $q\overline{q}$ combinations containing u, d, and s quarks group themselves into an octet and a singlet:

$$\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$$

States with the same IJ^P and additive quantum numbers can mix (if they are eigenstates of charge conjugation, they must also have the same value of C). Thus the $I = 0$ member of the ground-state pseudoscalar octet mixes with the corresponding pseudoscalar singlet to produce the η and η'. These appear as members of a nonet, which is shown as the middle plane in Fig. 1(a). Similarly, the ground-state vector nonet appears as the middle plane in Fig. 1(b).

A fourth quark such as charm can be included in this scheme by extending the symmetry to SU(4), as shown in Fig. 1. Bottom could be included in this way instead of charm, but if both are included the figure becomes four-dimensional.

For the pseudoscalar mesons, the Gell-Mann-Okubo formula is

$$m_\eta^2 = \frac{1}{3}(4m_K^2 - m_\pi^2) \ ,$$

assuming no octet-singlet mixing. However, the octet η_8 and singlet η_1 mix because of SU(3) breaking. The physical states η and η' are given by

$$\eta = \eta_8 \cos\theta_P - \eta_1 \sin\theta_P$$

$$\eta' = \eta_8 \sin\theta_P + \eta_1 \cos\theta_P \ .$$

QUARK MODEL (Cont'd)

Table 2. Standard quark-model assignments for some of the known mesons. Some assignments, especially for 0^{++}, are controversial. Only the states in the $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, and $b\bar{b}$ columns and the neutral states in the $I = 1$ column are eigenstates of charge conjugation C.

$^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I = 1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I = 0$	$c\bar{c}$ $I = 0$	$b\bar{b}$ $I = 0$	$\bar{s}u$, $\bar{s}d$ $I = 1/2$	$c\bar{u}$, $c\bar{d}$ $I = 1/2$	$c\bar{s}$ $I = 0$	$\bar{b}u$, $\bar{b}d$ $I = 1/2$
$^1S_0$	0^{-+}	π	η, η'	η_c		K	D	D_s	B
$^3S_1$	1^{--}	ρ	ϕ, ω	J/ψ	Υ	$K^*(892)$	$D^*(2010)$		
$^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170)$			K_{1B}	$D_1(2420)$	$D_{s1}(2536)$	
$^3P_0$	0^{++}	$a_0(980)$	$f_0(975)$, $f_0(1400)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$			
$^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285)$, $f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	K_{1A}			
$^3P_2$	2^{++}	$a_2(1320)$	$f_2'(1525)$, $f_2(1270)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$		
$^1D_2$	2^{-+}	$\pi_2(1670)$							
$^3D_1$	1^{--}			$\psi(3770)$					
$^3D_2$	2^{--}					$K_2(1770)$			
$^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670)$			$K_3^*(1780)$			

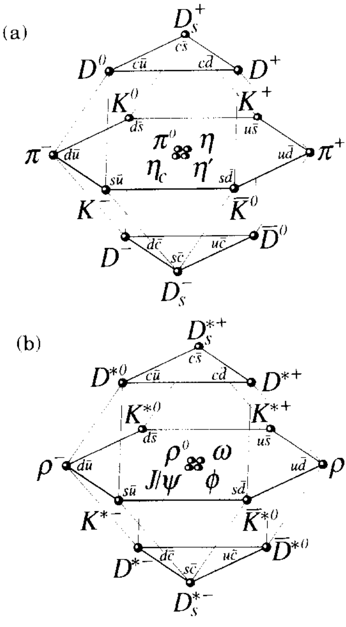

Fig. 1. The SU(4) hexadecuplets for the (a) pseudoscalar and (b) vector mesons made up of u, d, s, and c $q\bar{q}'$ combinations. The nonets mesons occupy the central planes, to which the $c\bar{c}$ members have been added. The neutral mesons at the center of these planes are mixtures of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ states.

These combinations diagonalize the mass-squared matrix

$$M^2 = \begin{pmatrix} M_{11}^2 & M_{18}^2 \\ M_{18}^2 & M_{88}^2 \end{pmatrix} ,$$

where $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)$. It follows that

$$\tan^2\theta_P = \frac{M_{88}^2 - m_\eta^2}{m_{\eta'}^2 - M_{88}^2} .$$

The sign of θ_P is meaningful in the quark model. If

$$\eta_1 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$$

$$\eta_8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6} ,$$

then the matrix element M_{18}^2, which is due mostly to the strange quark mass, is negative. From the relation

$$\tan\theta_P = \frac{M_{88}^2 - m_\eta^2}{M_{18}^2} ,$$

we find $\theta_P < 0$. However, we note that caution is suggested in the use of the η-η' mixing-angle formulas, as they are extremely sensitive to SU(3) breaking. If we allow $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)\ (1 + \Delta)$, the mixing angle is determined by

$$\tan^2\theta_P = 0.0319(1 + 17\Delta)$$

$$\theta_P = -10.1^\circ(1 + 8.5\Delta)$$

to first order in Δ. A small breaking of the Gell-Mann-Okubo relation can produce a major modification of θ_P.

For the vector mesons we replace $\pi \to \rho$, $K \to K^*$, $\eta \to \phi$, and $\eta' \to \omega$, so

$$\phi = \omega_8 \cos\theta_V - \omega_1 \sin\theta_V$$

$$\omega = \omega_8 \sin\theta_V + \omega_1 \cos\theta_V .$$

QUARK MODEL (Cont'd)

For "ideal mixing," $\phi = s\bar{s}$, $\tan\theta_V = 1/\sqrt{2}$, so $\theta_V = 35.3°$. Experimentally, θ_V is near 35°, the sign being determined by a formula analogous to that for $\tan\theta_P$. Following this procedure we find the mixing angles given in Table 3.

Table 3. Singlet-octet mixing for the pseudoscalar, vector, and tensor mesons. The sign conventions are given in the text. The value of $\theta_{\rm quad}$ is obtained from the equations in the text, and $\theta_{\rm lin}$ is obtained by replacing m^2 by m throughout. Of the two isosinglets, the mostly octet one is listed first.

J^{PC}	Nonet Members	$\theta_{\rm quad}$	$\theta_{\rm lin}$
0^{-+}	π, K, η, η'	$-10°$	$-23°$
1^{--}	ρ, $K^*(892)$, ϕ, ω	$39°$	$36°$
2^{++}	$a_2(1320)$, $K_2^*(1430)$, $f_2'(1525)$, $f_2(1270)$	$28°$	$26°$
3^{--}	$\rho_3(1690)$, $K_3^*(1780)$, $X(1850)$, $\omega_3(1670)$	$29°$	$28°$

In the quark model, the coupling of neutral mesons to two photons is proportional to $\sum_i Q_i^2$, where Q_i is the charge of the i-th quark. This provides an alternative characterization of mixing. For example, defining

$$\mathrm{Amp}\,[P \to \gamma(k_1)\,\gamma(k_2)] = M\epsilon^{\mu\nu\alpha\beta}\,\epsilon_{1\mu}^*\,k_{1\nu}\,\epsilon_{2\alpha}^*\,k_{2\beta}\ ,$$

where $\epsilon_{i\lambda}$ is the λ component of the polarization vector of the i^{th} photon, one finds

$$\frac{M(\eta\to\gamma\gamma)}{M(\pi^0\to\gamma\gamma)} = \frac{1}{\sqrt{3}}(\cos\theta_P - 2\sqrt{2}\sin\theta_P)$$

$$= \frac{1.73\pm0.18}{\sqrt{3}}$$

$$\frac{M(\eta'\to\gamma\gamma)}{M(\pi^0\to\gamma\gamma)} = 2\sqrt{2/3}\left(\cos\theta_P + \frac{\sin\theta_P}{2\sqrt{2}}\right)$$

$$= (0.78\pm0.04)2\sqrt{2/3}\ .$$

These data favor $\theta_P \approx -20°$, which is compatible with the quadratic mass mixing formula with ≈ 12% SU(3) breaking in M_{88}^2.

C. BARYONS

All the established baryons are apparently 3-quark (qqq) states, and each such state is an SU(3) color singlet, a completely antisymmetric state of the three possible colors. Since the quarks are fermions, the state function for any baryon must be antisymmetric under interchange of any two equal-mass quarks (up and down quarks in the limit of isospin symmetry). Thus the state function may be written as

$$|\,qqq\,\rangle_A = |\,\mathrm{color}\,\rangle_A \times |\,\mathrm{space,\ spin,\ flavor}\,\rangle_S\ ,$$

where the subscripts S and A indicate symmetry or antisymmetry under interchange of any two of the equal-mass quarks. Note the contrast with the state function for the three nucleons in ^{3}H or ^{3}He:

$$|\,NNN\,\rangle_A = |\,\mathrm{space,\ spin,\ isospin}\,\rangle_A\ .$$

This difference has major implications for internal structure, magnetic moments, etc. (For a nice discussion, see Ref. 1.)

The "ordinary" baryons are made up of d, u, and s quarks. The three flavors imply an approximate flavor SU(3), which requires that baryons made of these quarks belong to the multiplets on the right side of

$$\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A$$

(see the section on SU(n) Multiplets and Young Diagrams). Here the subscripts indicate symmetric, mixed-symmetry, or antisymmetric states under interchange of any two quarks. The **1** is a *sud* state (Λ_1) and the octet contains a similar state (Λ_8). If these have the same spin and parity they can mix. An example is the mainly octet D_{03} $\Lambda(1690)$ and mainly singlet D_{03} $\Lambda(1520)$. In the ground state multiplet, the SU(3) flavor singlet Λ is forbidden by Fermi statistics. The mixing formalism is the same as for η-η' or ϕ-ω (see above), except that for baryons the mass M instead of M^2 is used. The section SU(3) Isoscalar Factors shows how relative decay rates in, say, $\mathbf{10}\to\mathbf{8}\otimes\mathbf{8}$ decays may be calculated. A summary of results of fits to the observed baryon masses and decay rates for the best-known SU(3) multiplets is given in Appendix II of our 1982 edition.[2]

Figures 2(a) and 2(b) show the (badly broken) SU(4) multiplets that have as their "ground floors" the SU(3) octet that contains the nucleons and the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only charmed baryons that have been discovered each contain one charmed quark. These belong to the first floor of the multiplet shown in Fig. 2(a), which consists of two SU(3) multiplets: a $\overline{\mathbf{3}}$ which contains the Λ_c and Ξ_c, both of which decay weakly, and a **6** that contains the $\Sigma_c(2455)$, which decays strongly into $\Lambda_c\pi$. A second Ξ_c and a Ω_c^0 remain to be discovered to fill out the **6**, and a host of other baryons with one or more charmed quarks are still needed to fill out the SU(4) multiplets shown in Fig. 2. Furthermore, ***every*** N or Δ baryon resonance "starts" a multiplet like those shown in Figs. 2(a) and 2(b). Analogous SU(4) structures can be made by substituting b for c. If both are present, the figures are four-dimensional.

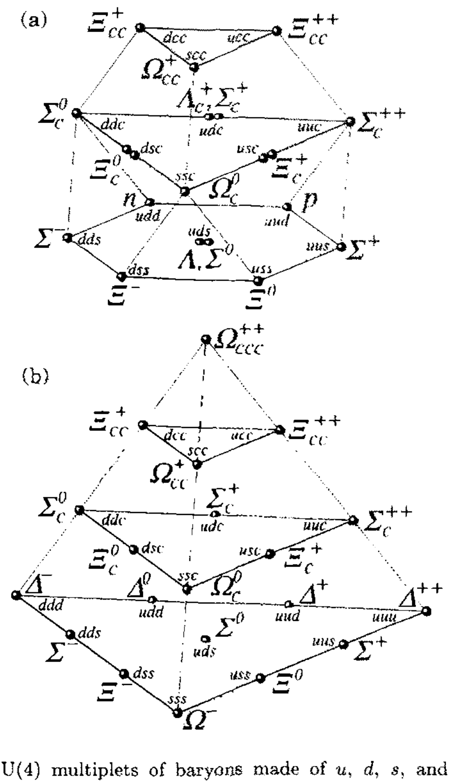

Fig. 2. SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

For the "ordinary" baryons, flavor and spin may be combined in an approximate flavor-spin SU(6) in which the six basic states are $d\uparrow$, $d\downarrow$, $\cdots$, $s\downarrow$ ($\uparrow$, $\downarrow$ = spin up, down). Then the baryons belong to the multiplets on the right side of

$$\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6} = \mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A\ .$$

These SU(6) multiplets decompose into flavor SU(3) multiplets as follows:

$$\mathbf{56} = {}^4\mathbf{10} \oplus {}^2\mathbf{8}$$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

$$\mathbf{20} = {}^2\mathbf{8} \oplus {}^4\mathbf{1}\ .$$

QUARK MODEL (Cont'd)

where the superscript $(2S+1)$ gives the net spin S of the quarks for each particle in the SU(3) multiplet. The $J^P = 1/2^+$ octet containing the nucleon and the $J^P = 3/2^+$ decuplet containing the $\Delta(1232)$ together make up the "ground-state" 56-plet in which the orbital angular momenta between the quark pairs are zero (so that the spatial part of the state function is trivially symmetric). The **70** and **20** require some excitation of the spatial part of the state function in order to make the overall state function symmetric. States with nonzero orbital angular momenta are classified in SU(6)⊗O(3) supermultiplets. Physical baryons with the same quantum numbers do not belong to a single supermultiplet, since SU(6) is broken by spin-dependent interactions, differences in quark masses, etc.; nevertheless, the SU(6)⊗O(3) basis provides a suitable framework for describing baryon state functions.

It is convenient to classify the baryons into bands that have the same number N of quanta of excitation. Each band consists of a number of supermultiplets, specified by (D, L_N^P), where D is the dimensionality of the SU(6) representation, L is the total quark orbital angular momentum, and P is the total parity. Supermultiplets contained in bands up to $N = 12$ are given in Ref. 3. The $N = 0$ band, which contains the nucleon and $\Delta(1232)$, consists only of the $(56,0_0^+)$ supermultiplet. The $N = 1$ band consists only of the $(70,1_1^-)$ multiplet and contains the negative-parity baryons with masses below about 1.9 GeV. The $N = 2$ band contains five supermultiplets: $(56,0_2^+)$, $(70,0_2^+)$, $(56,2_2^+)$, $(70,2_2^+)$, and $(20,1_2^+)$. Baryons belonging to the $(20,1_2^+)$ supermultiplet are not ever likely to be observed, since a coupling from the ground-state baryons requires a two-quark excitation. Selection rules are similarly responsible for the fact that many other baryon resonances have not been observed.[4]

In Table 4, quark-model assignments are given for many of the established baryons whose SU(6)⊗O(3) compositions are relatively unmixed. Note that the unestablished resonances $N(1540)P_{13}$, $\Delta(1550)P_{31}$, $\Sigma(1480)$, $\Sigma(1560)$, $\Sigma(1580)$, $\Sigma(1770)$, and $\Xi(1620)$ in our Baryon Full Listings are too low in mass to be accommodated in most modern quark models.[4,5]

Quark models for baryons are extensively reviewed in Ref. 6.

D. DYNAMICS

Many specific quark models exist, but most contain basically the same set of dynamical ingredients. These include:

i) Using a confining interaction, which is generally spin-independent.

ii) Adding a spin-dependent interaction, modeled after the effects of gluon exchange in QCD. For example, in the S-wave states, there is a spin-spin hyperfine interaction of the form

$$H_{HF} = -\alpha_S M \sum_{i>j} (\vec{\sigma}\lambda^A)_i (\vec{\sigma}\lambda^A)_j ,$$

where M is a constant with units of energy; λ^A, $A = 1, \cdots, 8$, is the set of SU(3) unitary spin matrices, defined in the "SU(3) Isoscalar Factors and Representation Matrices" section; and the sum runs over constituent quarks or antiquarks. Spin-orbit interactions, although allowed, seem to be small.

iii) Taking the strange quark mass to be somewhat larger than the up and down quark masses in order to split the SU(3) multiplets.

iv) In the case of isoscalar mesons, an interaction is needed for mixing $q\bar{q}$ configurations of different flavors (e.g., $u\bar{u} \leftrightarrow d\bar{d}, s\bar{s}$) in a manner which is generally chosen to be flavor independent.

These four ingredients provide the basic mechanisms which determine the hadron spectrum.

Table 4. Quark-model assignments for some of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses.

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

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1. F.E. Close, in *Quarks and Nuclear Forces* (Springer-Verlag, 1982), p. 56.
2. Particle Data Group, Phys. Lett. **111B** (1982).
3. R.H. Dalitz and L.J. Reinders, in *Hadron Structure as Known from Electromagnetic and Strong Interactions, Proceedings of the Hadron '77 Conference* (Veda, 1979), p. 11.
4. N. Isgur and G. Karl, Phys. Rev. **D18**, 4187 (1978); ibid. **D19**, 2653 (1979); ibid. **D20**, 1191 (1979); and K.-T. Chao, N. Isgur, and G. Karl, Phys. Rev. **D23**, 155 (1981).
5. C.P. Forsyth and R.E. Cutkosky, Z. Phys. **C18**, 219 (1983).
6. A.J.G. Hey and R.L. Kelly, Phys. Reports **96**, 71 (1983). Also see S. Gasiorowicz and J.L. Rosner, Am. J. Phys. **49**, 954 (1981).

MONTE CARLO PARTICLE NUMBERING SCHEME*

Most particle physics Monte Carlo and analysis systems use a numbering scheme to represent particles. The lack of standardization of such schemes inhibits interfacing different programs. The following table proposes a standard numbering scheme. Some of the properties of this scheme are:

1. Quarks and leptons are ordered by family, and within the family, by isospin. This puts the u and d in the opposite order than is often used in other numbering schemes. In our scheme we call the highest numbered quark the heaviest quark.
2. For multiple quark systems (mesons, baryons, and diquarks), the rightmost digit is generally $L = 2J + 1$. (The K^0_S and K^0_L are exceptions.)
3. Mesons are represented by the form NML and baryons by $NMKL$, where N, M, and K are quark numbers.
4. For these systems the heaviest quark is usually on the left and the quarks are in decreasing mass order from left to right. One exception to this convention is the K^0_L-K^0_S pair. A second exception is for the Λ's for which we invert the up and down quarks to distinguish the Λ from the Σ^0.
5. The other exception to this mass order rule is for some N's and Δ's. For N's, the u and d quark are reversed for spins 3/2 and 7/2. For Δ's, they are reversed for spins 1/2 and 5/2. The quarks are in the normal decreasing order when $I + J$ is odd.
6. Mesons, and only mesons, have the third digit nonzero and the fourth digit zero. (We designate the rightmost digit as the first digit.)
7. Only baryons and diquarks have the fourth digit nonzero.
8. Only quarks and diquarks have the second digit equal to zero.
9. Particles have positive numbers; each antiparticle has the negative of its counterpart.
10. The particle-antiparticle convention is the one used by the Particle Data Group, so that the K^+ and B^+ are particles.
11. The above rules imply that for mesons (as opposed to antimesons), when the number of the leftmost (heaviest) quark is even, it is a quark, and when the number of the leftmost quark is odd, it is an antiquark.
12. The gluon has two numbers. Its official number is 21 to place it with the other gauge bosons. Its number is also 9 so that a glueball is specified as 99.
13. The fifth digit is used to differentiate different particles with the same quark content and spin.
14. Although isospin is not manifest in this scheme, there is some isospin content. Mesons with $11J$ are isospin 1 and those with $22J$ are isospin 0. For nonstrange baryons, if the quarks are in the normal decreasing order, then $I + J$ is odd, otherwise $I + J$ is even. If a strange baryon does not have the normal decreasing quark order, it has $I = 0$.

More details about the motivation behind, and properties of, this scheme can be found in Ref. 1. Although this scheme has the advantage that a particle's number has considerable physics content, it has the disadvantage that it is not compact. An algorithm that translates this scheme into a more compact scheme is needed for its implementation. Contact the Berkeley Particle Data Group for further information on such an algorithm.

A list of particle numbers follows.

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* Written April 1988 by G.R. Lynch and T.G. Trippe.

1. T.G. Trippe and G.R. Lynch, "Particle I.D. Numbers, Decay Tables, and Other Possible Contributions of the Particle Data Group to Monte Carlo Standards," LBL-24287, in *Proceedings of the Workshop on Detector Simulation for the SSC* (August 1987).

ELEMENTARY PARTICLES

Quarks

d	1
u	2
s	3
c	4
b	5
t	6

Leptons

ν_e	12
ν_μ	14
ν_τ	16
e^-	11
μ^-	13
τ^-	15

Gauge and Higgs Bosons

γ	22
W^+	24
Z^0	23
g	21 and 9
H^0_1	25
H^0_2	35
H^0_3	36
H^+	37

DIQUARKS

dd_1	1103
ud_0	2101
ud_1	2103
uu_1	2203
sd_0	3101
sd_1	3103
su_0	3201
su_1	3203

MESONS

π^+	211
π^0	111
η	221
$\rho(770)^+$	213
$\rho(770)^0$	113
$\omega(783)$	223
$\eta'(958)$	331
$f_0(975)$	10221
$a_0(980)$	10211, 10111
$\phi(1020)$	333
$h_1(1170)$	10223
$b_1(1235)$	10213, 10113
$a_1(1260)$	20213, 20113
$f_2(1270)$	225
$\eta(1280)$	20221
$f_1(1285)$	20223
$\pi(1300)$	20211, 20111
$a_2(1320)$	215, 115
$\omega(1390)$	?
$f_0(1400)$	30221

MESONS (Cont'd)

$f_1(1420)$	30223
$\eta(1440)$	40221
$\rho(1450)$	?
$f_1(1510)$	40223
$f'_2(1525)$	335
$f_0(1590)$	50221
$\omega(1600)$	?
$\omega_3(1670)$	227
$\pi_2(1670)$	10215, 10115
$\phi(1680)$	10333
$\rho_3(1690)$	217, 117
$\rho(1700)$	30213, 30113
$f_2(1720)$	10225
$\phi_3(1850)$	?
$f_2(2010)$	20225
$f_4(2050)$	229
$f_2(2300)$	30225
$f_2(2340)$	40225
K^+	321
K^0	311
K^0_S	310
K^0_L	130
$K^*(892)^+$	323
$K^*(892)^0$	313
$K_1(1270)$	10323, 10313
$K^*(1370)$	30323, 30313
$K_1(1400)$	20323, 20313
$K^*_0(1430)$	10321, 10311
$K^*_2(1430)$	325, 315
$K^*(1680)$	40323, 40313

MONTE CARLO PARTICLE NUMBERING SCHEME (Cont'd)

MESONS (Cont'd)

$K_2(1770)$	10325, 10315
$K_3^*(1780)$	327, 317
$K_4^*(2045)$	329, 319
D^+	411
D^0	421
$D^*(2010)^+$	413
$D^*(2010)^0$	423
$D_1(2420)^0$	?
$D_2^*(2460)^0$	?
D_s^+	431
D_s^{*+}	433
$D_{s1}(2536)^+$	?
$B+$	521
B^0	511
$\eta_c(1S)$	441
$J/\psi(1S)$	443
$\chi_{c0}(1P)$	10441
$\chi_{c1}(1P)$	10443
$\chi_{c2}(1P)$	445
$\psi(2S)$	20443
$\psi(3770)$	30443
$\psi(4040)$	40443
$\psi(4160)$	50443
$\psi(4415)$	60443
$\Upsilon(1S)$	553
$\chi_{b0}(1P)$	551
$\chi_{b1}(1P)$	10553
$\chi_{b2}(1P)$	555
$\Upsilon(2S)$	20553
$\chi_{b0}(2P)$	10551
$\chi_{b1}(2P)$	70553
$\chi_{b2}(2P)$	10555
$\Upsilon(3S)$	30553
$\Upsilon(4S)$	40553
$\Upsilon(10860)$	50553
$\Upsilon(11020)$	60553

BARYONS

p		2212
n		2112
$N(1440)^+$	P_{11}	12212
$N(1440)^0$	P_{11}	12112
$N(1520)$	D_{13}	2124, 1214
$N(1535)$	S_{11}	22212, 22112
$N(1650)$	S_{11}	32212, 32112
$N(1675)$	D_{15}	2216, 2116
$N(1680)$	F_{15}	12216, 12116
$N(1700)$	D_{13}	22124, 21214
$N(1710)$	P_{11}	42212, 42112
$N(1720)$	P_{13}	32124, 31214
$N(2190)$	G_{17}	2128, 1218

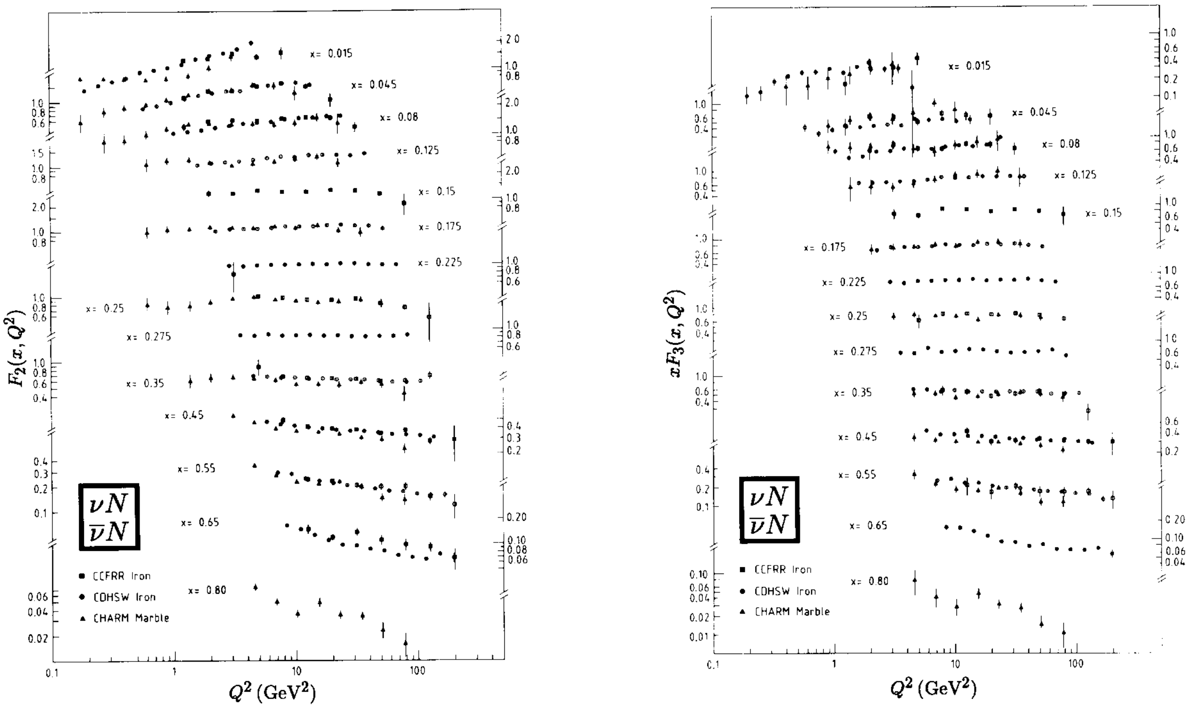
BARYONS (Cont'd)

$\Delta(1232)^{++}$	P_{33}	2224
$\Delta(1232)^+$	P_{33}	2214
$\Delta(1232)^0$	P_{33}	2114
$\Delta(1232)^-$	P_{33}	1114
$\Delta(1620)$	S_{31}	2222, 2122, 1212, 1112
$\Delta(1700)$	D_{33}	12224, 12214, 12114, 11114
$\Delta(1900)$	S_{31}	12222, 12122, 11212, 11112
$\Delta(1905)$	F_{35}	2226, 2126, 1216, 1116
$\Delta(1910)$	P_{31}	22222, 22122, 21212, 21112
$\Delta(1920)$	P_{33}	22224, 22214, 22114, 21114
$\Delta(1930)$	D_{35}	12226, 12126, 11216, 11116
$\Delta(1950)$	F_{37}	2228, 2218, 2118, 1118
Λ		3122
$\Lambda(1405)$	S_{01}	13122
$\Lambda(1520)$	D_{03}	3124
$\Lambda(1600)$	P_{01}	23122
$\Lambda(1670)$	S_{01}	33122
$\Lambda(1690)$	D_{03}	13124
$\Lambda(1800)$	S_{01}	43122
$\Lambda(1810)$	P_{01}	53122
$\Lambda(1820)$	F_{05}	3126
$\Lambda(1830)$	D_{05}	13126
$\Lambda(1890)$	P_{03}	23124
$\Lambda(2100)$	G_{07}	3128
$\Lambda(2110)$	F_{05}	23126
Σ^+		3222
Σ^0		3212
Σ^-		3112
$\Sigma(1385)^+$	P_{13}	3224
$\Sigma(1385)^0$	P_{13}	3214
$\Sigma(1385)^-$	P_{13}	3114
$\Sigma(1660)$	P_{11}	13222, 13212, 13112
$\Sigma(1670)$	D_{13}	13224, 13214, 13114
$\Sigma(1750)$	S_{11}	23222, 23212, 23112
$\Sigma(1775)$	D_{15}	3226, 3216, 3116
$\Sigma(1915)$	F_{15}	13226, 13216, 13116
$\Sigma(1940)$	D_{13}	23224, 23214, 23114
$\Sigma(2030)$	F_{17}	3228, 3218, 3118
Ξ^0		3322
Ξ		3312
$\Xi(1530)^0$	P_{13}	3324
$\Xi(1530)^-$	P_{13}	3314
$\Xi(1820)$	$_{13}$	13324, 13314
Ω^-		3334
Λ_c^+		4122
Σ_c^{++}		4222
Σ_c^+		4212
Σ_c^0		4112
Ξ_c^+		4322
Ξ_c^0		4312
Ω_c^0		4332
Λ_b^0		5122

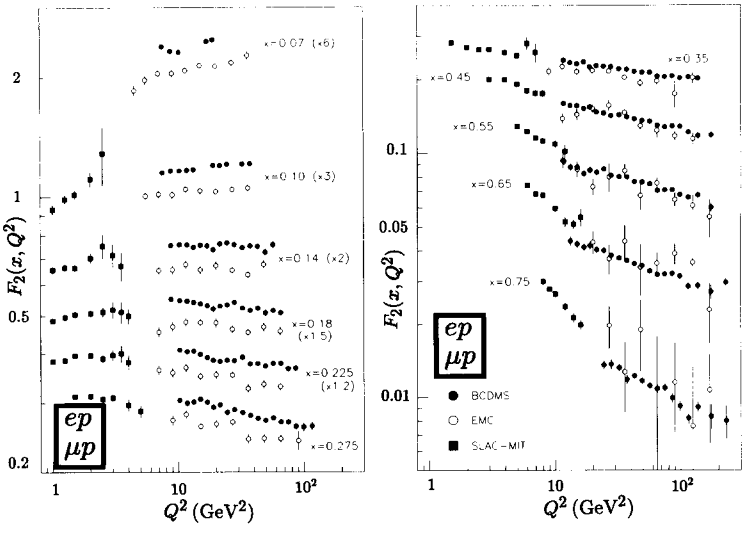
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES

NOTE: THE FIGURES IN THIS SECTION ARE INTENDED TO SHOW THE "BEST" OR "MOST REPRESENTATIVE" DATA IN THE OPINION OF THE COMPILER. THEY ARE NOT NECESSARILY COMPLETE COMPILATIONS OF ALL THE WORLD'S RELIABLE DATA

Structure Functions



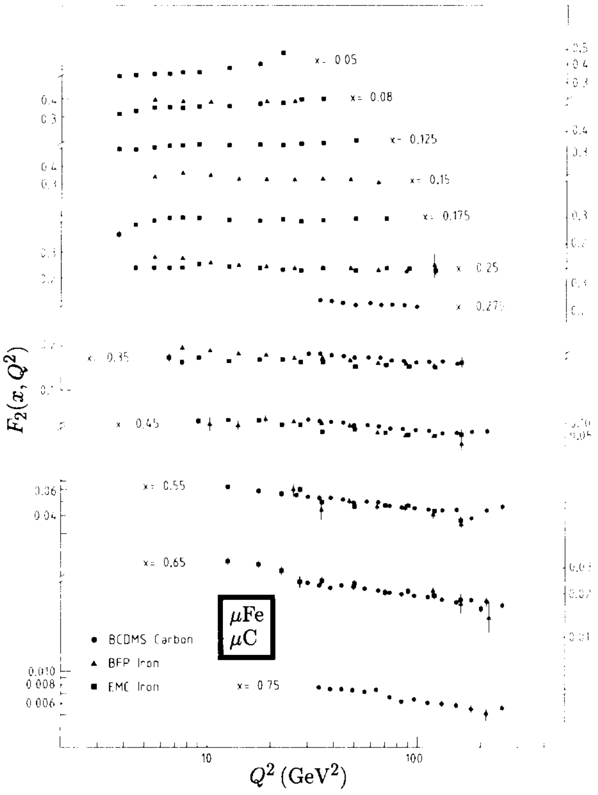
The nucleon structure functions F_2 and xF_3 measured in charged-current neutrino and antineutrino scattering on iron (CCFRR, CDHSW) and marble (CHARM) targets, versus Q^2, for fixed bins of x. Closed symbols are read on the right-hand scale, open symbols (appearing for alternate x values) on the left-hand scale. Only statistical errors are shown. $R = \sigma_L/\sigma_T = 0$ is used in the CHARM data, and a QCD-inspired parametrization for R is assumed in the CCFRR and CDHSW data. The CHARM measurements have not been corrected for the recalibration of the total neutrino and antineutrino cross sections in the CERN neutrino beam which was completed after the publication of these data. References: **CCFRR**—D.B. MacFarlane *et al.*, Z. Phys. **C26**, 1 (1984); **CDHSW**—P. Berge *et al.*, CERN-EP/89-103; **CHARM**—F. Bergsma *et al.*, Phys. Lett. **123B**, 269 (1983) and Phys. Lett. **141B**, 129 (1984).



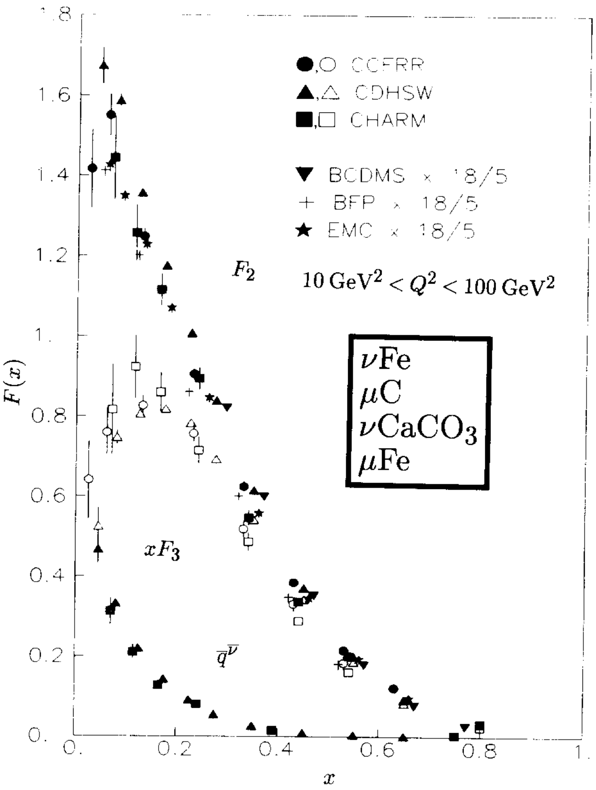
The proton structure function F_2^p measured in electromagnetic scattering of electrons (SLAC-MIT) and muons (BCDMS, EMC) on hydrogen targets, versus Q^2, for fixed bins of x. The data have been multiplied by the factors shown on the left-hand figure for convenience in plotting. Only statistical errors are shown. $R = \sigma_L/\sigma_T = 0.21$ is assumed in the SLAC-MIT data, $R = 0$ in the EMC data, and a QCD prediction for R in the BCDMS data. Where necessary, the SLAC-MIT and EMC data were interpolated to the x bins of the BCDMS data. Note that there are no SLAC-MIT data in the lowest x bin. References: **SLAC-MIT**—A. Bodek *et al.*, Phys. Rev. **D20**, 1471 (1979); **EMC**—J.J. Aubert *et al.*, Nucl. Phys. **B259**, 189 (1985); **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Structure Functions



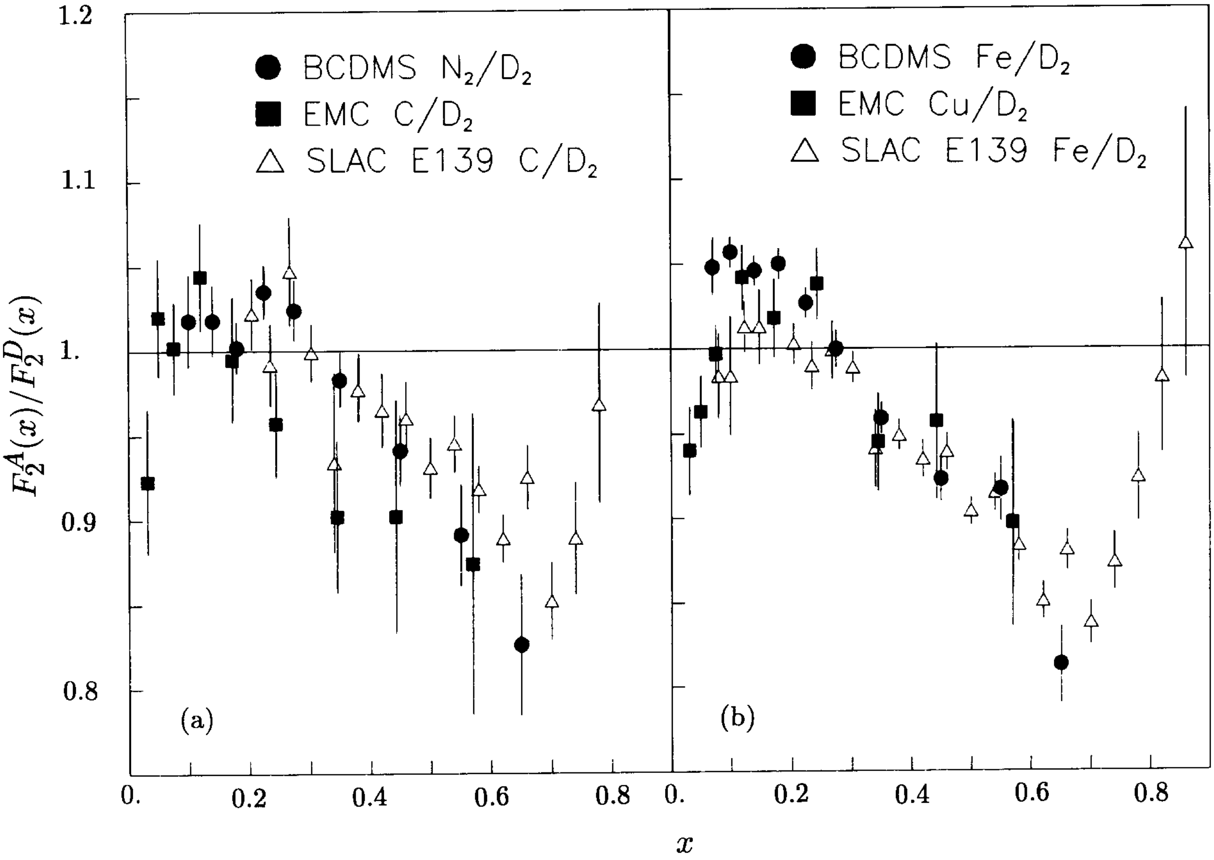
The nucleon structure function F_2 measured in electromagnetic scattering of muons on iron (BFP, EMC) and carbon (BCDMS) targets, versus Q^2, for fixed bins in x. For x of 0.05, 0.125, 0.175, 0.275, 0.45, and 0.65 use the right-hand scale; for all other bins of x, use the left-hand scale. Only statistical errors are shown. $R = \sigma_L/\sigma_T$ = 0 is used in the BFP and a QCD prediction for R is assumed in the BCDMS and EMC data. References: **BCDMS** A.C. Benvenuti *et al.*, Phys. Lett. **B195**, 91 (1987); **BFP**—P.D. Meyers *et al.*, Phys. Rev. **D34**, 1265 (1986); **EMC** J.J. Aubert *et al.*, Nucl. Phys. **B272**, 158 (1986).



The structure functions F_2, xF_3, and $\bar{q}^{\nu}$ measured in different experiments on isoscalar targets as functions of Bjorken x. The CCFRR, CDHSW, BFP, and EMC data were taken with iron targets; the CHARM data with a marble (CaCO$_3$) target; and the BCDMS data with a carbon target. Only statistical errors are shown. The CHARM and BFP collaborations assume $R = \sigma_L/\sigma_T = 0$, whereas a QCD prediction for R is assumed in the analysis of the CCFRR, CDHSW, BCDMS, and EMC data. The electromagnetic structure function $F_2^{\mu N}$ is compared to the charged-current structure function $F_2^{\nu N}$ correcting for the average squared quark charge 5/18. No corrections have been applied for the difference between the strange and charmed quark sea. References: **CCFRR** D.B. MacFarlane *et al.*, Z. Phys. **C26**, 1 (1984); **CDHSW** P. Berge *et al.*, CERN-EP/89-103; **CHARM** F. Bergsma *et al.*, Phys. Lett. **123B**, 269 (1983) and Phys. Lett. **141B**, 129 (1984); **BCDMS** A.C. Benvenuti *et al.*, Phys. Lett. **B195**, 91 (1987); **BFP** P.D. Meyers *et al.*, Phys. Rev. **D34**, 1265 (1986); **EMC** J.J. Aubert *et al.*, Nucl. Phys. **B272**, 158 (1986).

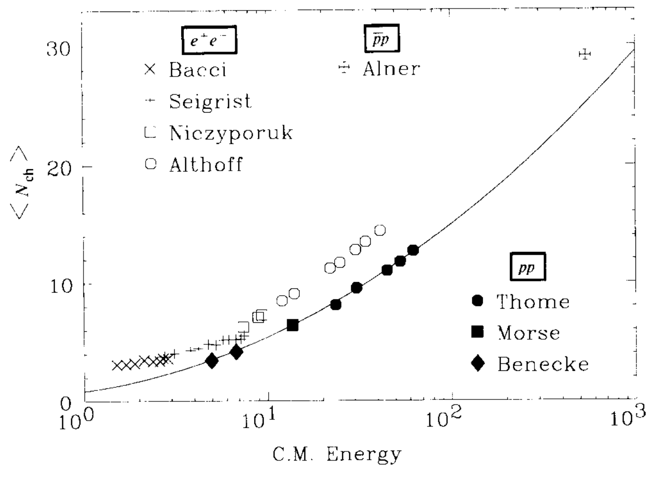
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

"EMC" Effect



The ratio of nucleon structure functions $F_2^A(x)/F_2^D(x)$ for nuclear targets A compared to deuterium D, measured in deep inelastic electron (SLAC-E139) and muon (BCDMS, EMC) scattering: (a) medium-weight targets (A = N, C), (b) heavy targets (A = Fe, Cu). Only statistical errors are shown. The SLAC-E139 data were evaluated as cross section ratios σ^A/σ^D but are equal to structure function ratios if $R = \sigma_L/\sigma_T$ is independent of A. References: **BCDMS**—G. Bari *et al.*, Phys. Lett. **163B**, 282 (1985); and A.C. Benvenuti *et al.*, Phys. Lett. **B189**, 483 (1987); **EMC**—J. Ashman *et al.*, Phys. Lett. **B202**, 603 (1988); **SLAC-E139**—R.G. Arnold *et al.*, Phys. Rev. Lett. **52**, 727 (1984); and SLAC-PUB-3257 (1983).

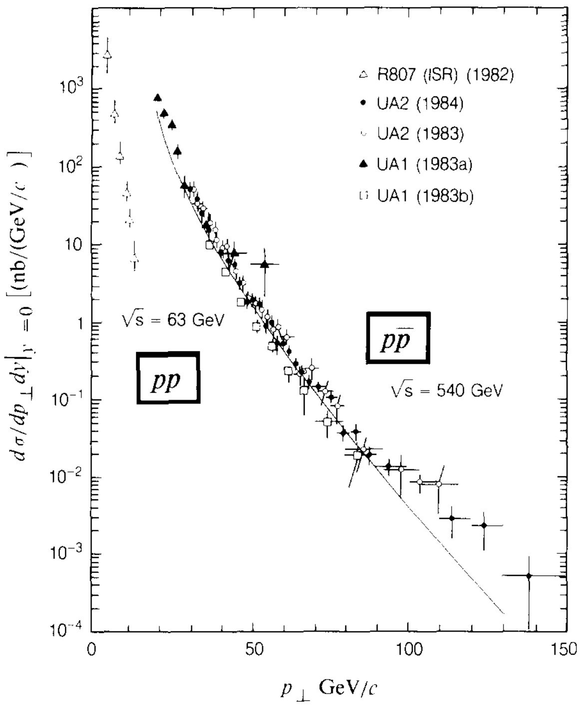
Average e^+e^-, pp, and $\bar{p}p$ Multiplicity



Average multiplicity as a function of $\sqrt{s}$ for $p\bar{p}$ at the S$p\bar{p}$S for pp at the ISR, (open circles) and for e^+e^-. Solid curve is a fit by Thomé *et al.* to their data (solid circles) with the form $\langle N_{ch} \rangle = 0.88 + 0.44 \ln s + 0.118 (\ln s)^2$. e^+e^- data points have been combined to reduce overlap; errors (not shown) are dominated by 10%–25% systematic effects. References: $p\bar{p}$—G.J. Alner *et al.*, Phys. Lett. **138B**, 304 (1984); pp—W. Thomé *et al.*, Nucl. Phys. **B129**, 365 (1977); W.M. Morse *et al.*, Phys. Rev. **D15**, 66 (1977); and J. Benecke *et al.*, Nucl. Phys. **B76**, 29 (1974); e^+e^- ADONE: C. Bacci *et al.*, Phys. Lett. **86B**, 234 (1979): MARK II: J.L. Siegrist *et al.*, Phys. Rev. **D26**, 969 (1982); LENA: B. Niczyporuk *et al.*, Z. Phys. **C9**, 1 (1981); and TASSO: M. Althoff *et al.*, Z. Phys. **C229**, 307 (1984).

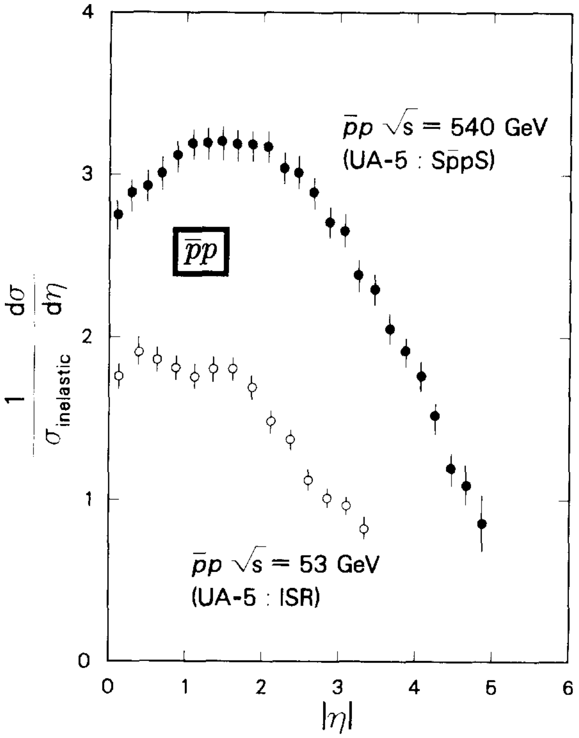
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Jet Production in pp and $\bar{p}p$ Interactions



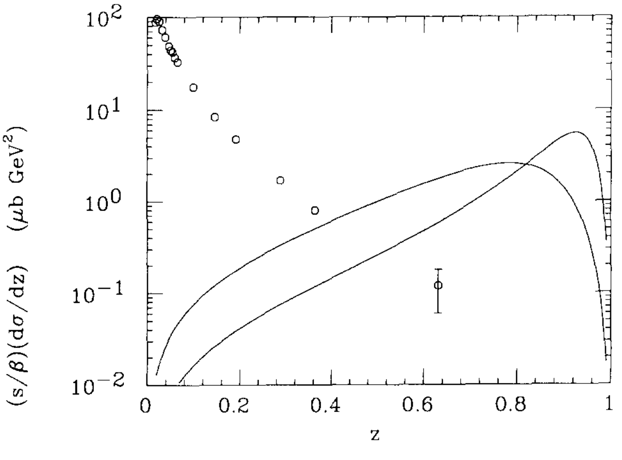
Differential cross sections for observation of a single jet of rapidity $y = 0$ as a function of the jet transverse momentum. ISR (pp) and S$\bar{p}p$S collider ($\bar{p}p$) data compared. Error bars include a contribution due to estimated systematic error in defining jet direction and p_T. Solid curve: QCD prediction; refer to the "Cross-Section Formulae for Specific Processes" section and the "Quantum Chromodynamics" section in the full-sized edition. References: **ISR**—T. Akesson *et al.*, Phys. Lett. **118B**, 185 (1982); **UA2**—P. Bagnaia *et al.*, Phys. Lett. **138B**, 430 (1984); and P. Bagnaia *et al.*, Z. Phys. **C20**, 117 (1983); **UA1**—G. Arnison *et al.*, Phys. Lett. **123B**, 115 (1983a); and G. Arnison *et al.*, Phys. Lett. **132B**, 144 (1983b).

Pseudorapidity in $\bar{p}p$ Interactions



Comparison of the distribution of the pseudorapidity $\eta = -\ln(\tan\theta_{\text{cm}}/2)$ for charged-particle production in proton-antiproton collisions at $\sqrt{s} = 53$ GeV (1) and 540 GeV (2). References: (1) K. Alpgard et al., Phys. Lett. **112B**, 209 (1982); (2) UA5 Collaboration, presented by J. Rushbrooke in the *Proceedings of the XIV International Symposium on Multiparticle Dynamics*, eds. J.F. Gunion and P.M. Yager (World Scientific Publishing Co., Singapore, 1984).

Fragmentation Function



The cross section $(s/\beta)\, d\sigma/dz$ versus z for producing a hadron h in e^+e^- annihilation, measured in different experiments, for fixed energies $Q^2 = s$. This quantity is closely related to the fragmentation function $D_i^h(z, Q^2)$ as discussed in the "Cross-Section Formulae for Specific Processes" section. Note that we use $z = (E + p_\parallel)_{\text{hadron}}/(E + p_\parallel)_{\text{quark}}$, whereas some experiments use $z' = E_{\text{hadron}}/E_{\text{beam}}$ or $z'' = p_{\text{hadron}}/(E^2_{\text{beam}} - m^2_{\text{had}})^{1/2}$. The data are shown for pions (singlet term) measured by the TPC at 29 GeV; they actually used z'' — for $z > 0.05$ the difference between z and z'' can be neglected at those energies. The data for heavy quarks are frequently parametrized by the Peterson *et al.* form, $D(z) = Nz(1-z)^2/[(1-z)^2 + \epsilon_i z]^2$. The parameter ϵ for quark type i depends on $\sqrt{s}$ and upon the heavy quark mass. At $\sqrt{s} \sim 30$ GeV, $\epsilon_b = 0.006 \pm 0.002$, $\epsilon_c = 0.06^{+0.03}_{-0.015}$. Curves corresponding to these values (N is chosen arbitrarily) are shown on the figure. References: C. Peterson *et al.*, Phys. Rev. **D27**, 105 (1983); **TPC**—H. Aihara *et al.*, Z. Phys. **C27**, 495 (1985); and J. Chrin, Z. Phys. **C36**, 163 (1987).

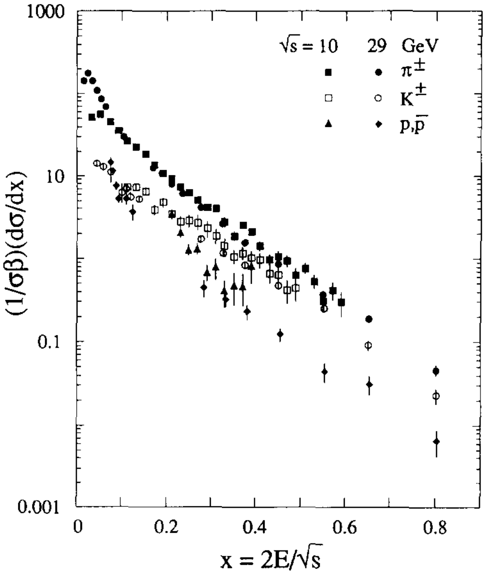
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Quark Fragmentation in Electron-Positron Annihilation

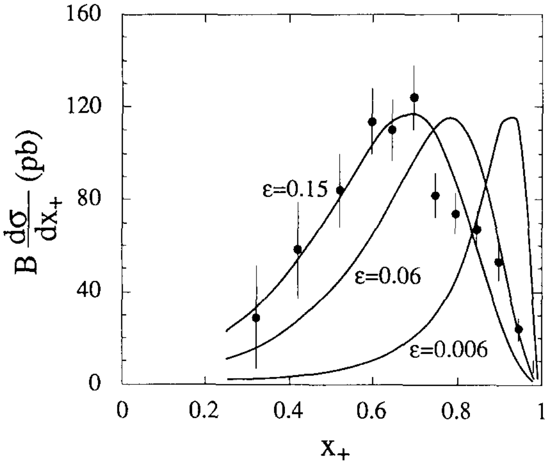
Average Hadron Multiplicities in e^+e^- Annihilation Events

	Particle	$\sqrt{s} \approx 10$ GeV		$\sqrt{s} = 29$ GeV	
Pseudoscalar mesons	π^+	6.6	± 0.2	10.3	± 0.4
	π^0	3.2	± 0.3	5.6	± 0.3
	K^+	0.90	± 0.04	1.48	± 0.09
	K^0	0.91	± 0.05	1.42	± 0.07
	η	0.19	± 0.06	0.60	± 0.08
	$\eta'(958)$	—		0.26	± 0.10
	D^+	0.16	± 0.03	0.17	± 0.03
	D^0	0.37	± 0.06	0.45	± 0.07
Vector mesons	$\rho(770)^0$	0.50	± 0.09	0.81	± 0.08
	$K^*(892)^+$	0.45	± 0.08	0.64	± 0.05
	$K^*(892)^0$	0.38	± 0.09	0.56	± 0.06
	$\phi(1020)$	0.045	± 0.007	0.085	± 0.011
	$D^*(2010)^+$	0.22	± 0.04	0.43	± 0.07
	$D^*(2010)^0$	0.23	± 0.06	0.27	± 0.11
Tensor mesons	$f_2(1270)$	—		0.14	± 0.04
	$K_2^*(1430)^+$	—		0.09	± 0.03
	$K_2^*(1430)^0$	—		0.12	± 0.06
Baryons	p	0.28	± 0.03	0.58	± 0.05
	Λ	0.080	± 0.013	0.214	± 0.012
	Σ^0	0.023	± 0.008	—	
	$\Delta(1232)^{++}$	0.040	± 0.010	—	
	Ξ^-	0.0059	± 0.0008	0.0178	± 0.0036
	$\Sigma(1385)^\pm$	0.0107	± 0.0020	0.035	± 0.009
	Ω^-	0.0007	± 0.0004	0.015	± 0.007

Average hadron multiplicity per e^+e^- annihilation event at $\sqrt{s} \approx 10$ GeV. and $\sqrt{s} = 29$ GeV. The rates given include decay products from resonances with $c\tau$, 10 cm, and include charge conjugated states. References: W. Hofmann, Ann. Rev. Nucl. and Part. Sci. **38**, 279 (1988); and H.D. Saxon, in *High Energy Electron Positron Physics*, World Sci., p. 540 (1988); R. Marshall, RAL-89-021 (1989).



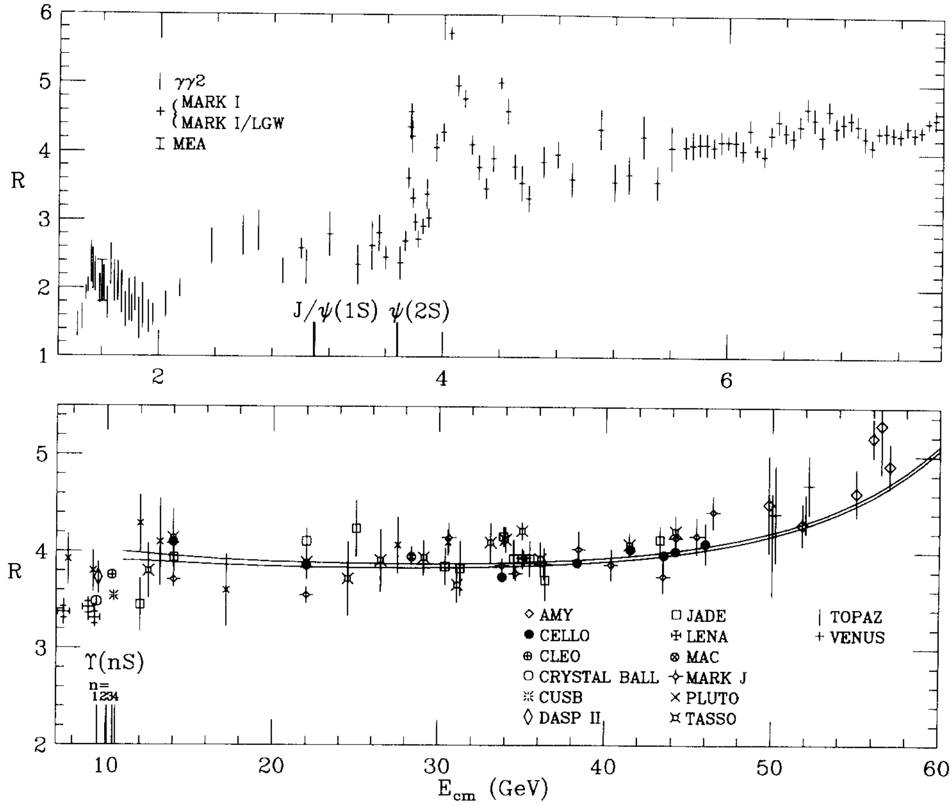
Fragmentation into light hadrons: Inclusive cross sections $(1/\sigma\beta)(d\sigma/dx)$ for production of charged hadrons (π, K, p) in e^+e^- annihilation at $\sqrt{s} \approx 10$ GeV and $\sqrt{s} = 29$ GeV, normalized to the total hadronic cross section, as a function of $x = 2E\sqrt{s}$. References: H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988); and H. Albrecht *et al.*, DESY-89-014 (1989).



Heavy quark fragmentation: Inclusive cross section for the production of $D^*(2010)^+$ mesons in e^+e^- annihilation at $\sqrt{s} \approx 10$ GeV, as a function of the scaling variable $x_+ = (E+p)/(E+p)_{\text{kinem. limit}}$. Also shown is the Peterson *et al.* form, $d\sigma/dz \sim z(1-z)^2/[(1-z)^2 + \epsilon z]^2$, for $\epsilon = 0.15$. We note that instead of the scaling variable x or x_+, some experiments prefer to define a scaling variable z as $z = (E + p_\parallel)_{\text{had.}}/(E+p)_{\text{quark}}$, correcting for gluon radiation before the final fragmentation. With this definition at $\sqrt{s} \approx 30$ GeV, $\langle z_C \rangle = 0.67 \pm 0.03$ $\langle z_B \rangle = 0.83 \pm 0.03$, corresponding to $\epsilon_C = 0.06^{+0.03}_{-0.02}$ and $\epsilon_B = 0.006 \pm 0.002$. The corresponding Peterson shapes are included here. References: D. Bortoletto *et al.*, Phys. Rev. **D37**, 1719 (1988); J. Chrin, Z. Phys. **C36**, 163 (1987); and C. Peterson *et al.*, Phys. Rev. **D27**, 105 (1983).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

R in e^+e^- Collisions

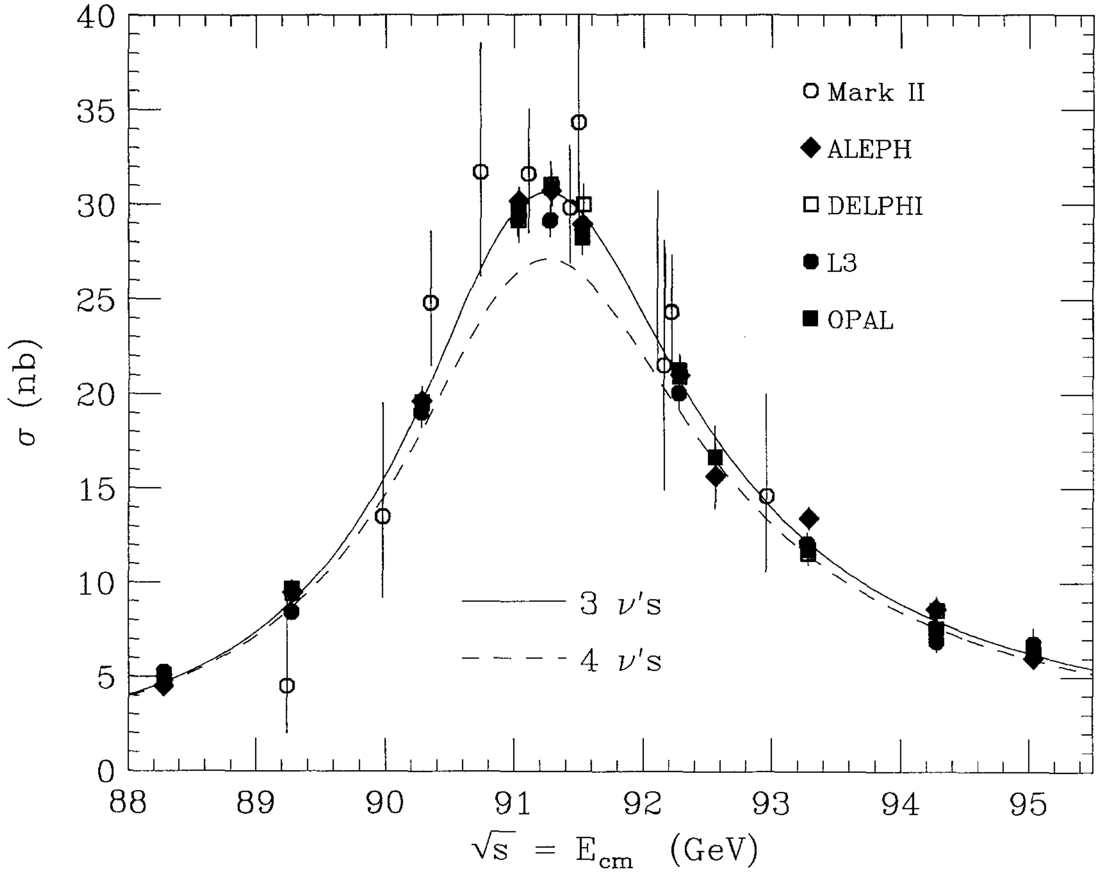


Selected measurements of $R \equiv \sigma(e^+e^- \rightarrow \text{ hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, where the annihilation in the numerator proceeds via one photon or via the Z^0. Measurements in the vicinity of the Z^0 mass are shown in the following figure. The denominator is the calculated QED single-photon process; see the section on Cross-Section Formulae for Specific Processes. Radiative corrections and, where important, corrections for two-photon processes and τ production have been made. Note that the ADONE data ($\gamma\gamma2$ and MEA) is for ≥ 3 hadrons. The points in the $\psi(3770)$ region are from the MARK I—Lead Glass Wall experiment. To preserve clarity only a representative subset of the available measurements is shown—references to additional data are included below. Also for clarity, some points have been combined or shifted slightly ($< 4\%$) in $E_{\rm cm}$, and some points with low statistical significance have been omitted. Systematic normalization errors are not included; they range from ~5–20%, depending on experiment. We caution that especially the older experiments tend to have large normalization uncertainties. Note the suppressed zero. The horizontal extent of the plot symbols has no significance. The positions of the $J/\psi(1S)$, $\psi(2S)$, and the four lowest Υ vector-meson resonances are indicated. Two curves are overlaid for $E_{\rm cm} > 11$ GeV, showing the theoretical prediction for R, including higher order QCD [M. Dine and J. Sapirstein, Phys. Rev. Lett. **43**, 668 (1979)] and electroweak corrections. The Λ values are for 5 flavors in the $\overline{\rm MS}$ scheme and are $\Lambda^{(5)}_{\overline{\rm MS}} = 60$ MeV (lower curve) and $\Lambda^{(5)}_{\overline{\rm MS}} = 250$ MeV (upper curve). References (including several references to data not appearing in the figure and some references to preliminary data):

AMY: T. Mori *et al.*, Phys. Lett. **B218**, 499 (1989);
CELLO: H.-J. Behrend *et al.*, Phys. Lett. **144B**, 297 (1984); and H.-J. Behrend *et al.*, Phys. Lett. **183B**, 400 (1987);
CLEO: R. Giles *et al.*, Phys. Rev. **D29**, 1285 (1984); and D. Besson *et al.*, Phys. Rev. Lett. **54**, 381 (1985);
CUSB: E. Rice *et al.*, Phys. Rev. Lett. **48**, 906 (1982);
CRYSTAL BALL: A. Osterheld *et al.*, SLAC-PUB-4160; and Z. Jakubowski *et al.*, Z. Phys. **C40**, 49 (1988);
DASP: R. Brandelik *et al.*, Phys. Lett. **76B**, 361 (1978);
DASP II: Phys. Lett. **116B**, 383 (1982);
DCI: G. Cosme *et al.*, Nucl. Phys. **B152**, 215 (1979);
DHHM: P. Bock *et al.* (DESY-Hamburg-Heidelberg-MPI München Collab.), Z. Phys. **C6**, 125 (1980);
γγ2: C. Bacci *et al.*, Phys. Lett. **86B**, 234 (1979);
HRS: D. Bender *et al.*, Phys. Rev. **D31**, 1 (1985);
JADE: W. Bartel *et al.*, Phys. Lett. **129B**, 145 (1983); and W. Bartel *et al.*, Phys. Lett. **160B**, 337 (1985);
LENA: B. Niczyporuk *et al.*, Z. Phys. **C15**, 299 (1982).
MAC: E. Fernandez *et al.*, Phys. Rev. **D31**, 1537 (1985);
MARK J: B. Adeva *et al.*, Phys. Rev. Lett. **50**, 799 (1983); and B. Adeva *et al.*, Phys. Rev. **D34**, 681 (1986);
MARK I: J.L. Siegrist *et al.*, Phys. Rev. **D26**, 969 (1982);
MARK I + Lead Glass Wall: P.A. Rapidis *et al.*, Phys. Rev. Lett. **39**, 526 (1977); and P.A. Rapidis, thesis, SLAC-Report-220 (1979);
MARK II: J. Patrick, Ph.D. thesis, LBL-14585 (1982);
MEA: B. Esposito *et al.*, Lett. Nuovo Cimento **19**, 21 (1977);
PLUTO: A. Bäcker, thesis Gesamthochschule Siegen, DESY F33-77/03 (1977); C. Gerke, thesis, Hamburg Univ. (1979); Ch. Berger *et al.*, Phys. Lett. **81B**, 410 (1979); and W. Lackas, thesis, RWTH Aachen, DESY Pluto-81/11 (1981);
TASSO: R. Brandelik *et al.*, Phys. Lett. **113B**, 499 (1982); and M. Althoff *et al.*, Phys. Lett. **138B**, 441 (1984);
TOPAZ: I. Adachi *et al.*, Phys. Rev. Lett. **60**, 97 (1988);
and **VENUS**: H. Yoshida *et al.*, Phys. Lett. **198B**, 570 (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

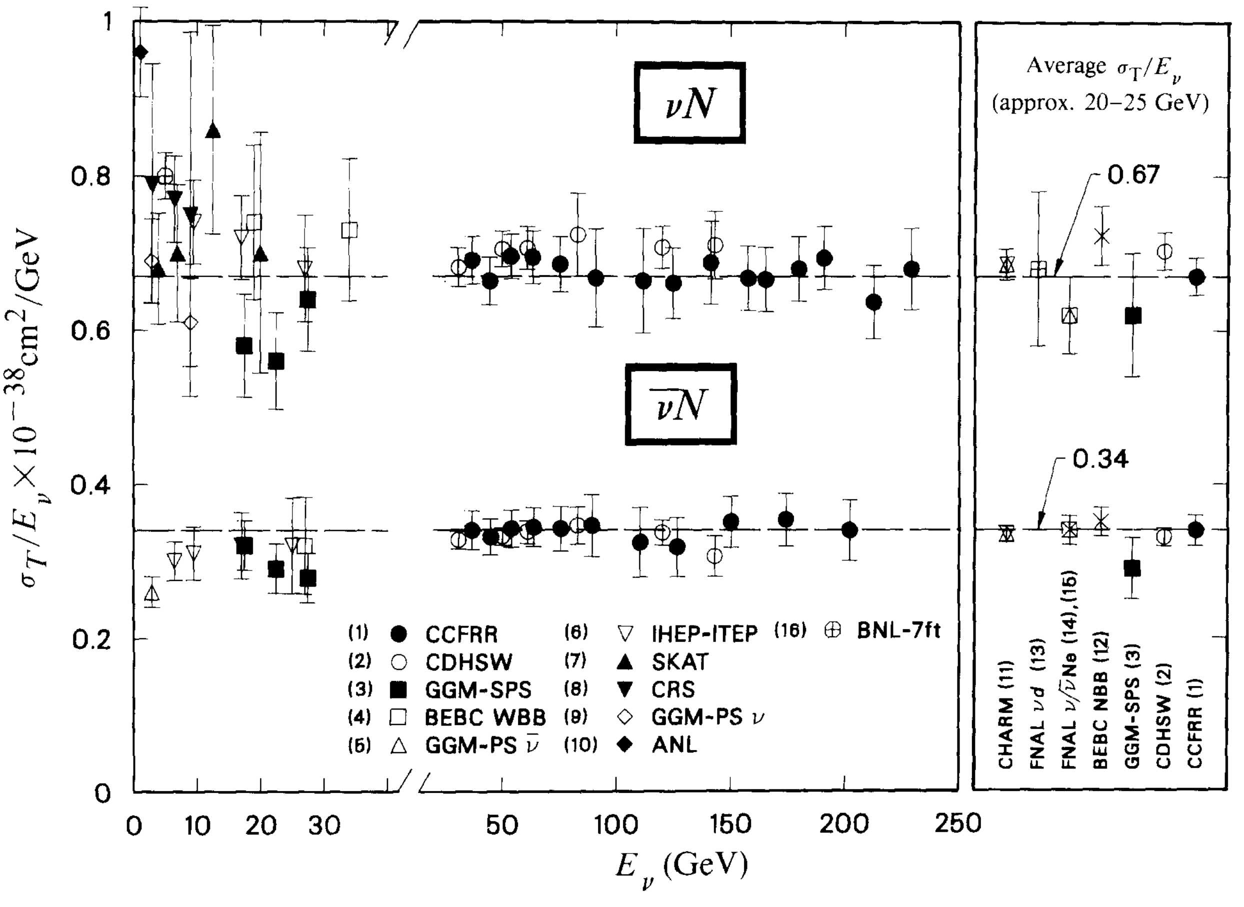
e^+e^- Annihilation Cross Section in Vicinity of M_Z



Data from the Mark II, ALEPH, DELPHI, L3, and OPAL Collaborations (Refs. 1 5) for the cross section in e^+e^- annihilation into hadronic final states as a function of c.m. energy near the Z. LEP detectors obtained data at the same energies; some of the points are obscured by overlap. The curves show the predictions of the Standard Model with three species (solid curve) and four species (dashed curve) of light neutrinos. The mass of the Z was fixed by the data to be 91.157 GeV, and there were no other free parameters. The resulting widths are respectively 2.488 GeV and 2.653 GeV, which include QCD corrections for the hadronic channels and assume no t-quark contribution. The asymmetry of the curves is produced by initial-state radiation.

1. Mark II G.S. Abrams *et al.*, Phys. Rev. Lett. **63**, 2173 (1989).
2. ALEPH—D. Decamp *et al.*, to be published in Phys. Lett. **B** (1990).
3. DELPHI—P. Abreu *et al.*, CERN-EP/90-32, to be published in Phys. Lett. **B** (1990).
4. L3—B. Adeva *et al.*, submitted to Phys. Lett. **B** (1990).
5. OPAL M.Z. Akrawy *et al.*, to be published in Phys. Lett. **B** (1990).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)



σ_T/E_ν for the muon neutrino and antineutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are averages for the CCFRR measurement. Note the change in the energy scale between 30 and 50 GeV. The data points on the right give averages for other high energy measurements. Courtesy M.H. Shaevitz, Columbia University (Nevis Laboratory).

(1) D.B. MacFarlane *et al.*, Z. Phys. **C26**, 1 (1984);
(2) P. Berge *et al.*, Z. Phys. **C35**, 443 (1987);
(3) J. Morfin *et al.*, Phys. Lett. **104B**, 235 (1981);
(4) D.C. Colley *et al.*, Z. Phys. **C2**, 187 (1979);
(5) O. Erriquez *et al.*, Phys. Lett. **80B**, 309 (1979);
(6) A.S. Vovenko *et al.*, Yad. Phys. **30**, 527 (1979);
(7) D.S. Baranov *et al.*, Phys. Lett. **81B**, 255 (1979);
(8) C. Baltay *et al.*, Phys. Rev. Lett. **44**, 916 (1980);
(9) S. Ciampolillo *et al.*, Phys. Lett. **84B**, 281 (1979);
(10) S.J. Barish *et al.*, Phys. Rev. **D19**, 2521 (1979);
(11) J.V. Allaby *et al.*, Z. Phys. **C38**, 403 (1988), E_ν = 10–160 GeV;
(12) P. Bosetti *et al.*, Phys. Lett. **110B**, 167 (1982), E_ν = 20–200 GeV, as revised in M. Aderholz *et al.*, Phys. Lett. **173B**, 211 (1986);
(13) T. Kitagaki *et al.*, Phys. Rev. Lett. **49**, 98 (1982), E_ν = 10–200 GeV;
(14) N.J. Baker *et al.*, Phys. Rev. Lett. **51**, 735 (1983), E_ν = 10–240 GeV;
(15) G.N. Taylor *et al.*, Phys. Rev. Lett. **51**, 739 (1983), E_ν = 5–250 GeV;
(16) N.J. Baker *et al.*, Phys. Rev. **D25**, 617 (1982), E_ν = 1.6–10 GeV.

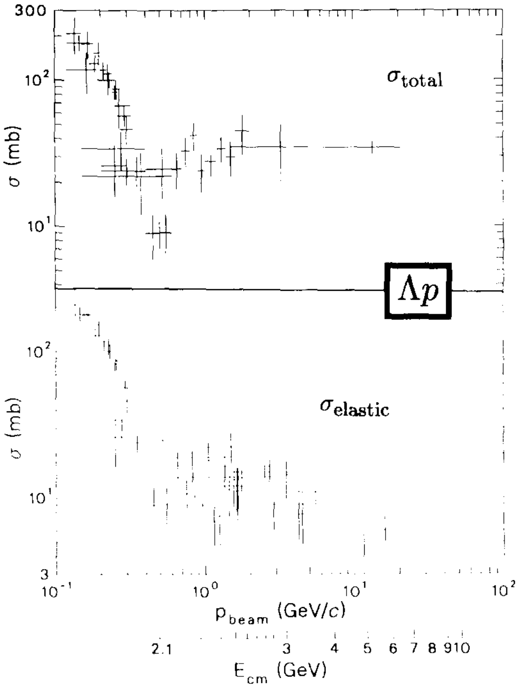
PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

High-energy Parametrizations of Hadron Cross Sections

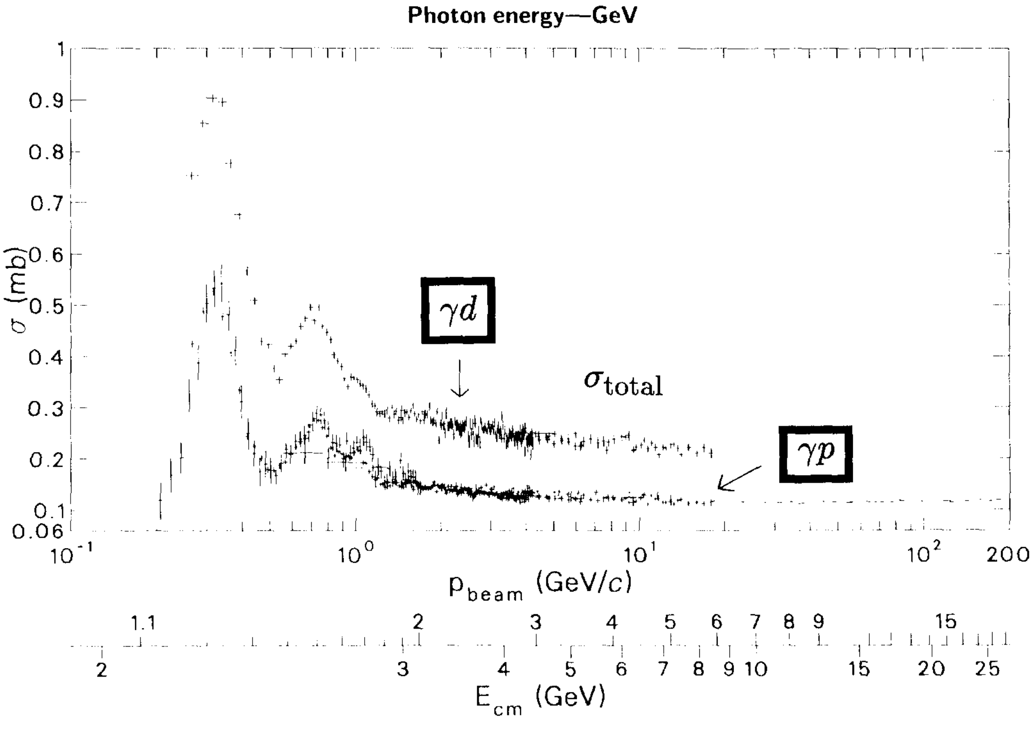
The CERN-HERA Group has done a least-squares fit to the cross section in the high-energy region for each of the hadron reactions plotted below. The parametrization they used was $\sigma = A + Bp^n + C\ln^2(p) + D\ln(p)$, where σ is in mb and p is in GeV/c. The best-fit coefficients A, B, C, and D and the fitted exponent n are tabulated here. The errors in these parameters are highly correlated; this should be taken into account before making any changes. The applicable momentum range is given in the right-hand column; use of these parameterizations outside of this range may give incorrect results.

Reaction	A	B	n	C	D	Momentum range (GeV/c) $p_{\min}$–$p_{\max}$
γp (total)	0.154 ± 0.021	−0.018 ± 0.023	−1.4 ± 3.7	0.0026 ± 0.0009	−0.020 ± 0.009	3.0–183
γd (total)	0.206 ± 0.007	0.111 ± 0.006	−0.78 ± 0.16	—	—	2.0–17.8
$\pi^+ p$ (total)	−5.0 ± 8.1	40.4 ± 7.7	−0.28 ± 0.05	—	3.7 ± 0.8	4.0–340
$\pi^+ p$ (elastic)	7.4 ± 1.4	11.2 ± 1.6	−1.67 ± 0.48	0.180 ± 0.079	−1.71 ± 0.67	2.0–200
$\pi^+ d$ (total)	28.4 ± 8.7	51.9 ± 3.4	−0.56 ± 0.17	—	2.9 ± 1.2	6.0–340
$\pi^- p$ (total)	33.0 ± 1.2	14.0 ± 1.8	−1.36 ± 0.29	0.456 ± 0.049	−4.03 ± 0.48	2.5–370
$\pi^- p$ (elastic)	1.76 ± 0.42	11.2 ± 0.3	−0.64 ± 0.07	0.043 ± 0.011	—	2.0–360
$\pi^- d$ (total)	41.6 ± 0.9	44.0 ± 2.5	−0.79 ± 0.07	0.150 ± 0.026	—	2.5–370
$K^+ p$ (total)	17.1 ± 0.9	5.5 ± 5.2	−2.7 ± 2.0	0.139 ± 0.076	−0.27 ± 0.53	2.0–310
$K^+ p$ (elastic)	5.73 ± 0.29	17.2 ± 1.1	−3.02 ± 0.21	0.191 ± 0.026	−1.62 ± 0.18	1.5–175
$K^+ n$ (total)	18.56 ± 0.31	(0.16±4.9) × 10^{-7}	3.0 ± 5.1	0.178 ± 0.050	−0.71 ± 0.26	2.0–310
$K^+ d$ (total)	34.2 ± 1.2	7.9 ± 3.8	−2.1 ± 1.1	0.346 ± 0.074	−0.99 ± 0.61	2.0–310
$K^- p$ (total)	−1.0 ± 5.4	36.4 ± 4.8	−0.34 ± 0.05	—	3.02 ± 0.57	3.0–310
$K^- p$ (elastic)	7.24 ± 0.16	46 ± 32	−4.7 ± 1.0	0.279 ± 0.017	−2.35 ± 0.11	2.0–175
$K^- n$ (total)	8 ± 11	22.6 ± 6.9	−0.45 ± 0.31	—	2.0 ± 1.3	10–310
$K^- d$ (total)	45.5 ± 9.2	26.7 ± 3.5	−1.12 ± 0.65	0.54 ± 0.32	−4.0 ± 3.4	3.0–310
pp (total)	45.64 ± 0.17	239 ± 126	−4.33 ± 0.50	0.414 ± 0.009	−3.44 ± 0.08	3.0–2100
pp (elastic)	11.9 ± 0.8	26.9 ± 1.7	−1.21 ± 0.11	0.169 ± 0.021	−1.85 ± 0.26	2.0–2100
pn (total)	47.70 ± 0.13	−100 ± 14	−4.56 ± 0.20	0.512 ± 0.012	−4.29 ± 0.09	2.0–280
pd (total)	92.2 ± 1.2	−0.08 ± 0.65	0.7 ± 1.0	1.36 ± 0.41	−9.82 ± 0.49	3.0–370
pd (elastic)	−237 ± 53000	253 ± 53000	0.1 ± 4.5	−0.5 ± 52	−20 ± 2600	2.0–384
$\bar{p}p$ (total)	39.8 ± 4.3	77.1 ± 3.0	−6.60 ± 0.68	0.278 ± 0.048	−1.5 ± 0.9	5.0–1.73 × 10^6
$\bar{p}p$ (elastic)	10.55 ± 0.72	52.7 ± 1.8	−1.176 ± 0.05	0.135 ± 0.016	−1.39 ± 0.22	2.0–1.73 × 10^6
$\bar{p}n$ (total)	41.8 ± 2.4	96.1 ± 4.6	−0.98 ± 0.07	—	−0.14 ± 0.46	1.1–280
$\bar{p}n$ (elastic)	38 ± 21	−3 ± 17	−3 ± 38	—	−13 ± 12	1.1–5.55
$\bar{p}d$ (total)	112 ± 13	125 ± 8	−1.08 ± 0.15	1.14 ± 0.49	−12.4 ± 4.9	2.0–280
Λp (total)	18.0 ± 1.9	0.121 ± 0.017	−3.92 ± 0.83	—	6.38 ± 0.74	0.1–21.0
Λp (elastic)	3.5 ± 5.6	26 ± 25	−1.0 ± 1.3	—	—	2.0–24.0

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)



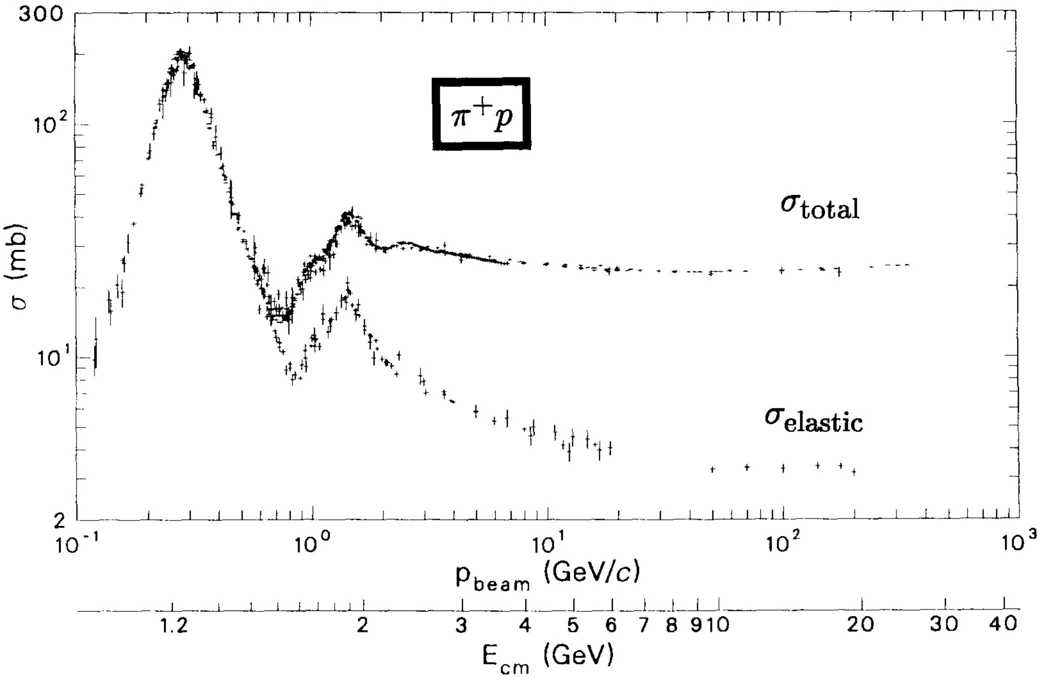
Λp total and elastic cross sections vs. laboratory beam momentum $p_{\rm beam}$ and total center-of-mass energy $E_{\rm cm}$. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

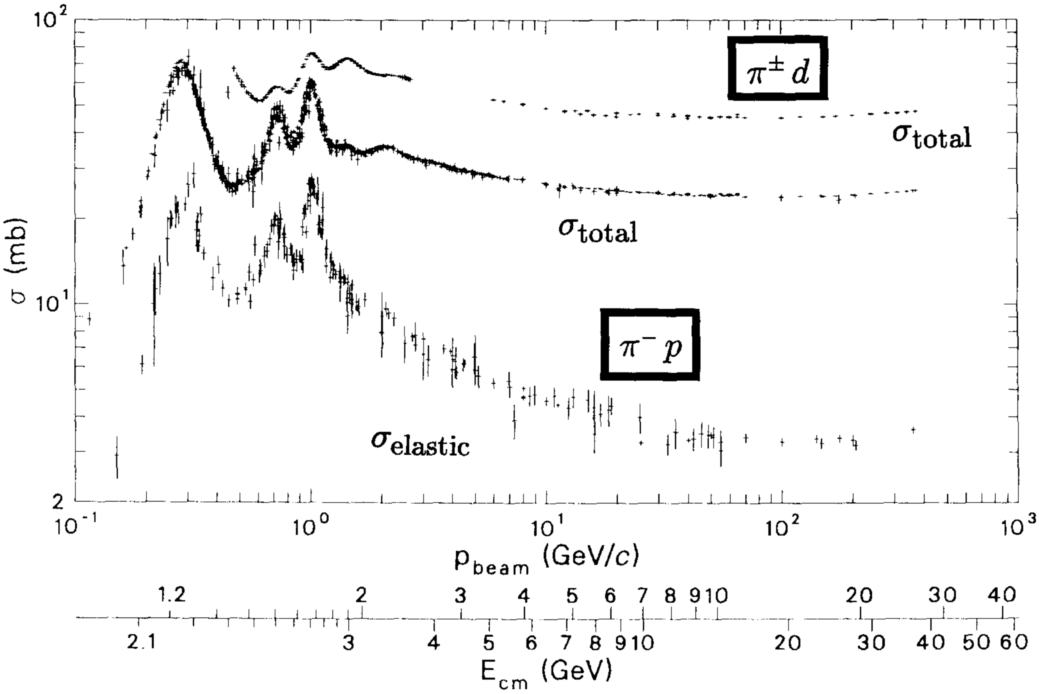


Photon cross sections vs. laboratory beam momentum $p_{\rm beam}$ and total center-of-mass energy $E_{\rm cm}$. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; COMPAS Group, IHEP, Serpukhov, USSR; and G.M. Lewis, Glasgow. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Hadronic Cross Sections

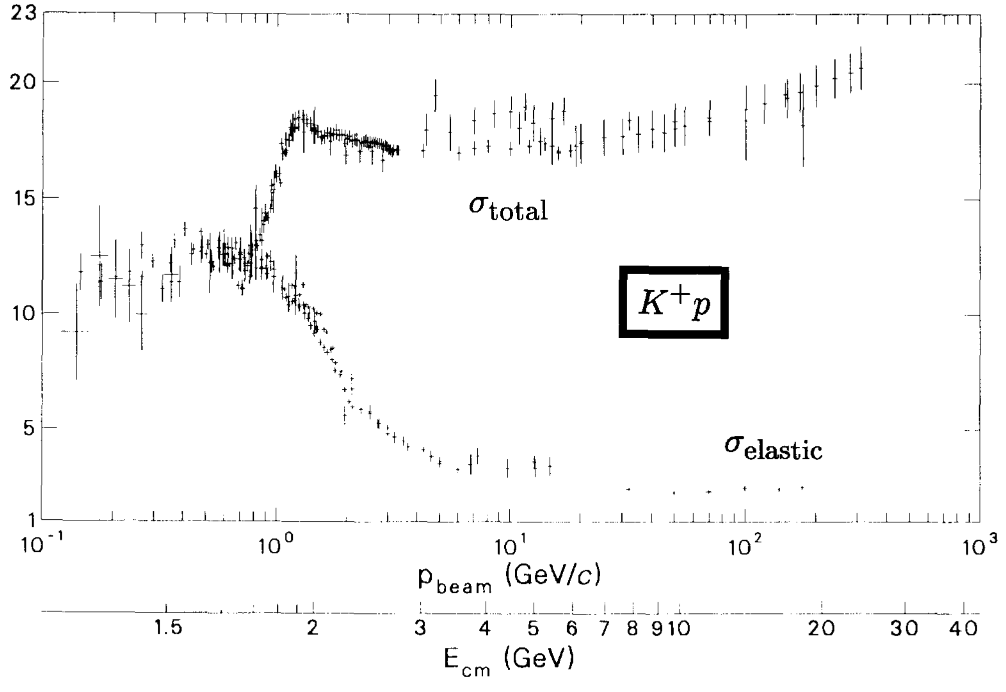


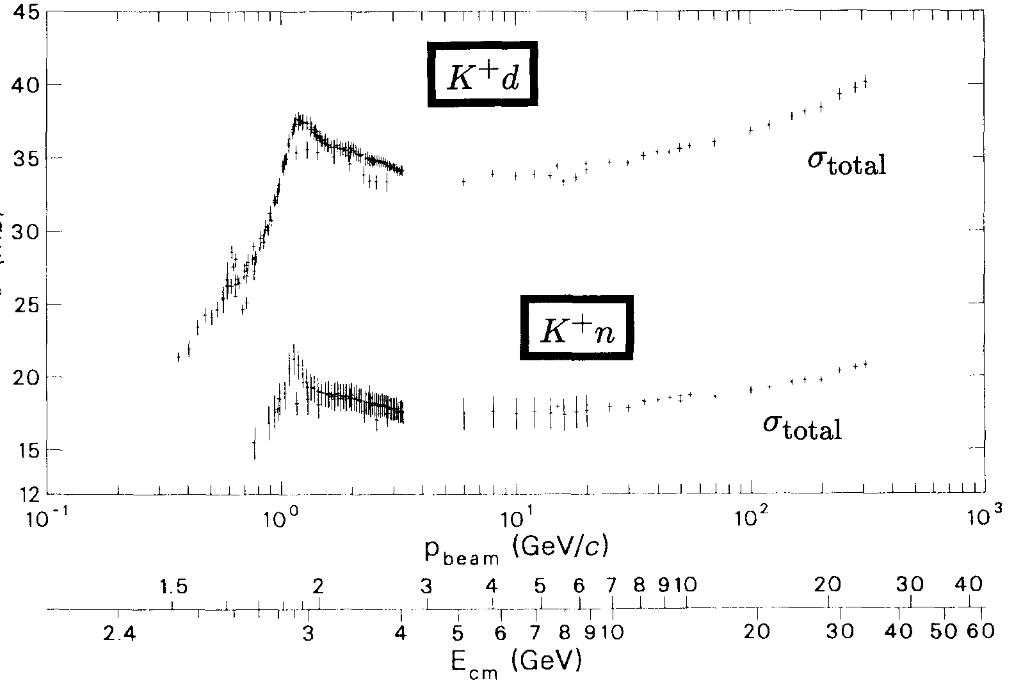


Hadronic total and elastic cross sections vs. laboratory beam momentum $p_{\rm beam}$ and total center-of-mass energy $E_{\rm cm}$. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Hadronic Cross Sections

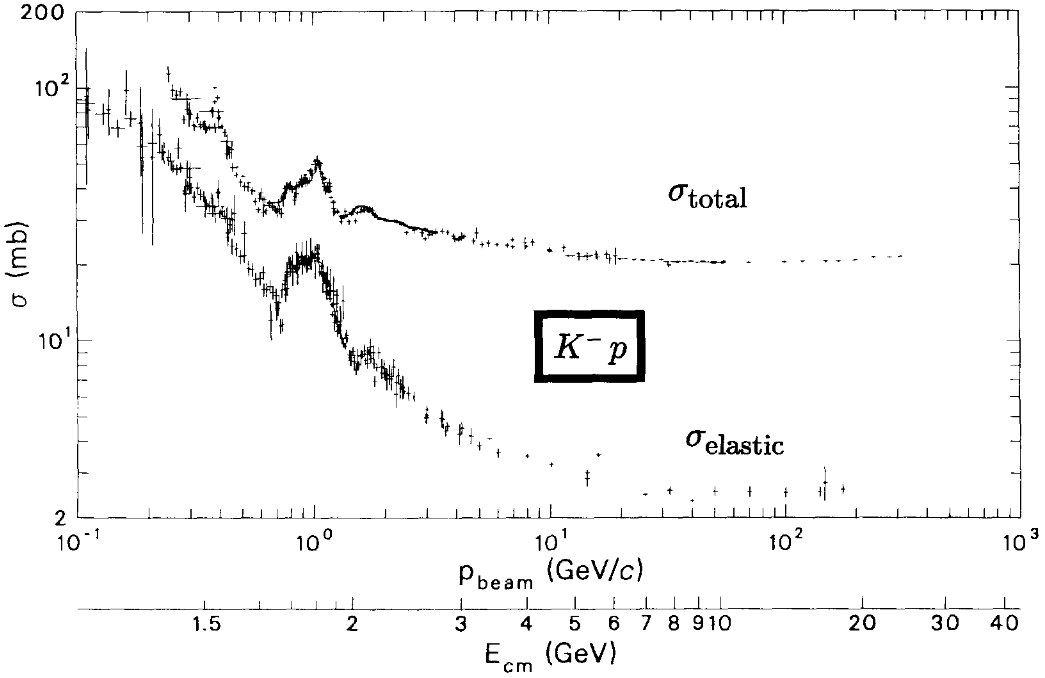


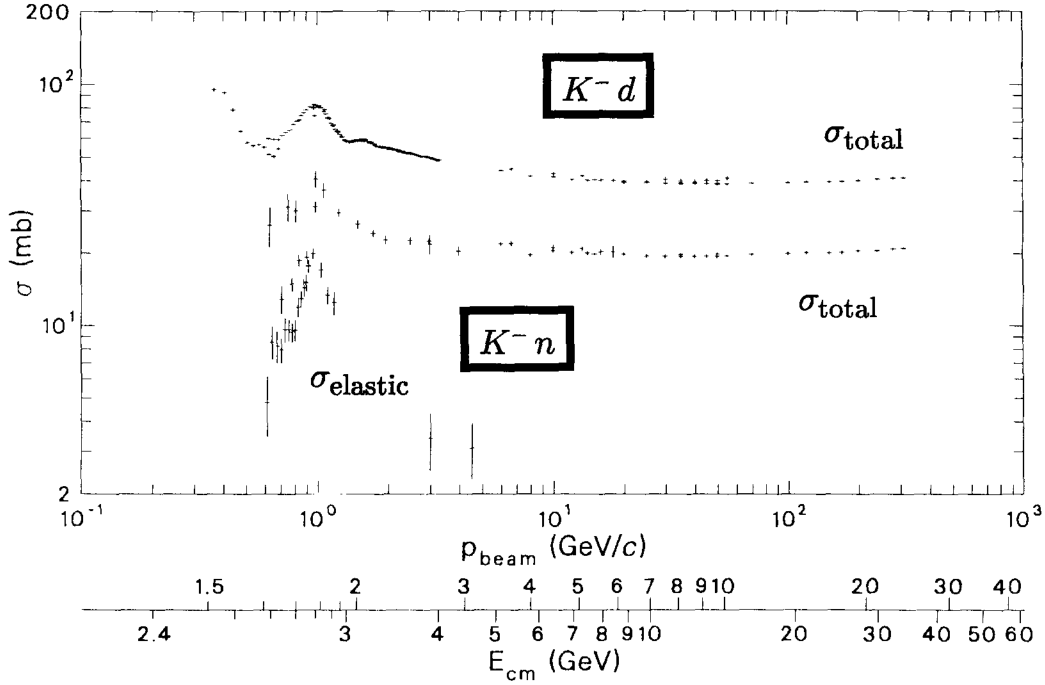


Hadronic total and elastic cross sections vs. laboratory beam momentum p_{beam} and total center-of-mass energy E_{cm}. Data courtesy A. Baldini. V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Hadronic Cross Sections

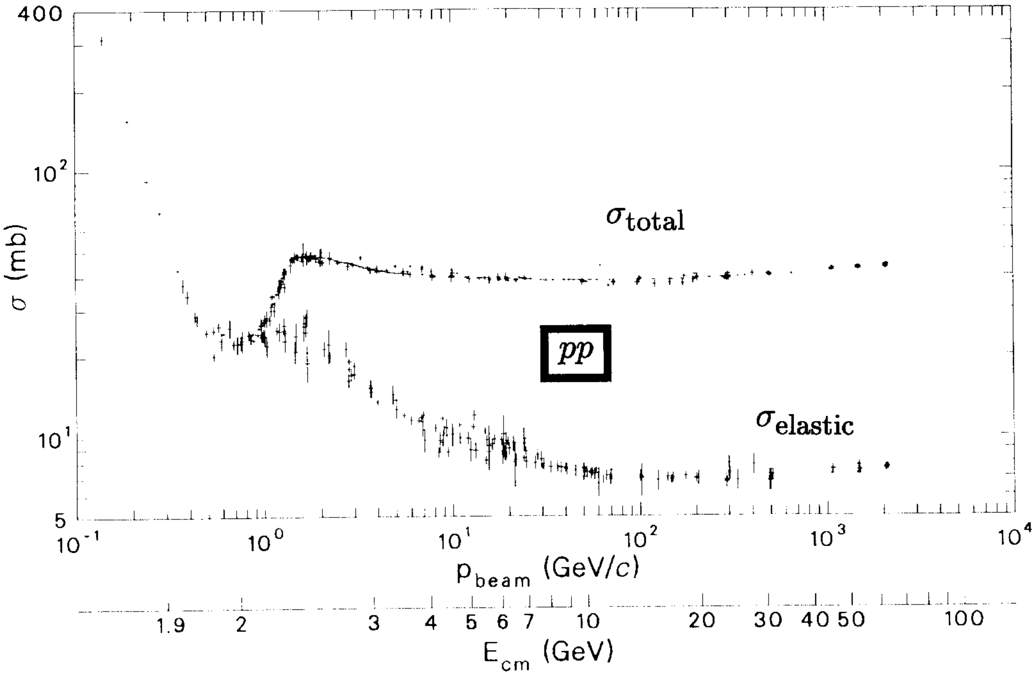


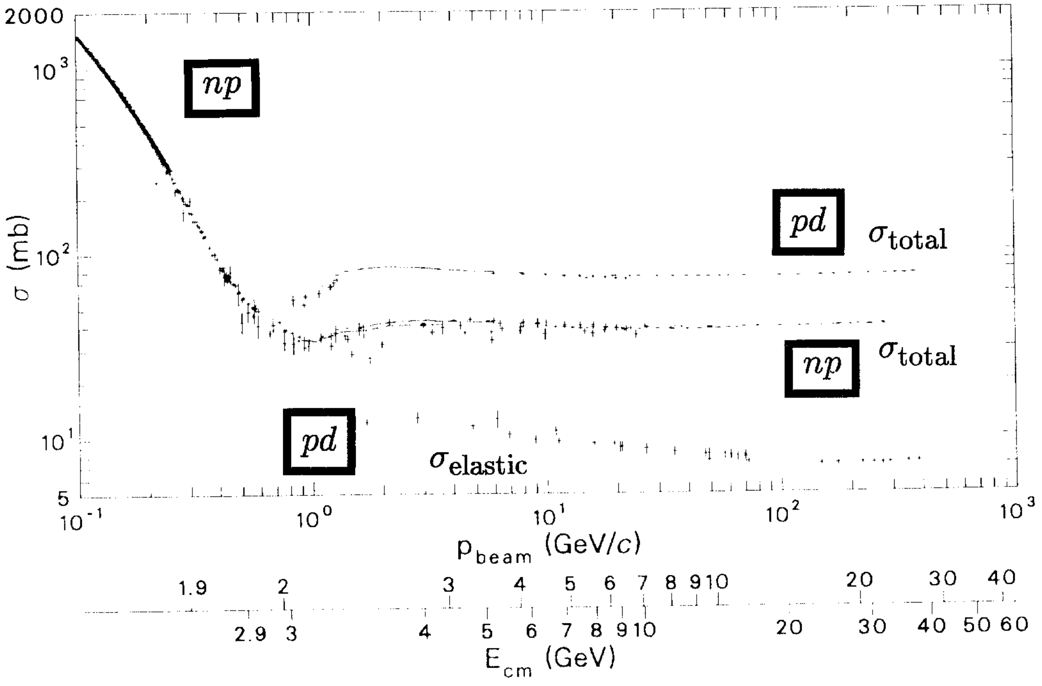


Hadronic total and elastic cross sections vs. laboratory beam momentum p_{beam} and total center-of-mass energy E_{cm}. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Hadronic Cross Sections

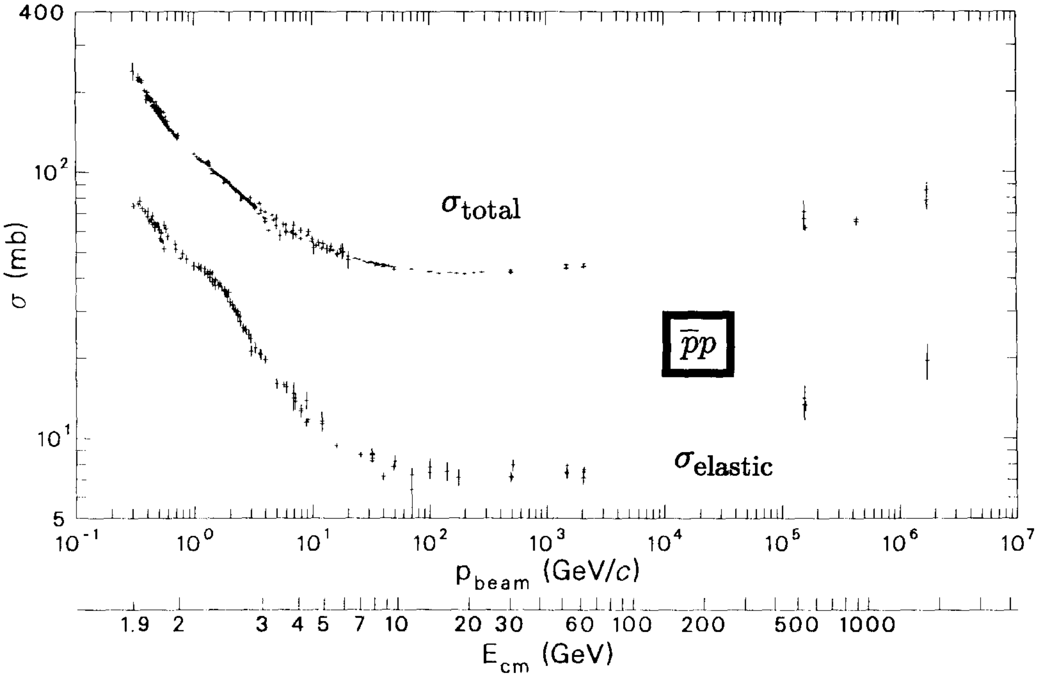


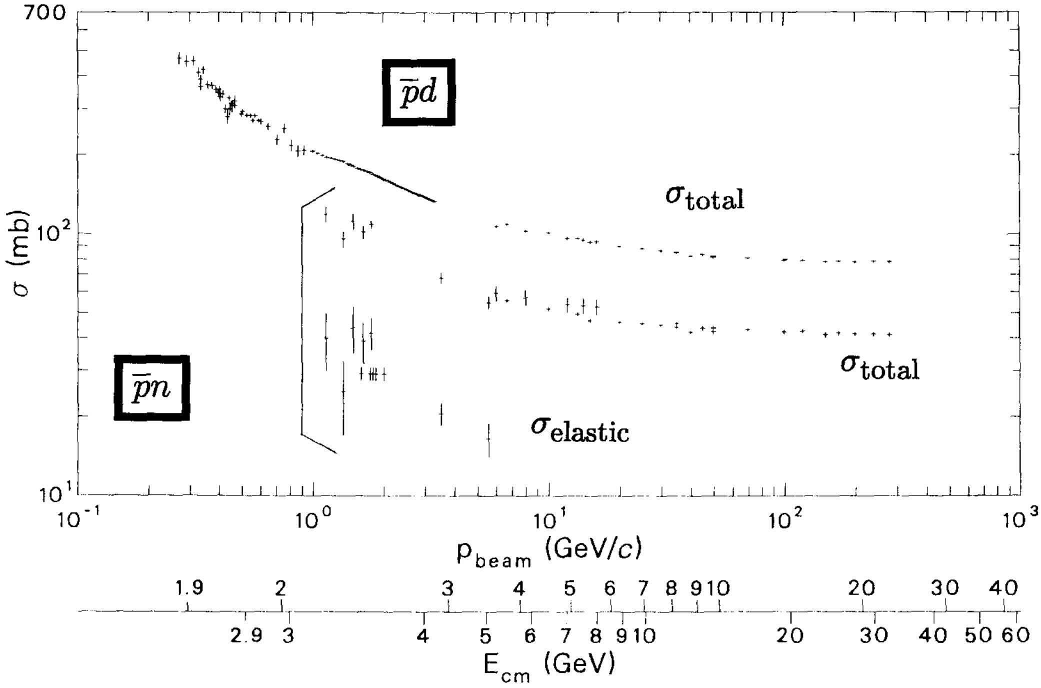


Hadronic total and elastic cross sections vs. laboratory beam momentum p_{beam} and total center-of-mass energy E_{cm}. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES (Cont'd)

Hadronic Cross Sections





Hadronic total and elastic cross sections vs. laboratory beam momentum p_{beam} and total center-of-mass energy E_{cm}. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, USSR. See *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Bornstein, New Series, Vol. 12a and 12b, H. Schopper, Ed. (1987).

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

For a review of the photon mass, see BYRNE 77.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
$<3 \times 10^{-33}$		CHIBISOV	76		Galactic mag. field
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6 \times 10^{-22}$	99.7	DAVIS	75		Jupiter magfield
$<7.3 \times 10^{-22}$		HOLLWEG	74		Alfven waves
$<6 \times 10^{-23}$		[1] FRANKEN	71		Low freq. res. cir.
$<1. \times 10^{-20}$		WILLIAMS	71	CNTR	Tests Gauss law
$<2.3 \times 10^{-21}$		GOLDHABER	68		Satellite data
$<6 \times 10^{-21}$		[1] PATEL	65		Satellite data
$<6 \times 10^{-21}$		GINTSBURG	64		Satellite data

[1] Validity questionable. See criticism in KROLL 71 and GOLDHABER 71.

γ CHARGE

VALUE (10^{-32} e)	DOCUMENT ID		TECN	COMMENT
<2	COCCONI	88	TOF	Pulsar f_1, f_2 TOF

REFERENCES FOR γ

COCCONI	88	PL B206 705		(CERN)
BYRNE	77	Ast.Sp.Sci. 46 115		(LOIC)
CHIBISOV	76	SPU 19 624		(LEBD)
DAVIS	75	PRL 35 1402	+Goldhaber, Nieto	(CIT, STON, LASL)
HOLLWEG	74	PRL 32 961		(NCAR)
FRANKEN	71	PRL 26 115	+Ampulski	(MICH)
GOLDHABER	71	RMP 43 277	+Nieto	(STON, BOHR, UCSB)
KROLL	71	PRL 26 1395		(SLAC)
WILLIAMS	71	PRL 26 721	+Faller, Hill	(WESL)
GOLDHABER	68	PRL 21 567	+Nieto	(STON)
PATEL	65	PL 14 105		(DUKE)
GINTSBURG	64	Sov. Astr. AJ7 536		(ASCI)

W

$J = 1$

W MASS

The fit uses the W and Z mass and mass difference measurements.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
80.6 ± 0.4 OUR FIT Error includes scale factor of 1.1.					
80.9 ± 0.8 OUR AVERAGE					
$80.79 \pm 0.31 \pm 0.84$		[1] ALITTI	90B	UA2	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
$80.0 \pm 3.3 \pm 2.4$	22	[2] ABE	89I	CDF	$E_{cm}^{p\bar{p}} = 1800$ GeV
$82.7 \pm 1.0 \pm 2.7$	149	[3] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$81.8 {}^{+6.0}_{-5.3} \pm 2.6$	46	[4] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
$89 \pm 3 \pm 6$	32	[5] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
$80.2 \pm 0.6 \pm 1.4$	251	[6] ANSARI	87	UA2	Repl. by ALITTI 90B
$81.2 \pm 1.0 \pm 1.4$	119	[6] APPEL	86	UA2	Repl. by ANSARI 87
$83.5 {}^{+1.1}_{-1.0} \pm 2.7$	86	[7] ARNISON	86	UA1	Repl. by ALBAJAR 89
$81. {}^{+6.}_{-7.}$	14	[8] ARNISON	84D	UA1	Repl. by ALBAJAR 89
$83.1 \pm 1.9 \pm 1.3$	37	BAGNAIA	84	UA2	Repl. by ALITTI 90B
$81. \pm 5.$	6	ARNISON	83	UA1	Repl. by ARNISON 83D
80.9 ± 2.9	27	ARNISON	83D	UA1	Repl. by ARNISON 86
81.0 ± 2.8		BAGNAIA	83	UA2	Repl. by BAGNAIA 84
$80. {}^{+10.}_{-6.}$	4	BANNER	83B	UA2	Repl. by ALITTI 90B

[1] There are two contributions to the systematic error (± 0.84): one (± 0.81) which cancels in $m(W)/m(Z)$ and one (± 0.21) which is non-cancelling. These were added in quadrature.

[2] ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.

[3] ALBAJAR 89 result is from a total sample of 299 $W \to e\nu$ events.

[4] ALBAJAR 89 result is from a total sample of 67 $W \to \mu\nu$ events.

[5] ALBAJAR 89 result is from $W \to \tau\nu$ events.

[6] There are two contributions to the systematic error (± 1.4): one (± 1.3) which cancels in $m(W)/m(Z)$ and one (± 0.5) which is non-cancelling. These were added in quadrature.

[7] This is enhanced subsample of 172 total events.

[8] Using $W^{\pm} \to \mu^{\pm}\nu$.

W WIDTH

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.25 ± 0.14 OUR AVERAGE						
2.19 ± 0.20			[9] ABE	90	CDF	Extracted value
$2.30 \pm 0.19 \pm 0.06$			[10] ALITTI	90C	UA2	Extracted value
$2.8 {}^{+1.4}_{-1.5} \pm 1.3$		149	[11] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5.4	90	149	[11] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
<7	90	251	ANSARI	87	UA2	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
<7	90	119	APPEL	86	UA2	$E_{cm}^{p\bar{p}} = 546{,}630$ GeV
<6.5	90	86	[12] ARNISON	86	UA1	Repl. by ALBAJAR 89
<7	90	27	ARNISON	83D	UA1	Repl. by ARNISON 86

[9] ABE 90 measure $R = \sigma(W \to e\nu)/\sigma(Z \to e^+e^-)$ which is equal to $[\sigma(W)/\sigma(Z)][\Gamma(W \to e\nu)/\Gamma(Z \to ee)]\,\Gamma(Z)/\Gamma(W)$. The bracketed quantities can be calculated with plausible reliability. ABE 90 then extract $\Gamma(W)$ by using the value $\Gamma(Z) = 2.57 \pm 0.07$ GeV. They measured $R = 10.2 \pm 0.8 \pm 0.4$, assumed $\sin^2\theta_W = 0.229 \pm 0.007$, and took predicted values $\sigma(W)/\sigma(Z) = 3.23 \pm 0.03$ and $\Gamma(W \to e\nu)/\Gamma(Z \to ee) = 2.70 \pm 0.02$. This yields $\Gamma(W)/\Gamma(Z) = 0.85 \pm 0.08$. The quoted error for $\Gamma(W)$ includes systematic uncertainties. $E_{cm}^{p\bar{p}} = 1800$ GeV.

[10] ALITTI 90C used the same technique as described for ABE 90. They measured $R = 9.38^{+0.82}_{-0.72} \pm 0.25$, obtained $\Gamma(W)/\Gamma(Z) = 0.902 \pm 0.074 \pm 0.024$. Using $\Gamma(Z) = 2.546 \pm 0.032$ GeV, they obtained the $\Gamma(W)$ value quoted above and the limits $\Gamma(W) <$ 2.56 (2.64) GeV at the 90% (95%) CL. $E_{cm}^{p\bar{p}} = 546{,}630$ GeV.

[11] ALBAJAR 89 result is from a total sample of 299 $W \to e\nu$ events.

[12] If systematic error is neglected, result is $2.7^{+1.4}_{-1.5}$ GeV. This is enhanced subsample of 172 total events.

W ANOMALOUS MAGNETIC MOMENT ($\Delta\kappa$)

The full magnetic moment is given by $\mu(W) = e(2-\Delta\kappa)/2m(W)$. In the Standard Model, $\Delta\kappa = 0$. The parameter Λ appearing below is a regularization cutoff and may correspond to the energy scale where the structure of the W boson becomes manifest.

VALUE ($e/2m(W)$)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[13] GRIFOLS	88	THEO
	[14] GROTCH	87	THEO
	[15] VANDERBIJ	87	THEO
	[16] GRAU	85	THEO
	[17] SUZUKI	85	THEO
	[18] HERZOG	84	THEO

[13] GRIFOLS 88 uses deviation from ρ parameter to set limit $\Delta\kappa \lesssim 65\ (M_W^2/\Lambda^2)$.

[14] GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \to \nu\bar{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.

[15] VANDERBIJ 87 uses existing limits to the photon structure to obtain $|\Delta\kappa| < 33\ (m(W)/\Lambda)$. In addition VANDERBIJ 87 discusses problems with using the ρ parameter of the Standard Model to determine $\Delta\kappa$.

[16] GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole (λ) moments $1.05 > \Delta\kappa \ln(\Lambda/m(W)) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.

[17] SUZUKI 85 uses partial-wave unitarity at high energies to obtain $|\Delta\kappa| \lesssim 190\ (m(W)/\Lambda)^2$. From the anomalous magnetic moment of the muon, SUZUKI 85 obtains $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m(W))$. Finally SUZUKI 85 uses deviations from the ρ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150\ (m(W)/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.

[18] HERZOG 84 consider the contribution of W-boson to muon magnetic moment including anomalous coupling of $WW\gamma$. Obtain a limit $-1 < \Delta\kappa < 3$ for $\Lambda \gtrsim 1$ TeV.

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^+\nu$	$(10.0^{+2.4}_{-3.3})$ %	
Γ_2	$e^+\nu\gamma$	[a] < 1.0 %	90%
Γ_3	$\mu^+\nu$	$(10.0^{+2.9}_{-3.7})$ %	
Γ_4	$\mu^+\nu\gamma$		
Γ_5	$\tau^+\nu$	$(10.2^{+3.4}_{-4.1})$ %	

[a] See the Listings below for the γ energy range used in this measurement.

W BRANCHING RATIOS

$\Gamma(e^+\nu)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.10 \pm 0.014^{+0.02}_{-0.03}$	248	[19] ANSARI	87C	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	299	[20] ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
seen	119	APPEL	86	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
seen	172	ARNISON	86	UA1	Repl. by ALBAJAR 89

[19] The first error was obtained by adding the statistical and systematic experimental uncertainties in quadrature. The second error reflects the dependence on theoretical prediction of total *W* cross section: $\sigma(546\ {\rm GeV}) = 4.7^{+1.4}_{-0.7}$ nb and $\sigma(630\ {\rm GeV}) = 5.8^{+1.8}_{-1.0}$ nb. See ALTARELLI 85B.

[20] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

$\Gamma(e^+\nu\gamma)/\Gamma(e^+\nu)$ Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.1	90	1	[21] ARNISON	84	UA1	$E^{p\bar{p}}_{\rm cm} = 546$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
none in 119 $W \to e\nu$ evts		0	APPEL	86	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV

[21] After accounting for selection efficiency and geometric acceptance, and requiring $E_T(\gamma) > 10$ GeV. ARNISON 84 $W \to e\nu\gamma$ one event in 52 $W \to e\nu$ events is consistent with QED Bremsstrahlung. Mass not restricted to *W* mass.

$\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$1.00 \pm 0.14 \pm 0.08$	67	ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.24^{+0.6}_{-0.4}$	14	ARNISON	84D	UA1	Repl. by ALBAJAR 89

$\Gamma(\mu^+\nu\gamma)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none in 18 $W \to \mu\nu$ evts	0	[22] ARNISON	84	UA1	$E^{p\bar{p}}_{\rm cm} = 546$ GeV

[22] Mass not restricted to *W* mass.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_5/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$1.02 \pm 0.20 \pm 0.12$	32	ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.02 \pm 0.20 \pm 0.10$	32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

REFERENCES FOR *W*

ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALITTI	90B	PL B (to be pub.)	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
CERN-EP/90-22				
ALITTI	90C	ZPHY C (to be pub.)	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
CERN-EP/90-20				
ABE	89I	PRL 62 1005	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
GRIFOLS	88	IJMP A3 225	+Peris, Sola	(BARC, DESY)
Also	87	PL B197 437	Grifols, Peris, Sola	(BARC, DESY)
ALBAJAR	87	PL B185 233	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ANSARI	87C	PL B194 158	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
GROTCH	87	PR D36 2153	+Robinett	(PSU)
VANDERBIJ	87	PR D35 1088	van der Bij	(FNAL)
APPEL	86	ZPHY C30 1	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ARNISON	86	PL 166B 484	+Albrow, Allkofer, Astbury+	(UA1 Collab.) J
ALTARELLI	85B	ZPHY C27 617	+Ellis, Martinelli	(CERN, FNAL, FRAS)
GRAU	85	PL 154B 283	+Grifols	(BARC)
SUZUKI	85	PL 153B 289		(LBL)
ARNISON	84	PL 135B 250	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	84D	PL 134B 469	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	84	ZPHY C24 1	+Banner, Battiston, Blech+	(UA2 Collab.)
HERZOG	84	PL 148B 355		(WISC)
Also	84B	PL 155B 468 erratum	Herzog	(WISC)
ARNISON	83	PL 122B 103	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	83D	PL 129B 273	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	83	PL 129B 130	+Banner, Battiston, Bloch+	(UA2 Collab.)
BANNER	83B	PL 122B 476	+Battiston, Bloch, Bonaudi+	(UA2 Collab.)

Z

$J = 1$

Z MASS

The fit uses the *W* and *Z* mass and mass difference (see below) measurements.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
91.161±0.031 OUR FIT					
91.160±0.031 OUR AVERAGE					
$91.171 \pm 0.030 \pm 0.030$	11k	[1] ABREU	90	DLPH	$E^{ee}_{\rm cm} = 88.3$–95.0 GeV
$91.160 \pm 0.024 \pm 0.030$	17k	[1] ADEVA	90C	L3	$E^{ee}_{\rm cm} = 88.28$–95.04 GeV
$91.154 \pm 0.021 \pm 0.030$	28k	[1] AKRAWY	90E	OPAL	$E^{ee}_{\rm cm} = 88.28$–95.04 GeV
$91.182 \pm 0.026 \pm 0.030$	20k	[1] DECAMP	90D	ALEP	$E^{ee}_{\rm cm} = 88.28$–95.04 GeV
$90.9 \pm 0.3 \pm 0.2$	188	[2] ABE	89C	CDF	$E^{p\bar{p}}_{\rm cm} = 1800$ GeV
91.14 ± 0.12	480	[3] ABRAMS	89B	MRK2	$E^{ee}_{\rm cm} = 89.2$–93.0 GeV
$88.6\ ^{+2.0}_{-1.8}$		[4] MORI	89	RVUE	$E^{ee}_{\rm cm} \le 57$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$91.49 \pm 0.35 \pm 0.93$		[5] ALITTI	90B	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
$91.06 \pm 0.09 \pm 0.045$	1066	[6] AARNIO	89	DLPH	$E^{ee}_{\rm cm} = 89.26$–93.27 GeV
91.11 ± 0.23	106	ABRAMS	89	MRK2	Repl. by ABRAMS 89B
$91.132 \pm 0.057 \pm 0.046$	2538	[6] ADEVA	89	L3	Repl. by ADEVA 90C
$91.01 \pm 0.05 \pm 0.045$	4350	[6] AKRAWY	89	OPAL	Repl. by AKRAWY 90E
$93.1 \pm 1.0 \pm 3.0$	24	[7,8] ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
$90.7\ ^{+5.2}_{-4.8} \pm 3.2$	14	[9] ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
$91.174 \pm 0.055 \pm 0.045$	3320	[6] DECAMP	89	ALEP	Repl. by DECAMP 90D
$91.5 \pm 1.2 \pm 1.7$	25	[7] ANSARI	87	UA2	Repl. by ALITTI 90B
$92.5 \pm 1.3 \pm 1.5$	13	APPEL	86	UA2	Repl. by ANSARI 87
$93.0 \pm 1.4 \pm 3.0$	14	ARNISON	86	UA1	Repl. by ALBAJAR 89
$85.8\ ^{+7.0}_{-5.4}$		[10] ARNISON	84E	UA1	Repl. by ALBAJAR 89
$92.7 \pm 1.7 \pm 1.4$	4	[11] BAGNAIA	84	UA2	Repl. by ALITTI 90B
95.2 ± 2.5	5	ARNISON	83C	UA1	Repl. by ARNISON 83D
95.6 ± 3.2	5	ARNISON	83D	UA1	Repl. by ARNISON 86
91.9 ± 1.9	4	BAGNAIA	83	UA2	Repl. by ALITTI 90B

[1] The systematic error (0.03) is an error in common to the 4 LEP experiments.

[2] First error of ABE 89 is combination of statistical and systematic contributions; second is mass scale uncertainty.

[3] ABRAMS 89B uncertainty includes 35 MeV due to the absolute energy measurement.

[4] MORI 89 result is from all existing measurements of *R* below the *Z* region including AMY, VENUS, and TOPAZ at TRISTAN plus data from PEP, PETRA, CESR, and DORIS. Assuming $\Gamma(Z) = 2.5$ GeV and $\Delta r = 0.070$.

[5] Enters fit through *W*/*Z* mass ratio below.

[6] The systematic error (0.045) is an error in common to the 4 LEP experiments.

[7] Enters fit through *Z*-*W* mass difference below.

[8] ALBAJAR 89 result is from a total sample of 33 $Z \to e^+e^-$ events.

[9] ALBAJAR 89 result is from a total sample of 19 $Z \to \mu^+\mu^-$ events.

[10] ARNISON 84E is from 4 $\mu^+\mu^-$, $1\mu^+\mu^-\gamma$.

[11] BAGNAIA 84 is a reanalysis of BAGNAIA 83 after recalibration of calorimeter.

W/*Z* MASS RATIO

VALUE	DOCUMENT ID		TECN	COMMENT
0.884 ±0.005 OUR FIT Error includes scale factor of 1.1.				
$0.8831 \pm 0.0048 \pm 0.0026$	[12] ALITTI	90B	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV

[12] ALITTI 90B scale error cancels in this ratio.

Z – *W* MASS DIFFERENCE

The fit uses the *W* and *Z* mass and mass difference measurements.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.5±0.4 OUR FIT Error includes scale factor of 1.1.				
$10.4 \pm 1.4 \pm 0.8$	ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$11.3 \pm 1.3 \pm 0.9$	ANSARI	87	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV

Z WIDTH

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.534±0.027 OUR AVERAGE						
2.511 ± 0.065		11k	ABREU	90	DLPH	$E^{ee}_{\rm cm} = 88.3$–95.0 GeV
2.539 ± 0.054		17k	ADEVA	90C	L3	$E^{ee}_{\rm cm} = 88.28$–95.04 GeV
2.536 ± 0.045		28k	AKRAWY	90E	OPAL	$E^{ee}_{\rm cm} = 88.28$–95.04 GeV
2.541 ± 0.056		20k	DECAMP	90D	ALEP	$E^{ee}_{\rm cm} = 88.28$–95.04 GeV
$3.8 \pm 0.8 \pm 1.0$		188	ABE	89C	CDF	$E^{p\bar{p}}_{\rm cm} = 1800$ GeV
$2.42\ ^{+0.45}_{-0.35}$		480	[13] ABRAMS	89B	MRK2	$E^{ee}_{\rm cm} = 89.2$–93.0 GeV
$2.7\ ^{+1.2}_{-1.0} \pm 1.3$		24	[14] ALBAJAR	89	UA1	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV
$2.7 \pm 2.0 \pm 1.0$		25	[15] ANSARI	87	UA2	$E^{p\bar{p}}_{\rm cm} = 546{,}630$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$2.42 \pm 0.21 \pm 0.09$		1066	[16] AARNIO	89	DLPH	E^{ee}_{cm} = 89.26–93.27 GeV
$1.61^{+0.60}_{-0.43}$		106	ABRAMS	89	MRK2	Repl. by ABRAMS 89B
2.588 ± 0.137		2538	ADEVA	89	L3	Repl. by ADEVA 90C
2.60 ± 0.13		4350	AKRAWY	89	OPAL	Repl. by AKRAWY 90E
< 5.2	90	24	[14] ALBAJAR	89	UA1	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
2.68 ± 0.15		3320	DECAMP	89	ALEP	Repl. by DECAMP 90D
< 5.6	90	25	[15] ANSARI	87	UA2	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
< 3.2	90	13	[17] APPEL	86	UA2	Repl. by ANSARI 87
$2.2^{+0.7}_{-0.5} \pm 0.2$		13	[17] APPEL	86	UA2	Repl. by ANSARI 87
< 4.6	90	13	APPEL	86	UA2	Repl. by ANSARI 87
< 8.3	90	14	[18] ARNISON	86	UA1	Repl. by ALBAJAR 89
< 6.5	90	4	[19] BAGNAIA	84	UA2	Repl. by ANSARI 87
< 2.6	90	4	BAGNAIA	84	UA2	Repl. by ANSARI 87
<10.2	90	4	ARNISON	83C	UA1	Repl. by ARNISON 86
< 8.5	90	4	ARNISON	83D	UA1	Repl. by ARNISON 86
$<11.$	90	4	BAGNAIA	83	UA2	Repl. by ANSARI 87

[13] ABRAMS 89B uncertainty includes 50 MeV due to the miniSAM background subtraction error.

[14] ALBAJAR 89 result is from a total sample of 33 $Z \rightarrow e^+ e^-$ events.

[15] Quoted values of ANSARI 87 are from direct fit. Ratio of Z and W production gives either $\Gamma(Z) < (1.09 \pm 0.07) \times \Gamma(W)$, CL = 90% or $\Gamma(Z) = (0.82^{+0.19}_{-0.14} \pm 0.06) \times \Gamma(W)$. Assuming Standard-Model value $\Gamma(W) = 2.65$ GeV then gives $\Gamma(Z) < 2.89 \pm 0.19$ or $= 2.17^{+0.50}_{-0.37} \pm 0.16$.

[16] The systematic error (0.09) originates in a 6% systematic error on the absolute value of the cross section.

[17] Ratio of Z and W production gives either $\Gamma(Z) < \Gamma(W) \times (1.2 \pm 0.1)$, CL = 90% or $\Gamma(Z) = \Gamma(W) \times (0.83^{+0.26}_{-0.22})$. Assuming Standard-Model value $\Gamma(W) = 2.65$ GeV then gives $\Gamma(Z) < (3.2 \pm 0.2)$ or $= 2.2^{+0.7}_{-0.5} \pm 0.22$.

[18] If systematic error is neglected, result is $3.9^{+2.3}_{-1.5}$ GeV.

[19] Ratio of Z and W production gives $\Gamma(Z) < \Gamma(W) \times (0.93 \pm 0.09)$. Assuming $\Gamma(W) = 2.77$ GeV, gives $\Gamma(Z) < 2.6 \pm 0.3$ GeV.

Z DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^+ e^-$	(3.21 ± 0.07) %	
Γ_2	$\mu^+ \mu^-$	(3.36 ± 0.11) %	
Γ_3	$\tau^+ \tau^-$	(3.33 ± 0.13) %	
Γ_4	$\nu\bar{\nu}$ (or other invisible modes)	(19.2 ± 1.0) %	
Γ_5	$e^+ e^- \gamma$		
Γ_6	$\mu^+ \mu^- \gamma$		
Γ_7	$e^\pm \mu^\mp$	$< 2.2 \times 10^{-3}$	90%
Γ_8	hadrons	(70.9 ± 0.9) %	
Γ_9	$B\bar{B}$	(14.6 ± 1.9) %	
Γ_{10}	non-$B\bar{B}$ hadrons	(56.3 ± 2.0) %	
Γ_{11}	$\pi^0 \gamma$	$< 3.9 \times 10^{-4}$	95%
Γ_{12}	$\eta\gamma$	$< 4.6 \times 10^{-4}$	95%
Γ_{13}	$\eta'(958)\gamma$	$< 2.2 \times 10^{-4}$	95%
Γ_{14}	$\gamma\gamma$	$< 3.7 \times 10^{-4}$	95%
Γ_{15}	$\gamma\gamma\gamma$	$< 2.8 \times 10^{-4}$	95%

CONSTRAINED FIT INFORMATION

An overall fit to 10 branching ratios uses 21 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 = 5.6$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	2				
x_3	1	3			
x_4	−12	−25	−31		
x_9	1	1	2	−9	
x_{10}	2	5	7	−36	−89
	x_1	x_2	x_3	x_4	x_9

Z BRANCHING RATIOS

$\Gamma(e^+ e^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0321 ± 0.0007 OUR FIT				
0.0322 ± 0.0007 OUR AVERAGE				
0.0331 ± 0.0018	263	[20] AARNIO 90	DLPH	E^{ee}_{cm} = 88.28–95.04 GeV
$0.0319 \pm 0.0013 \pm 0.0005$	651	[21] ADEVA 90D	L3	E^{ee}_{cm} = 88.28–94.28 GeV
0.0320 ± 0.0009	908	[22] AKRAWY 90E	OPAL	E^{ee}_{cm} = 88.28–95.04 GeV
$0.046 \pm 0.009\ ^{+0.008}_{-0.014}$	39	[23] ANSARI 87C	UA2	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0342 \pm 0.0015 \pm 0.0011$	103	AKRAWY 90	OPAL	E^{ee}_{cm} = 89.3–93.3 GeV
$0.034 \pm 0.004 \pm 0.003$	95	[24] ADEVA 89	L3	E^{ee}_{cm} = 89.26–93.27 GeV
seen	33	[25] ALBAJAR 89	UA1	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
seen	13	APPEL 86	UA2	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
seen	16	ARNISON 86	UA1	Repl. by ALBAJAR 89
seen	4	ARNISON 83C	UA1	Repl. by ARNISON 86
seen	8	[26] BAGNAIA 83	UA2	$E^{p\bar{p}}_{cm}$ = 546 GeV

[20] AARNIO 90 result is from $\Gamma(ee) = 83.2 \pm 3.0 \pm 2.4$ MeV.

[21] ADEVA 90D result is from $\Gamma(ee) = 81.1 \pm 2.8 \pm 1.2 \pm 0.7$ MeV.

[22] AKRAWY 90E result is from $\Gamma(ee) = 81.2 \pm 2.6$ MeV and includes both statistical and systematic errors.

[23] The first error is obtained by adding the statistical and systematic experimental uncertanties in quadrature. The second error reflects the dependence on theoretical prediction of total Z cross section: $\sigma(546 \text{ GeV}) = 1.3^{+0.4}_{-0.2}$ nb and $\sigma(630 \text{ GeV}) = 1.7^{+0.5}_{-0.3}$ nb. See ALTARELLI 85B.

[24] ADEVA 89 result is from $\Gamma(ee) = 88 \pm 9 \pm 7$ MeV.

[25] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

[26] BAGNAIA 83 interpret their events as either $(Z \rightarrow e^+ e^-)$ or $(Z \rightarrow e^+ e^- \gamma)$.

$\Gamma(e^+ e^-)/\Gamma(\text{hadrons})$ — $\Gamma_1/(\Gamma_9+\Gamma_{10})$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0453 ± 0.0011 OUR FIT				
0.0444 ± 0.0031 OUR AVERAGE				
$0.0448 \pm 0.0030 \pm 0.0012$	323	DECAMP 90D	ALEP	E^{ee}_{cm} = 90–92.5 GeV
$0.037\ ^{+0.016}_{-0.012}$	12	[27] ABRAMS 89D	MRK2	E^{ee}_{cm} = 89.2–93.0 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0472 ± 0.0061	127	[28] DECAMP 90B	ALEP	E^{ee}_{cm} = 90–92.5 GeV

[27] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

[28] DECAMP 90B have added statistical and systematic errors in quadrature.

$\Gamma(\mu^+ \mu^-)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0336 ± 0.0011 OUR FIT				
0.0333 ± 0.0014 OUR AVERAGE				
0.0345 ± 0.0023	484	[29] ADEVA 90D	L3	E^{ee}_{cm} = 88.28–94.28 GeV
0.0326 ± 0.0018	585	[30] AKRAWY 90E	OPAL	E^{ee}_{cm} = 88.28–95.04 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.036 \pm 0.002 \pm 0.001$	97	[31] ADEVA 90	L3	E^{ee}_{cm} = 89.3–93.3 GeV
$0.0328 \pm 0.0034 \pm 0.0017$	101	AKRAWY 90	OPAL	E^{ee}_{cm} = 89.3–93.3 GeV

[29] ADEVA 90D result is from $\Gamma(\mu\mu) = 87.6 \pm 0.053$ MeV. Error includes systematics.

[30] AKRAWY 90E result is from $\Gamma(\mu\mu) = 82.6 \pm 5.8$ MeV and includes both statistical and systematic errors.

[31] ADEVA 90 result is from $\Gamma(\mu\mu) = 92 \pm 5 \pm 3$ MeV. They assume e-μ universality.

$\Gamma(\mu^+ \mu^-)/\Gamma(\text{hadrons})$ — $\Gamma_2/(\Gamma_9+\Gamma_{10})$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0474 ± 0.0016 OUR FIT				
0.0481 ± 0.0026 OUR AVERAGE				
$0.0480 \pm 0.0026 \pm 0.0005$	380	DECAMP 90D	ALEP	E^{ee}_{cm} = 88.3–95.0 GeV
$0.053\ ^{+0.020}_{-0.015}$	13	[32] ABRAMS 89D	MRK2	E^{ee}_{cm} = 89.2–93.0 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0435 ± 0.0060	117	[33] DECAMP 90B	ALEP	E^{ee}_{cm} = 90–92.5 GeV
$0.056 \pm 0.006 \pm 0.002$	97	[34] ADEVA 89	L3	E^{ee}_{cm} = 89.26–93.27 GeV

[32] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

[33] DECAMP 90B have added statistical and systematic errors in quadrature.

[34] ADEVA 89 result gives $\Gamma(\mu\mu) = 92 \pm 6$ MeV.

$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-)$ — Γ_2/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.05 ± 0.04 OUR FIT				
$1.04 \pm 0.30 \pm 0.08$	19	ALBAJAR 89	UA1	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	1	ARNISON 83C	UA1	Repl. by ALBAJAR 89

$\Gamma(\tau^+\tau^-)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0333±0.0013 OUR FIT				
0.0330±0.0019 OUR AVERAGE				
0.032 ±0.002 ±0.002	83	[35] ADEVA 90	L3	$E^{ee}_{\rm cm}$ = 89.3–93.3 GeV
0.0338±0.0025	506	[36] AKRAWY 90E	OPAL	$E^{ee}_{\rm cm}$ = 88.28–95.04 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0333±0.0037±0.0026	87	AKRAWY 90	OPAL	$E^{ee}_{\rm cm}$ = 89.3–93.3 GeV

[35] ADEVA 90 result if from $\Gamma(\tau\tau) = 84 \pm 5 \pm 4$ MeV.

[36] AKRAWY 90E result is from $\Gamma(\tau\tau) = 85.7 \pm 7.1$ MeV and includes both statistical and systematic errors.

$\Gamma(\tau^+\tau^-)/\Gamma(\text{hadrons})$ — $\Gamma_3/(\Gamma_9+\Gamma_{10})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0470±0.0018 OUR FIT				
0.0474±0.0024 OUR AVERAGE				
0.047 ±0.0021±0.0011	534	DECAMP 90D	ALEP	$E^{ee}_{\rm cm}$ = 90–92.5 GeV
$0.066 ^{+0.021}_{-0.017}$	21	[37] ABRAMS 89D	MRK2	$E^{ee}_{\rm cm}$ = 89.2–93.0 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0483±0.0051	130	[38] DECAMP 90B	ALEP	$E^{ee}_{\rm cm}$ = 90–92.5 GeV

[37] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

[38] DECAMP 90B have added statistical and systematic errors in quadrature.

$\Gamma(e^\pm\mu^\mp)/\Gamma(e^+e^-)$ — Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.07	90	ALBAJAR 89	UA1	$E^{p\bar{p}}_{\rm cm}$ = 546,630 GeV

$\Gamma(\text{hadrons})/\Gamma_{\rm total}$ — $(\Gamma_9+\Gamma_{10})/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.709±0.009 OUR FIT				
0.710±0.010 OUR AVERAGE				
0.693±0.030	11k	[39] ABREU 90	DLPH	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV
0.687±0.025	17k	[40,41] ADEVA 90D	L3	$E^{ee}_{\rm cm}$ = 88.28–94.28 GeV
0.725±0.017	26k	[42] AKRAWY 90E	OPAL	$E^{ee}_{\rm cm}$ = 88.28–95.04 GeV
0.710±0.015	17k	DECAMP 90D	ALEP	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.687±0.031±0.020	3701	[40] AKRAWY 90	OPAL	$E^{ee}_{\rm cm}$ = 89.3–93.3 GeV
0.689±0.030		[40] DECAMP 90B	ALEP	$E^{ee}_{\rm cm}$ = 90–92.5 GeV

[39] ABREU 90 result is from $\Gamma(\text{hadrons}) = 1.741 \pm 0.061$ GeV.

[40] Obtained branching ratio using $\sigma(\text{hadron}) = (12\pi/m^2(Z))\ \Gamma(e)\Gamma(h)/\Gamma^2(Z)$.

[41] ADEVA 90D result is from $\Gamma(\text{hadrons}) = 1.744 \pm 0.053$ GeV.

[42] AKRAWY 90E result is from $\Gamma(\text{hadrons}) = 1.838 \pm 0.046$ GeV and assumes lepton universality. Both statistical and systematic errors are included.

$\Gamma(B\overline{B})/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.146±0.020 OUR FIT				
$0.17 ^{+0.07}_{-0.06} {}^{+0.04}_{-0.03}$	15	[43] KRAL 90	MRK2	$E^{ee}_{\rm cm}$ = 89.2–93.0

[43] KRAL 90 used isolated leptons and found $\Gamma(B\overline{B})/\Gamma(\text{hadrons}) = 0.23^{+0.10}_{-0.08}{}^{+0.05}_{-0.04}$.

$\Gamma(B\overline{B})/\Gamma(\text{hadrons})$ — $\Gamma_9/(\Gamma_9+\Gamma_{10})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.207±0.028 OUR FIT				
0.204±0.014±0.024	171	[44] ADEVA 90E	L3	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV

[44] ADEVA 90E used isolated muons and found $B(B \to \mu)\Gamma(b\bar{b}) = 41.7 \pm 2.9 \pm 3.0$ MeV. The systematic error of ±0.024 above includes 0.02 due to uncertainty in $B(B \to \mu)$ added in quadrature to ±0.014 systematic.

$\Gamma(\pi^0\gamma)/\Gamma_{\rm total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.9 \times 10^{-4}$	95	AKRAWY 90F	OPAL	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.9 \times 10^{-4}$	95	DECAMP 90J	ALEP	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV

$\Gamma(\eta\gamma)/\Gamma_{\rm total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.6 \times 10^{-4}$	95	DECAMP 90J	ALEP	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.8 \times 10^{-4}$	95	AKRAWY 90F	OPAL	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV

$\Gamma(\eta'(958)\gamma)/\Gamma_{\rm total}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.2 \times 10^{-4}$	95	DECAMP 90J	ALEP	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV

$\Gamma(\gamma\gamma)/\Gamma_{\rm total}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.7 \times 10^{-4}$	95	AKRAWY 90F	OPAL	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV

$\Gamma(\gamma\gamma\gamma)/\Gamma_{\rm total}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.8 \times 10^{-4}$	95	AKRAWY 90F	OPAL	$E^{ee}_{\rm cm}$ = 88.3–95.0 GeV

CHARGE ASYMMETRY IN $e^+e^- \to \mu^+\mu^-$ (including radiative corrections)

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−25 ±15	(−11)	89.94	ADEVA 90D	L3
− 9 ±11	(−1)	91.03	ADEVA 90D	L3
18 ± 8	(+1)	91.28	ADEVA 90D	L3
9 ±10	(+3)	91.53	ADEVA 90D	L3
8 ±12	(+11)	93.09	ADEVA 90D	L3
0.05± 0.22	(0.026)	91.14	[45] ABRAMS 89D	MRK2
−43.4 ±17.0	(−24.9)	52.0	[46] BACALA 89	AMY
−11.0 ±16.5	(−29.4)	55.0	[46] BACALA 89	AMY
−30.0 ±12.4	(−31.2)	56.0	[46] BACALA 89	AMY
−46.2 ±14.9	(−33.0)	57.0	[46] BACALA 89	AMY
−29 ±13	(−25.9)	53.3	ADACHI 88C	TOPZ
+ 5.3 ± 5.0 ±0.5	(−1.2)	14.0	ADEVA 88	MRKJ
−10.4 ± 1.3 ±0.5	(−8.6)	34.8	ADEVA 88	MRKJ
−12.3 ± 5.3 ±0.5	(−10.7)	38.3	ADEVA 88	MRKJ
−15.6 ± 3.0 ±0.5	(−14.9)	43.8	ADEVA 88	MRKJ
− 1.0 ± 6.0	(−1.2)	13.9	BRAUNSCH... 88D	TASS
− 9.1 ± 2.3 ±0.5	(−8.6)	34.5	BRAUNSCH... 88D	TASS
$-10.6\ ^{+\ 2.2}_{-\ 2.3}\ \pm0.5$	(−8.9)	35.0	BRAUNSCH... 88D	TASS
$-17.6\ ^{+\ 4.4}_{-\ 4.3}\ \pm0.5$	(−15.2)	43.6	BRAUNSCH... 88D	TASS
− 4.8 ± 6.5 ±1.0	(−11.5)	39	BEHREND 87C	CELL
−18.8 ± 4.5 ±1.0	(−15.5)	44	BEHREND 87C	CELL
+ 2.7 ± 4.9	(−1.2)	13.9	BARTEL 86C	JADE
−11.1 ± 1.8 ±1.0	(−8.6)	34.4	BARTEL 86C	JADE
−17.3 ± 4.8 ±1.0	(−13.7)	41.5	BARTEL 86C	JADE
−22.8 ± 5.1 ±1.0	(−16.6)	44.8	BARTEL 86C	JADE
− 6.3 ± 0.8 ±0.2	(−6.3)	29	ASH 85	MAC
− 4.9 ± 1.5 ±0.5	(−5.9)	29	DERRICK 85	HRS

[45] ABRAMS 89D asymmetry includes both 9 $\mu^+\mu^-$ and 15 $\tau^+\tau^-$ events.

[46] BACALA 89 systematic error is about 5%.

CHARGE ASYMMETRY IN $e^+e^- \to \tau^+\tau^-$ (including radiative corrections)

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−18.4±19.2	(−24.9)	52.0	[47] BACALA 89	AMY
−17.7±26.1	(−29.4)	55.0	[47] BACALA 89	AMY
−45.9±16.6	(−31.2)	56.0	[47] BACALA 89	AMY
−49.5±18.0	(−33.0)	57.0	[47] BACALA 89	AMY
−20 ±14	(−25.9)	53.3	ADACHI 88C	TOPZ
−10.6± 3.1±1.5	(−8.5)	34.7	ADEVA 88	MRKJ
− 8.5± 6.6±1.5	(−15.4)	43.8	ADEVA 88	MRKJ
− 6.0± 2.5±1.0	(8.8)	34.6	BARTEL 85F	JADE
−11.8± 4.6±1.0	(14.8)	43.0	BARTEL 85F	JADE

[47] BACALA 89 systematic error is about 5%.

CHARGE ASYMMETRY IN $e^+e^- \to c\bar{c}$

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−12.8± 4.4±4.1	(−13.6)	35	ELSEN 90	JADE
−10.9±12.9±4.6	(−23.2)	44	ELSEN 90	JADE
−14.9± 6.7	(−13.3)	35	OULD-SAADA 89	JADE

CHARGE ASYMMETRY IN $e^+e^- \to b\bar{b}$

Experimental and Standard Model values are somewhat event-selection dependent. Standard Model expectations contain some assumptions on $B - \overline{B}^0$ mixing.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−16.6± 7.7± 4.8	(−24.3)	35	ELSEN 90	JADE
−33.6±22.2± 5.2	(−39.9)	44	ELSEN 90	JADE
3.4± 7.0± 3.5	(−16.0)	29.0	BAND 89	MAC
−72 ±28 ±13	(−56)	55.2	SAGAWA 89	AMY

CHARGE ASYMMETRY IN $e^+ e^- \rightarrow q\overline{q}$

Summed over five lighter flavors.

Experimental and Standard Model values are somewhat event-selection dependent. Standard Model expectations contain some assumptions on $B-\overline{B}^0$ mixing.

ASYMMETRY (%)	*STD. MODEL*	*$\sqrt{s}$ (GeV)*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.0±1.3	(5.0)	34.8	GREENSHAW	89	JADE
8.2±2.9	(8.5)	43.6	GREENSHAW	89	JADE

REFERENCES FOR Z

AARNIO	90	PL B (to be pub.)	+Abreu, Adam, Adami+	(DELPHI Collab.)
CERN-EP/90-31				
ABREU	90	PL B (to be pub.)	+Adam, Adami+	(DELPHI Collab.)
CERN-EP/90-32				
ADEVA	90	PL B236 109	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ADEVA	90C	PL B237 136	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ADEVA	90D	PL B238 (L3 no. 5)	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ADEVA	90E	PL B (L3 no.6)	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
AKRAWY	90	PL B235 379	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90E	PL B (to be pub.)	+Alexander, Allison, Allport+	(OPAL Collab.)
CERN-EP/90-27				
AKRAWY	90F	PL B (to be pub.)	+Alexander, Allison, Allport+	(OPAL Collab.)
CERN-EP/90-29				
ALITTI	90B	PL B (to be pub.)	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
CERN-EP/90-22				
DECAMP	90B	PL B234 399	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90D	PL B235 399	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90J	PL B (to be pub.)	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
CERN-EP/90-23				
ELSEN	90	Z. Phys. (to be pub.)	+Allison, Ambrus, Barlow+	(JADE Collab.)
KRAL	90	PRL 64 1211	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
AARNIO	89	PL B231 539	+Abreu, Adam, Adrianos, Adye+	(DELPHI Collab.)
ABE	89	PRL 62 613	+Amidei, Apollinari, Ascori, Atac+	(CDF Collab.)
ABE	89C	PRL 63 720	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABRAMS	89	PRL 63 724	+Adolphsen, Aleksan, Alexander, Allen+	(Mark II Collab.)
ABRAMS	89B	PRL 63 2173	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ABRAMS	89D	PRL 63 2780	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ADEVA	89	PL B231 509	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
AKRAWY	89	PL B231 530	+Alexander, Allison, Allport+	(OPAL Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BACALA	89	PL B218 112	+Malchow, Sparks, Imlay, Kirk+	(AMY Collab.)
BAND	89	PL B218 369	+Camporesi, Chadwick, Delfino, Desangro+	(MAC Collab.)
DECAMP	89	PL B231 519	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
GREENSHAW	89	ZPHY C42 1	+Warming, Allison, Ambrus, Barlow+	(JADE Collab.)
MORI	89	PL B218 499	+Nozaki, Blanis, Bodek, Budd+	(AMY Collab.)
OULD-SAADA	89	ZPHY C44 567	+Allison, Ambrus, Barlow, Bartel+	(JADE Collab.)
SAGAWA	89	PRL 63 2341	+Lim, Abe, Fujii, Higashi+	(AMY Collab.)
ADACHI	88C	PL B208 319	+Aihara, Dijkstra, Enomoto, Fujii+	(TOPAZ Collab.)
ADEVA	88	PR D38 2665	+Anderhub, Ansari, Becker+	(Mark-J Collab.)
BRAUNSCH...	88D	ZPHY C40 163	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ANSARI	87C	PL B194 158	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
BEHREND	87C	PL B191 209	+Buerger, Criegee, Dainton+	(CELLO Collab.)
APPEL	86	ZPHY C30 1	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ARNISON	86	PL 166B 484	+Albrow, Allkofer, Astbury+	(UA1 Collab.)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
Also	85B	ZPHY C26 507	Bartel, Becker, Bowdery, Cords+	(JADE Collab.)
Also	82	PL 108B 140	Bartel, Cords, Dittmann, Eichler+	(JADE Collab.)
ALTARELLI	85B	ZPHY C27 617	+Ellis, Martinelli	(CERN, FNAL, FRAS)
ASH	85	PRL 55 1831	+Band, Blume, Camporesi+	(MAC Collab.)
BARTEL	85F	PL 161B 188	+Becker, Cords, Felst+	(JADE Collab.)
DERRICK	85	PR D31 2352	+Fernandez, Fries, Hyman+	(HRS Collab.)
ARNISON	84E	PL 147B 241	+Allkofer, Astbury, Aubert+	(UA1 Collab.)
BAGNAIA	84	ZPHY C24 1	+Banner, Battiston, Blech+	(UA2 Collab.)
ARNISON	83C	PL 126B 398	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	83D	PL 129B 273	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	83	PL 129B 130	+Banner, Battiston, Bloch+	(UA2 Collab.)

Searches for Higgs Bosons — H^0 and $H^{\pm}$

NOTE ON THE HIGGS BOSON

The Standard Model[1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2)× U(1) symmetry and generates the W and Z boson masses. The Higgs couples to quarks and leptons of mass m_f with a strength $gm_f/2M_W$. Its coupling to W and Z bosons is of strength g, where g is the coupling constant of the SU(2) gauge theory. Consequently its coupling to stable matter is very small, and its production and detection in experiments is very difficult. An exception is its production in the decay of the Z boson. Since large numbers of Z's can be produced and the coupling of the Z to the Higgs is unsuppressed, experiments at LEP are now able to rule out a significant range of Higgs masses.

If the Higgs mass is very large, the couplings of the Higgs to itself and to longitudinally polarized gauge bosons become large. Requiring that these couplings remain weak enough so that perturbation theory is applicable implies that $M_H \lesssim 1$ TeV.[2] While this is not an absolute bound, it is an indication of the mass scale at which one can no longer speak of an elementary Higgs boson. This fact is made more clear if one notes that the width of the Higgs boson is proportional to the cube of its mass and that a boson of mass 1 TeV has a width of 500 GeV.

It is believed that scalar field theories of the type used to describe Higgs self-interactions can only be effective theories valid over a limited range of energies if the Higgs self-coupling and hence Higgs mass is nonzero. A theory of this type that is valid at all energy scales must have zero coupling. The range of energies over which the interacting theory is valid is a function of the Higgs self-coupling and hence its mass. An upper bound on the Higgs mass can then be determined by requiring that the theory be valid (i.e., have a nonzero value of the renormalized Higgs self-coupling) at all scales up to the Higgs mass.[3] Non-perturbative calculations using lattice[4] gauge theory which can be used to compute at arbitrary values of the Higgs mass indicate that $M_H < 640$ GeV.

If the Higgs mass were small, then the vacuum (ground) state with the correct value of M_W would cease to be the true ground state of the theory.[5] A theoretical constraint can then be obtained from the requirement that this is not the case, i.e., that the our universe is in the true minimum of the Higgs potential. The constraint can be parameterized approximately as[6]

$$M_H > 1.85\,(m_{\rm top} - 85\ {\rm GeV})\ .$$

If the top mass lies below 85 GeV and above the experimental limit of 77 GeV,[7] there is no constraint. This constraint may be too restrictive. Strictly speaking we can only require that the predicted lifetime of our universe, if it is not at the true minimum of the Higgs potential, be longer than its observed age. This constraint can be approximated by[8,9]

$$M_H > (m_{\rm top} - 85\ {\rm GeV})/3 \quad : \ {\rm for}\ M_H < 30\ {\rm GeV}$$

$$M_H > 5.9\,(m_{\rm top} - 170\ {\rm GeV}) \quad : \ {\rm for}\ M_H > 30\ {\rm GeV}$$

Experiments at LEP[10] are able to exclude a large range of Higgs masses. They search for the decay $Z \rightarrow HZ^*$. Here Z^* refers to a virtual Z boson that can appear in the detector as e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\overline{\nu}$ (i.e., missing energy) or hadrons. If $M_H > 2m_\mu$, the lifetime is short, the Higgs decays close to the production vertex, and a search for a final state with at least two charged tracks and missing energy is able to rule out masses from 212 MeV to 24 GeV.[10] For Higgs bosons of mass less than 212 MeV where the decay is largely to e^+e^- and the lifetime is long, a search for separated vertices can be made. Such a search rules out the range of masses from 32 MeV to 212 MeV. Higgs bosons of mass below 32 MeV are too long lived to be seen.[10]

A very light Higgs boson would produce an additional long range component to the nuclear force. No such component has been seen and the constraint[11,12] $M_H > 15$ MeV can be obtained. A light Higgs could be emitted in K meson decay via the process $K \to \pi H$. If the Higgs is lighter than $2m_\mu$, the final state will be πe^+e^- or $\pi\gamma\gamma$ (the former has at least twice the rate of the latter provided it is kinematically accessible)[12,13] The branching ratio $K \to \pi H$ has been computed.[14,15] Its value depends on the unknown top quark mass and the elements of the Cabibbo-Kobayashi-Maskawa matrix. The hadronic matrix element of this quark decay operator must then be evaluated; this gives rise to an additional uncertainty. Evaluation[16] of this for $M_H < 2m_\mu$ gives $B(K \to \pi H) \gtrsim 4.5 \times 10^{-6}$.

The range $M_H < 26$ MeV is ruled out by an experiment at BNL[17] which looks for $K^{\pm} \to \pi^{\pm} + nothing$. If the Higgs mass is greater than 26 MeV, the Higgs decays within the detector and no limit can be set.

Barr et al.[18] at CERN search for $K_L^0 \to \pi^0 H \to \pi^0 e^+ e^-$. They set a limit on the product branching ratio $B(K \to \pi H)B(H \to e^+e^-)$ of less than 10^{-7}. This suffices to exclude Higgs bosons between 15 MeV and $2m_\mu$. The experiment has no acceptance below this range due in part to the long lifetime of the Higgs boson.

In summary, a Standard Model Higgs boson of mass less than 24 GeV is unambiguously excluded: a significant step forward from the situation that prevailed when the last version of this note was written.

Extensions of the standard model, such as those based on supersymmetry,[19] can have more complicated spectra of Higgs bosons. The simplest extension has two Higgs doublets whose neutral components have vacuum expectation values v_1 and v_2, both of which contribute to the W and Z masses. The physical particle spectrum contains one charged Higgs boson ($H^{\pm}$), two neutral scalars (H_1^0, H_2^0), and one pseudoscalar (P^0) if CP is conserved in the scalar sector.[20] In the simplest version of the supersymmetric model one of these neutral scalars has mass less than the Z boson. In models where all fermions of the same electric charge receive their masses from only one of the two doublets (v_2 gives mass to the charge 2/3 quarks, while v_1 gives mass to the charged leptons and the charge 1/3 quarks), there are, as in the standard model, no flavor-changing neutral currents at lowest order in perturbation theory. The H_i^0 and P^0 couplings to fermions depend on v_2/v_1 and are either enhanced or suppressed relative to the couplings in the standard model. Experiments at LEP are able to exclude neutral Higgs particles in these models if their masses are between 50 MeV and 20 GeV if $v_2/v_1 > 0.6$ (Ref. 21).

Searches for charged Higgs bosons exclude them if their mass is below 35 GeV[22] independent of the branching fractions to $\nu\tau$, $c\bar{s}$, and $c\bar{b}$.

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H^0 (Higgs Boson) MASS LIMIT

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. Limits that depend on the $Ht\bar{t}$ coupling may also apply to a Higgs boson of an extended Higgs sector whose couplings to up-type quarks are comparable to or larger than those of the standard one-doublet model H^0 couplings.

Some of the experiments for a light Higgs utilize its coupling with nucleons. We parameterize the Higgs-nucleon coupling (which is dominantly isosclar) as $g_{HNN} = \eta_{HNN}(\sqrt{2}G_F)^{1/2}\ m(N)$. The limits depend on the value of η_{HNN} used. Shifman *et al.* [Phys. Lett. **78B**, 443 (1978)] obtained $\eta_{HNN} = 0.22$ assuming three heavy flavors. More recently, T.P. Cheng [Phys. Rev. **D38**, 2869 (1988)], H.-Y. Cheng [Phys. Lett. **B219**, 347 (1989)], and Barbieri and Curci [Phys. Lett. **B219**, 503 (1989)] took into account the strange-quark content of the proton as well as the heavy quark effects, and derived $\eta_{HNN} = 0.56$.

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VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>24 (CL = 95%) OUR LIMIT					
none 3.0–19.3	95	[1,2] AKRAWY	90c	OPAL	$Z \to H^0 + (e^- e^-, \mu^+\mu^-, \nu\bar{\nu})$
> 0.026	90	[3] ATIYA	90	CNTR	$K^{\pm} \to \pi^{\pm} H^0$
none 0.012–0.211	90	[4] BARR	90	CNTR	$K_L^0 \to \pi^0 H^0$ $(H^0 \to e^+e^-)$
> 0.32		[5] DAWSON	90	RVUE	K decays

none 0.032–15	95	[2,6] DECAMP	90	ALEP	$Z \to H^0 + (e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu\overline{\nu}, q\overline{q})$
none 11–24	95	[7] DECAMP	90H	ALEP	$Z \to H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$
none 0.0012–0.052	90	DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ $(H^0 \to e^+e^-)$
none 0.010–0.10	90	[8] EGLI	89	CNTR	$\pi^+ \to e^+ \nu H^0$ $(H^0 \to e^+e^-)$
> 0.010	68	[9] BELTRAMI	86	SPEC	Muonic atoms
none 0.003–0.012	95	[10] FREEDMAN	84	CNTR	$\mathrm{He}^* \to \mathrm{He} H^0$ $(H^0 \to e^+e^-)$
none 0.00103–0.00584		[11] MUKHOPAD...	84	RVUE	$\mathrm{O}^* \to \mathrm{O} H^0$ $(H^0 \to e^+e^-)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

none 0.21–3.57		[12] DAWSON	90	RVUE	$B \to \mu^+\mu^- X$; $B \to K(\mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
> 0.3		[13] LEUTWYLER	90	RVUE	$K^+ \to \pi^+ H^0$
none 0.21–1.0	90	[14] ALAM	89B	CLEO	$B \to H^0 K, (H^0 \to \mu^+\mu^-, \pi^+\pi^-)$
none 1.0–3.6	90	[14] ALAM	89B	CLEO	$B \to H^0 X$ $(H^0 \to \mu^+\mu^-)$
none 0.29–0.57	90	[15] ALBRECHT	89	ARG	$\Upsilon(1S) \to H^0 \gamma$ $(H^0 \to \pi^+\pi^-)$
none 0.22–0.32		[16] ATIYA	89	CNTR	$K^+ \to \pi^+ H^0$ $(H^0 \to \mu^+\mu^-)$
> 0.28		[17] CHENG	89	RVUE	$K^\pm \to \pi^\pm H$
none 3.6–4.6		[18] EILAM	89	RVUE	$B \to H^0 X,$ $(H^0 \to \mu^+\mu^-)$
> 0.018		[19] GRIFOLS	89	RVUE	$\sigma_{\mathrm{tot}}(n\mathrm{Pb})$
		[20] LINDNER	89	THEO	Vacuum stability
none 0.211–0.700		[21] RABY	89	RVUE	$B \to \mu^+\mu^- X$ $m(\mathrm{top}) > 80$ GeV
none 0.07–0.21	90	[22] SNYDER	89	MRK2	$B \to H^0 X$ $(H^0 \to e^+e^-)$
none 0.015–0.04	90	[23] YEPES	89	RVUE	$\pi^\pm \to e^\pm \nu H^0$ $(H^0 \to e^+e^-)$
none 0.03–0.20		[24] YEPES	89B	RVUE	$pN \to H^0 X$ $(H^0 \to e^+e^-)$
> 0.36		[25] CHIVUKULA	88	RVUE	$K \to \pi^+ H^0$
none 0.00103–3.57		[21] CHIVUKULA	88	RVUE	$B \to H^0 X,$ $m(\mathrm{top}) > 80$ GeV
none 2–3.7		[21] GRINSTEIN	88	RVUE	$B \to H^0 X,$ $m(\mathrm{top}) > 80$ GeV
none 0.21–5	90	[26] LEE-FRANZINI	88	CUSB	$\Upsilon(1S,3S) \to \gamma H^0$
	90	[27] BAKER	87	CALO	$K^\pm \to \pi^\pm H^0$ $(H^0 \to e^+e^-)$
		[28] DRUZHININ	87	ND	$\phi \to \gamma H^0$ $(H^0 \to \pi^0\pi^0)$
none 0.05–0.211		[29] WILLEY	86	RVUE	$K^\pm \to \pi^\pm H^0$ $(H^0 \to e^+e^-)$
		[30] HOFFMAN	83	CNTR	$\pi p \to n H^0$ $(H^0 \to e^+e^-)$
		[31] DZHELYADIN	81		$\eta' \to \eta H^0$ $(H^0 \to \mu^+\mu^-)$
		[32] WITTEN	81	COSM	
		[32] GUTH	80	COSM	
		[32] SHER	80	COSM	
> 0.006		[33] BARBIERI	75	RVUE	$nN \to nN$

[1] AKRAWY 90C based on 825 nb^{-1}. The decay $Z \to H^0 \nu\overline{\nu}$ with $H^0 \to \tau\overline{\tau}$ or $q\overline{q}$ provides the most powerful search means, but the quoted results sum all channels.

[2] These limits do not apply to pseudoscalar Higgs bosons (supersymmetric models, for example, have a pseudoscalar boson in addition to scalars).

[3] ATIYA 90 sets limits on $\mathrm{B}(K^\pm \to \pi^\pm H^0)$ varying from $< 6.4 \times 10^{-9}$ for $m(H^0) \approx 0$ MeV to $< 10^{-6}$ for $m(H^0) = 26$ MeV.

[4] BARR 90 set $m(H^0)$-dependent limits on $\mathrm{B}(K_L^0 \to \pi^0 H^0)$ in the region where $\mathrm{B}(H^0 \to e^+e^-) \approx 1$. The limit varies from $\mathrm{B}(K_L^0 \to \pi^0 H^0) < 10^{-7}$ at $m(H^0) = 12$ MeV to $< 2 \times 10^{-8}$ for $50 \leq m(H^0) \leq 211$ MeV. BARR 90 allow for nonzero H^0 lifetime.

[5] Based on ASANO 81B, YAMAZAKI 84, BAKER 87, ATIYA 89, and BARR 90. DAWSON 90 used theoretical calculations and various assumptions such as $m(t) > 80$ GeV and Im $V_{td}^* V_{ts} > 0.2 \sin^5\theta_C$.

[6] DECAMP 90 limits based on 11,550 Z events. The decay $Z \to H^0 \nu\overline{\nu}$ provides the most powerful search means, but the quoted results sum all channels. Different analysis methods are used for $m(H^0) < 2m(\mu)$ where Higgs would be long-lived. The 99% confidence limits exclude $m(H^0) = 0.040$–12 GeV.

[7] DECAMP 90H limits based on 25,000 $Z \to$ hadron events.

[8] EGLI 89 give a limit for $\mathrm{B}(\pi^+ \to e^+ \nu H^0) \cdot \mathrm{B}(H^0 \to e^+e^-)$ ranging from 10^{-9} to 10^{-11} for the mass range 10–110 MeV. The theoretical prediction they use is too large by a factor of 162/49 (see DAWSON 89, DAWSON 90, and CHENG 89). The lower limit given above is reevaluated by us.

[9] BELTRAMI 86 measured the wavelengths of the $3d_{5/2}-2p_{3/2}$ X-ray transitions in muonic ^{24}Mg and ^{28}Si and found the deviation from QED $\delta\lambda/\lambda = (-0.2 \pm 3.1) \times 10^{-6}$. The listed limit uses $\eta_{HNN} = 0.23$. The experiment excludes $m(H^0) \lesssim 1$ MeV by more than 3 s.d.

[10] FREEDMAN 84 is ANL experiment with dynamitron proton bombarding tritium to form He*. $\eta_{HNN} = 0.30$ is used to derive the limit . They also reanalyze KOHLER 74 He* data to find no mass region is excluded by that data. See also footnote for MUKHOPADHYAY 84 below.

[11] MUKHOPADHYAY 84 examine KOHLER 74 He* and C* data. Claim that no mass region can be excluded by 74 He* data since He* decay width to proton is large $\left[\mathrm{B}(\mathrm{He}^* \to H^0 \mathrm{He}) = 3.4 \times 10^{-11}\right.$ is very small$\left.\right]$. Above limit is from KOHLER 74 O* decay data.

[12] Based on ALTHOFF 84G, ALAM 89B, and ALBRECHT 87D. Some processes considered require the assumption $\mathrm{B}(B \to H^0 K)/\mathrm{B}(B \to H^0 X) > 0.01$. Other processes require theoretical assumptions regarding $\mathrm{B}(H \to \pi^+\pi^-)$ when considering masses in the interval 0.9–1.2 GeV.

[13] LEUTWYLER 90 give a consistent analysis of the $K \to \pi H^0$ amplitude based on chiral theory and find that all contributions except the t-quark loop are unimportant numerically provided the t-quark mass is of order or bigger than 100 GeV. Hence, a light Higgs can probably be ruled out.

[14] ALAM 89B searched for inclusive and exclusive decays of B mesons into H^0 and can exclude the mass range $2m(\mu)$–$2m(\tau)$ with a wide margin provided $m(t) \gtrsim m(W)$, possibly except for masses near $\chi_0(3410)$, where the mixing effect can reduce $\mathrm{B}(H^0 \to \mu^+\mu^-)$ significantly.

[15] ALBRECHT 89 give a limit $\mathrm{B}(\Upsilon(1S) \to H^0\gamma) \cdot \mathrm{B}(H^0 \to \pi^+\pi^-) < 3$–$4.5 \times 10^{-5}$ for $m(H^0) = 290$–570 MeV, which is lower than the predition including first order QCD corrections and assuming $\mathrm{B}(H^0 \to \pi^+\pi^-) > 45\%$.

[16] ATIYA 89 give a limit $\mathrm{B}(K^+ \to \pi^+ H^0) \cdot \mathrm{B}(H^0 \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ (90% CL) for $m(H^0) = 220$–320 MeV, which is lower than the prediction unless there is an accidental cancellation in the CP-conserving part of the amplitude and the CP-violating part is unexpectedly small. See WILLEY 89 and CHENG 89.

[17] CHENG 89 concludes even if real part of $K^+ \to \pi^+ H$ amplitude is cancelled accidentally, the imaginary contribution alone rules out $m(H) < 2m(\pi)$.

[18] EILAM 89 assume $m(\mathrm{top}) > 90$ GeV and vary $|V_{ub}/V_{cb}|^2$ from 0 to 0.026.

[19] GRIFOLS 89 use the neutron-lead total cross-section measurement at kinetic energies of 50 eV – 50 keV by SCHMIEDMAYER 88 and argue that the agreement of the measured energy dependence with the prediction of a hard-core potential model is lost by light-Higgs exchange. The limit of 18 MeV is obtained for $\eta_{HNN} = 0.56$ and is reduced to 12 MeV for $\eta_{HNN} = 0.22$.

[20] LINDNER 89 require vacuum stability and numerically solve the renormalization equations to two-loop order. If $m(\mathrm{top}) = 100, 110, 120$ GeV, then $m(\mathrm{Higgs}) > 20, 34, 50$ GeV. However, it is possible that the vacuum is not stable but is very long-lived.

[21] Limits assume $m(\mathrm{top}) > 80$ GeV and $|V_{ts} V_{tb}^* / V_{cb}| \approx 1$. CHIVUKULA 88 excludes $m(H^0)$ between $2m(e)$ and $2m(\tau)$ from the limits on $B \to \mu^+\mu^- + X$ by taking the $\mathrm{B}(H^0 \to \mu^+\mu^-)$ estimate of VOLOSHIN 86. GRINSTEIN 88 argues that this estimate of VOLOSHIN 86 is unreliable, and excludes $m(H^0)$ between 2 GeV and 3.7 GeV where perturbative QCD is used to estimate $\mathrm{B}(H^0 \to \mu^+\mu^-)$.

[22] SNYDER 89 exclude the mass range 70–210 MeV with a wide margin provided that $m(t) \gtrsim m(W)$. A limit $\mathrm{B}(B \to H^0 X) \cdot \mathrm{B}(H^0 \to e^+e^-) < 22\%$ (90% CL) is given for $m(H^0) = 50$ MeV.

[23] YEPES 89 reanalyzed a BNL beam-dump experiment (JACQUES 80) which looked for electron pairs in 7 foot BC downstream from the dump and found none.

[24] YEPES 89B reanalyzed a Fermilab neutral-hyperon beam experiment (BECHIS 78), which looked for a long-lived neutral lepton and found none, and argues that their limit is many orders of magnitude lower than expected from low-mass Higgs bremsstrahlung production followed by the decay to e^+e^-.

[25] CHIVUKULA 88 uses chiral perturbation theory to estimate $K \to \pi^+ H^0$ amplitudes with a conservative sign assignment for the relative sign of the $\Delta I = 1/2$ term, and exclude $m(H^0)$ below 0.36 GeV barring cancellation among terms, by using the limits on $K \to \pi^+ X$ with $X = \mu^+\mu^-, e^+e^-$, or missing particles. For a criticism see DAWSON 90.

[26] LEE-FRANZINI 88 presents updated results from the CUSB experiment (see FRANZINI 87 for more details). First order QCD correction included with $\alpha_S \sim 0.2$ ($\Lambda = 0.2$ GeV and $n(f) = 4$). The order α_S correction reduced the rate for $\Upsilon(1S) \to H^0\gamma$ by a factor of 2 (yielding these limits). The impact of order α_S^2 and of relativistic corrections are unknown. If they amounted to another factor of 2 suppression, the above limit would be essentially eliminated.

[27] BAKER 87 sets limit $\mathrm{B}(K^\pm \to \pi^\pm H^0)\mathrm{B}(H^0 \to e^+e^-) < 8 \times 10^{-7}$ at CL=90% for $m(H^0) < 100$ MeV if H^0 travels much less than 1.4 cm in the lab frame ($p(K^+) = 5.8$ GeV). The expected lifetime of the standard H^0 is too long to be effectively detected by the experiment and their limit on the branching ratio is significantly weakened accordingly. In view of the uncertainty in the theoretical prediction for $\mathrm{B}(K \to \pi H)$, no definite conclusion can be drawn from the result. See also DAWSON 90.

[28] DRUZHININ 87 sets limit $\mathrm{B}(\phi \to \gamma H^0)\mathrm{B}(H^0 \to \pi^0\pi^0) < 8 \times 10^{-5}$ at CL=90% for $m(H^0) = 0.6$–1 GeV which is still far from the standard Higgs model prediction and does not exclude the existence of light Higgs bosons.

[29] WILLEY 86 re-examined the theoretical estimate of the decay $K^\pm \to \pi^\pm H^0$ rate via the one-loop $s d H^0$ coupling. The experimental bound $\mathrm{B}(K \to \pi\mu\mu) < 2.4 \times 10^{-6}$ is not strong enough to rule out $2m(\mu) < m(H^0) < 2m(\pi^0)$. For a criticism see DAWSON 90.

[30] HOFFMAN 83 looked for e^+e^- peak from Higgs produced in $\pi^- p \to H^0 n$ at 300 MeV/c. Set CL = 90% limit $d\sigma/dt\,\mathrm{B}(e^+e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for $140 < m(H^0) < 160$ MeV, which does not exclude H^0 with the standard one-doublet-model couplings.

[31] DZHELYADIN 81 obtained $\mathrm{B}(\eta' \to \eta\mu^+\mu^-) < 1.5 \times 10^{-5}$ (CL = 90%), and argued that it excludes H^0 with the standard one-doublet-model couplings in $\mu^+\mu^-$ channel for $m(H^0) = 0.25$–0.409 GeV. However, the number 0.409 is not well-determined due to theoretical uncertainties in $\mathrm{B}(H^0 \to \mu^+\mu^-)$.

[32] Limits from cosmological considerations of $SU(2) \times U(1)$ symmetry-breaking phase transition occurring only after extreme supercooling, resulting in too high a ratio of entropy to baryon number. Limits apply to the standard one-doublet model H^0, with 'zero bare mass' whose physical mass is determined by the Coleman-Weinberg mechanism of dynamical symmetry breakdown. These limits depend on the mass of the top quark approximately according to $m(H^0) > 10.4[1 - 4m(t)^4/(2m_W^4 + m_Z^4)]^{1/2}$ GeV when $m(t) < 80$ GeV. So for $m(t) \approx 80$ GeV, there is no limit. If $m(t) > 80$ GeV, then vacuum stability arguments may give bounds on $m(H)$, see LINDNER 89 above.

[33] BARBIERI 75 studied Higgs boson exchange effect in neutron-lead scattering data of ALEKSANDROV 66 and found limit $(g^2_{H^0 nn}/4\pi)\,(m(H^0)/\mathrm{MeV})^{-4} \lesssim 3.4 \times 10^{-11}$ for $m(H^0) \gtrsim 1$ MeV. This gives the listed limit for $\eta_{HNN} = 0.2$ and 10 MeV for $\eta_{HNN} = 0.56$. Lighter mass region $m(H^0) \lesssim 1$ MeV would be incompatible with the measured angular distribution.

H^0 (Higgs Boson) MASS LIMIT in Extended Higgs Models

The parameter x denotes the Higgs coupling to charge $-1/3$ quarks and charged leptons relative to the value in the standard one-Higgs-doublet model.

In order to prevent flavor-changing neutral currents in models with more than one Higgs doublet, only one of the Higgs doublets can couple to quarks of charge 2/3. The same requirement applies independently to charge $-1/3$ quarks and to leptons. Higgs couplings can be enhanced or suppressed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[34] DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ $(H^0 \to e^+ e^-)$
		[35] SNYDER	89	MRK2	$B \to H^0 X$ $(H^0 \to e^+ e^-)$
none 0.6–6.2	90	[36] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, $x=2$
none 0.6–7.9	90	[36] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, $x=4$
none 3.7–5.6	90	[37] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, $x=2$
none 3.7–8.2	90	[37] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, $x=4$

[34] DAVIER 89 give excluded region in $m(H^0)$-x plane for $m(H^0)$ ranging from 1.2 MeV to 50 MeV.

[35] SNYDER 89 give limits on $B(B \to H^0 X) \cdot B(H^0 \to e^+ e^-)$ for $100 < m(H^0) < 200$ MeV, $c\tau < 24$ mm.

[36] First order QCD correction included with $\alpha_S \approx 0.2$. Their figure 4 shows the limits vs. x.

[37] ALBRECHT 85J found no mono-energetic photons in both $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays in the range 0.5 GeV $< E(\gamma) < 4.0$ GeV with typically BR<0.01 for $\Upsilon(1S)$ and BR< 0.02 for $\Upsilon(2S)$ at 90% CL. These upper limits are 5–10 times the prediction of the standard Higgs-doublet model. The quoted 90% limit $B(\Upsilon(1S) \to H^0 \gamma) < 1.5 \times 10^{-3}$ at $E(\gamma) = 1.07$ GeV contradicts previous Crystal Ball observation of $(4.7 \pm 1.1) \times 10^{-3}$; see their reference 3. Their figure 8a shows the upper limits of x^2 as a function of $E(\gamma)$ by assuming no QCD corrections. We used $m(H^0) = m(\Upsilon)\,(1-2E(\gamma)/m(\Upsilon))^{1/2}$.

H_1^0 (Higgs Boson) MASS LIMIT in Supersymmetric Models

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars (H_1^0 and H_2^0), a pseudoscalar (P^0) and two charged Higgs (H^+ and H^-). Their masses are restrained by the model to be: $m(H_1^0) < m(Z)$, $m(H_2^0) > m(Z)$, $m(P^0) > m(H_1^0)$, and $m(H^\pm) > m(W)$. There are two free parameters in the theory which can be chosen to be $m(H_1^0)$ (the lightest Higgs scalar) and $\tan\beta = v_2/v_1$, the ratio of the vacuum expectation values of the two Higgs doublets.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
none 0.05–3.1	95	[38] DECAMP	90E	ALEP	any v_2/v_1
>37.1	95	[38] DECAMP	90E	ALEP	$v_2/v_1 > 6$
none 0.05–20	95	[39] DECAMP	90H	ALEP	$v_2/v_1 > 0.6$
none 0.006–21.4	95	[39] DECAMP	90H	ALEP	$v_2/v_1 > 2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 0.05–13	95	[38] DECAMP	90E	ALEP	$v_2/v_1 > 0.6$
none 0.006–20	95	[38] DECAMP	90E	ALEP	$v_2/v_1 > 2$

[38] DECAMP 90E look for $Z \to H_1^0 P^0$ with 18610 Z^0 decays. Their search includes signatures in which H_1^0 and P^0 decay to $\gamma\gamma$, $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, or $q\bar{q}$. See their figures of $m(H_1^0)$ vs. v_2/v_1.

[39] DECAMP 90H is similar to DECAMP 90E but with 25,000 Z^0 decays.

MASS LIMIT for Associated Higgs Production in $e^+ e^-$ Interactions

In multi-Higgs models, associated production of Higgs via virtual or real Z^0 in $e^+ e^-$ annihilation, $e^+ e^- \to H_1^0 H_2^0$, is possible if H_1^0 and H_2^0 have opposite *CP* eigenvalues. Limits are for the mass of the heavier Higgs H_2^0 in two-doublet models.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45	95	[40] DECAMP	90H	ALEP	$m(H_1^0) < 20$ GeV
>37.5	95	[40] DECAMP	90H	ALEP	$m(H_1^0) < m(H_2^0)$
> 8	90	[41] KOMAMIYA	89	MRK2	$H_1^0 \to \mu^+ \mu^-$, $H_2^0 \to q\bar{q}, \tau^+\tau^-$
>28	95	[42] LOW	89	AMY	$m(H_1^0) \lesssim 20$ MeV, $H_2^0 \to q\bar{q}$
none 2–9	90	[43] AKERLOF	85	HRS	$m(H_1^0) = 0$, $H_2^0 \to f\bar{f}$
none 4–10	90	[44] ASH	85C	MAC	$m(H_1^0) = 0.2$ GeV, $H_2^0 \to \tau^+\tau^-, c\bar{c}$
none 1.3–24.7	95	[43] BARTEL	85L	JADE	$m(H_1^0) = 0.2$ GeV, $H_2^0 \to f\bar{f}$ or $f\bar{f}H_1^0$
none 1.2–13.6	95	[43] BEHREND	85	CELL	$m(H_1^0) = 0$, $H_2^0 \to f\bar{f}$
none 1–11	90	[43] FELDMAN	85	MRK2	$m(H_1^0) = 0$, $H_2^0 \to f\bar{f}$
none 1–9	90	[43] FELDMAN	85	MRK2	$m(H_1^0) = m(H_2^0)$, $H_2^0 \to f\bar{f}$

[40] DECAMP 90H search for $Z^0 \to H_1^0 e^+ e^-$, $H_1^0 \mu^+ \mu^-$, $H_1^0 \tau^+ \tau^-$, $H_1 q\bar{q}$, low multiplicity final states, τ-τ-jet-jet final states and 4-jet final states.

[41] KOMAMIYA 89 assume $B(H_1^0 \to \mu^+ \mu^-) = 100$ %, $2m(\mu) < m(H_1^0) < m(\tau)$. The limit is for maximal mixing. A limit of $m(H_2^0) > 18$ GeV for the case $H_2^0 \to H_1^0 H_1^0$ $(H_1^0 \to \mu^+ \mu^-)$ is also given. From PEP at $\sqrt{s} = 29$ GeV.

[42] LOW 89 assume that H_1^0 escapes the detector. The limit is for maximal mixing. A reduced limit of 24 GeV is obtained for the case $H_2^0 \to H_1^0 f\bar{f}$. Limits for a Higgs-triplet model are also discussed. $E_{cm}^{ee} = 50$–60.8 GeV.

[43] The limit assumes maximal mixing and that H_1^0 escapes the detector.

[44] ASH 85 assumes that H_1^0 escapes undetected. The bound applies up to a mixing suppression factor of 5.

$H^\pm$ (Charged Higgs or Techni-pion) MASS LIMIT

Most of the following limits assume $B(H^+ \to \tau^+ \nu) + B(H^+ \to c\bar{s}) = 1$. DECAMP 90I, BEHREND 87, and BARTEL 86 assume $B(H^+ \to \tau^+ \nu) + B(H^+ \to c\bar{s}) + B(H^+ \to c\bar{b}) = 1$. For a discussion of techni-particles, see EICHTEN 86.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>35	95	[45] DECAMP	90I	ALEP	$B(\tau\nu) = 0$–1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>19	95	[45] BEHREND	87	CELL	$B(\tau\nu) = 0$–1
>18	95	[46] BARTEL	86	JADE	$B(\tau\nu)=0.1$–1.0
>17	95	[46] ADEVA	85	MRKJ	$BR(\tau\nu)=0.25$–1.0
none 5–13	95	[47] ALTHOFF	83B	TASS	$BR(\tau\nu)=0.$–0.26
$>m(B)$		[48] CHEN	83	RVUE	B decay at $\Upsilon(4S)$
none 5–13	95	[46] ADEVA	82B	MRKJ	$BR(\tau\nu)=0.25$
none 3–13	95	[46] BARTEL	82D	JADE	$BR(\tau\nu)=0.2$–1.0
none 7–14.9	95	[49] BEHREND	82B	CELL	$BR(\tau\nu)=0.80$
none 4–9	90	[46] BLOCKER	82	MRK2	$BR(\tau\nu)=0.10$–0.90

[45] Studied $H^+ H^- \to (\tau\nu) + (\tau\nu)$, $H^+ H^- \to (\tau\nu)$ + hadrons, $H^+ H^- \to$ hadrons. If $B(H^+ \to \tau^+ \nu) = 100\%$, the DECAMP 90I limit improves to 43 GeV.

[46] Studied $H^+ H^- \to (\tau\nu) + (\tau\nu)$, $H^+ H^- \to (\tau\nu)$ + hadrons. Search for muon opposite hadronic shower.

[47] ALTHOFF 83 analyzed $H^+ H^- \to$ 4-jets. The same limit is obtained for $B(\nu\tau) = 0$–1.0 if $B(H^+ \to c\bar{b})/B(H^+ \to c\bar{s}) = 1$. See their figure 3.

[48] CHEN 83 excluded a model where $b \to H^-$ light-quark at BR = 1. Observed $B(b \to e X)$ would require $B(H^+ \to \tau X) = 1$ but then charged energy fraction would be smaller than experiment value (0.60 ± 0.03). (CLEO data)

[49] BEHREND 82B studied $H^+ H^- \to (\tau\nu) + (\tau\nu)$. See their figure 3.

Searches for $X(2200)$ (A Neutral Higgs Candidate)

Limits are for branching ratios or products of branching ratios. The notation ξ below refers to $X(2200)$.

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29	90	[50] ALBRECHT	89	ARG	$\Upsilon(1S) \to K^+ K^-$ mode
< 0.68	90	[50] ALBRECHT	89	ARG	$\Upsilon(2S) \to K^+ K^-$ mode
< 2	90	[51] BARU	89	MD1	$\Upsilon(1S) \to K^+ K^-$ mode
<30	90	[51] BARU	89	MD1	$\Upsilon(1S) \to \phi\phi$ mode
< 0.31	90	[52] BEAN	86	CLEO	$\Upsilon(1S) \to K^+ K^-$ mode
< 2	90	[53] BEHRENDS	84	CLEO	$\Upsilon(1S) \to K^+ K^-$ mode
< 0.9	90	[53] BEHRENDS	84	CLEO	$\Upsilon(2S) \to K^+ K^-$ mode
<30	90	[53] BEHRENDS	84	CLEO	B meson, $K^+ K^-$ mode
<4–12	90	[54] YOUSSEF	84	CUSB	$\Upsilon(1,2S)$ 2-charged
<5–15	90	[54] YOUSSEF	84	CUSB	$\Upsilon(1S) \to \gamma X$

[50] ALBRECHT 89 give limits for $B(\Upsilon(1S, 2S) \to H^0 \gamma) \cdot B(H^0 \to \pi^+ \pi^-, K^+ K^-, p\bar{p})$ for the mass range 1–3.5 GeV.

[51] BARU 89 limits are for $B(\Upsilon(1S) \to \gamma\xi) \cdot B(\xi \to K^+ K^-, \phi\phi)$. Spin zero is assumed for ξ.

[52] BEAN 86 looked for cascade decays $\Upsilon(1S) \to \gamma H^0$ $(H^0 \to h^+ h^-)$ for the 3 modes, $\pi^+ \pi^-$, $K^+ K^-$, and $p\bar{p}$. See their figure 4 for limits on branching fractions as function of $m(H^0)$ in the range $2m(h) < m(H^0) < 8$ GeV.

[53] BEHRENDS 84 first and second limits are for $B(\Upsilon \to \gamma\xi)B(\xi \to K^+ K^-)$, the third is for $B(B \to \xi X)B(\xi \to K^+ K^-)$. All for $m(\xi) = 2.2$ GeV, but are similar for 1.5–4 GeV(first,second) and for 2–3 GeV(third).

[54] YOUSSEF 84 first limit is for inclusive radiative decay, the second is for $B(\Upsilon \to \xi\gamma)B(\xi \to 2$ charged). For $m(\xi) = 1$–7 GeV.

REFERENCES FOR H^0 and $H^\pm$

AKRAWY	90C	PL B236 224	+Alexander, Allison, Allport+	(OPAL Collab.)
ATIYA	90	PRL 64 21	+Chiang, Frank, Haggerty+	(BNL, LANL, PRIN, TRIU)
BARR	90	PL B235 356	+Clark+	(CERN, EDIN, MANZ, LALO, PISA, SIEG)
DAWSON	90	PR D41 (to be pub.)	+Gunion, Haber	(BNL, UCD, UCSC)
DECAMP	90	PL B236 233	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90E	PL B237 291	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90H	PL B (CERN-EP/90-16)	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
DECAMP	90I	PL B (to be pub.)	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
LEUTWYLER	90	NP B	+Shifman	(BERN, ITEP)
BUTP-89/29-BERN				
ALAM	89B	PR D40 712	+Katayama, Kim, Li, Lou, Sun+	(CLEO Collab.)
Also	89C	PR D40 3790 erratum	Alam, Katayama, Kim, Li, Lou, Sun+	(CLEO Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ATIYA	89	PRL 63 2177	+Chiang, Frank, Haggerty+	(BNL, LANL, PRIN, TRIU)
BARU	89	ZPHY C42 505	+Beilin, Blinov+	(NOVO)
CHENG	89	PR D40 2980	+Yu	(AST)
DAVIER	89	PL B229 150	+Nguyen Ngoc	(LALO)
DAWSON	89	PL B222 143		(BNL)
EGLI	89	PL B222 533	+Engfer, Grab, Hermes, Kraus+	(SINDRUM Collab.)
EILAM	89	PL B231 184	+Nakada, Wyler	(PSI, ZURI)
GRIFOLS	89	PRL 63 1346	+Masso, Peris	(BARC)
KOMAMIYA	89	PR D40 721	+Fordham, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
LINDNER	89	PL B228 139	+Sher, Zaglauer	(FNAL, WUSL)
LOW	89	PL B228 548	+Xu, Abashian, Gotow, Hu, Mattson+	(AMY Collab.)

RABY	89	PR D39 828	+West, Hoffman	(LANL)
SNYDER	89	PL B229 169	+Murray, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
WILLEY	89	PR D39 2784		(PITT)
YEPES	89	PL B227 182		(MCGI)
YEPES	89B	PL B229 156		(MCGI)
CHIVUKULA	88	PL B207 86	+Manohar	(BOST, MIT)
Also	89	PL B217 568 (erratum)	Chivukula, Manohar	(BOST, MIT)
GRINSTEIN	88	PL B211 363	+Hall, Randall	(LBL, UCB)
LEE-FRANZINI	88	Munich HEP Conf. p. 1432		(CUSB Collab.)
SCHMIEDM...	88	PRL 61 1065	Schmiedmayer, Rauch, Riehs	(TUW)
Also	88B	PRL 61 2509 erratum	Schmiedmayer, Rauch, Riehs	(TUW)
ALBRECHT	87D	PL B199 451	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
BAKER	87	PRL 59 2832	+Gordon, Lazarus+	(BNL, SIN, WASH, YALE)
Also	88	PRL 60 472 erratum	Baker, Gordon+	(BNL, SIN, WASH, YALE)
BEHREND	87	PL B193 376	+Buerger, Criegee, Dainton+	(CELLO Collab.)
DRUZHININ	87	ZPHY C37 1	+Dubrovin, Eidelman, Golubev+	(NOVO)
FRANZINI	87	PR D35 2883	+Son, Tuts, Youssef, Zhao+	(CUSB Collab.)
BARTEL	86	ZPHY C31 359	+Becker, Felst, Haidt+	(JADE Collab.)
BEAN	86	PR D34 905	+Bobbink, Brock, Engler+	(CLEO Collab.)
BELTRAMI	86	NP A451 679	+Aas, Beer, Dechambrier, Goudsmit+	(ETH, FRIB)
EICHTEN	86	PR D34 1547	+Hinchliffe, Lane, Quigg+	(FNAL, LBL, OSU)
VOLOSHIN	86	SJNP 43 495 Translated from YAF 43 779.	+Okun	(ITEP)
WILLEY	86	PL B173 480		(PITT)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
AKERLOF	85	PL 156B 271	+Bonvicini, Chapman, Errede+	(HRS Collab.)
ALBRECHT	85J	ZPHY C29 167	+Binder, Harder+	(ARGUS Collab.)
ASH	85	PRL 55 1831	+Band, Blume, Camporesi+	(MAC Collab.)
ASH	85C	PRL 54 2477	+Band, Blume, Camporesi+	(MAC Collab.)
BARTEL	85L	PL 155B 288	+Becker, Cords, Felst, Hagiwara+	(JADE Collab.)
BEHREND	85	PL 161B 182	+Burger, Criegee, Fenner+	(CELLO Collab.)
FELDMAN	85	PRL 54 2289	+Abrams, Amidei, Baden+	(Mark II Collab.)
ALTHOFF	84G	ZPHY C22 219	+Braunschweig, Kirschfink+	(TASSO Collab.)
BEHRENDS	84	PL 137B 277	+Chadwich, Chauveau, Gentile+	(CLEO Collab.)
FREEDMAN	84	PRL 52 240	+Napolitano, Camp, Kroupa	(ANL, CHIC)
MUKHOPAD...	84	PR D29 565	Mukhopadhyay, Goudsmit+	(RPI, SIN, LISB)
YAMAZAKI	84	PRL 52 1089	+Ishikawa, Taniguchi, Yamanaka+	(TOKY, KEK)
YOUSSEF	84	PL 139B 332	+Franzini, Son, Tuts+	(CUSB Collab.)
ALTHOFF	83	PL 121B 216	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)
ALTHOFF	83B	PL 122B 95	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)
CHEN	83	PL 122B 317	+Goldberg, Alam, Andrews+	(CLEO Collab.)
HOFFMAN	83	PR D28 660	+Frank, Mischke, Moir, Schardt	(LANL, ARZS)
ADEVA	82B	PL 115B 345	+Barber, Becker, Berdugo+	(Mark-J Collab.)
BARTEL	82D	PL 114B 211	+Cords, Elsen, Bethke+	(JADE Collab.)
BEHREND	82B	PL 114B 287	+Chen, Fenner, Field+	(CELLO Collab.)
BLOCKER	82	PRL 49 517	+Matteuzzi, Abrams, Amidei+	(Mark II Collab.)
ASANO	81B	PL 107B 159	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, OSAK)
DZHELYADIN	81	PL 105B 239	+Golovkin, Konstantinov, Kubarovski+	(SERP)
WITTEN	81	NP B177 477		(HARV)
GUTH	80	PRL 45 1131	+Weinberg	(SLAC)
JACQUES	80	PR D21 1206	+Kalelkar, Miller, Plano+	(RUTG, STEV, COLU)
SHER	80	PR D22 2989		(UCSC)
Also	83	ANP 148 95	Flores, Sher	(UCSC, UCI)
BECHIS	78	PRL 40 602	+Chang, Dombeck, Ellsworth, Glasser, Lau+	(UMD)
BARBIERI	75	PL 57B 270	+Ericson	(CERN)
KOHLER	74	PRL 33 1628	+Watson, Becker	(LOCK)
ALEKSANDROV	66	JETPL 4 134 Translated from ZETF 4 196.	+Samosvat, Sereeter, Tsoi	(JINR)

Searches for Heavy Bosons Other Than Higgs Bosons

We list here various limits on charged and neutral heavy vector bosons (other than W's and Z's), heavy scalar bosons (other than Higgs bosons), vector or scalar leptoquarks, and axigluons.

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 406	90	[1] JODIDIO	86	ELEC	Any L-R mixing angle
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 160	90	[2] BALKE	88	CNTR	$\mu \rightarrow e\nu\overline{\nu}$
> 482	90	[1] JODIDIO	86	ELEC	L-R mix angle =0
> 800		MOHAPATRA	86	RVUE	$SU(2)_L\times SU(2)_R\times U(1)$
> 400	95	[3] STOKER	85	ELEC	Any L-R mix ang.
> 475	95	[3] STOKER	85	ELEC	L-R mix ang <0.041
		[4] BERGSMA	83	CHRM	$\nu_\mu e \rightarrow \mu\nu e$
> 380	90	[5] CARR	83	ELEC	μ^+ decay
>1600		[6] BEALL	82	THEO	K^0_L–K^0_S mass difference

[1] JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point e^+ spectrum in the decay of the highly polarized μ^+. Alternative results can be obtained by fixing $m(W_R)$ and obtaining limits on the L-R mixing angle ζ: If $m(W_R) = \infty$, then $|\zeta| < 0.040$ whereas for unconstrained $m(W_R)$, $-0.056 < \zeta < 0.040$.

[2] BALKE 88 limit is for $m(\nu_{eR}) = 0$ and $m(\nu_{\mu R}) \leq 50$ MeV. Limits come from precise measurements of the muon decay asymmetry as a function of the positron energy.

[3] STOKER 85 is same TRIUMF experiment as CARR 83. Here they measure the decay e^+ spectrum asymmetry above 46 MeV/c using a muon-spin-rotation technique. Assumed a light right-handed neutrino. Quoted limits are from combining with CARR 83.

[4] BERGSMA 83 set limit $m(W_2)/m(W_1) > 1.9$ at CL = 90%.

[5] CARR 83 is TRIUMF experiment with a highly polarized μ^+ beam. Looked for deviation from V−A at the high momentum end of the decay e^+ energy spectrum. Limit from previous world-average muon polarization parameter is $m(W_R) > 240$ GeV. Assumes a light right-handed neutrino.

[6] BEALL 82 limit is obtained assuming that W_R contribution to K^0_L–K^0_S mass difference is smaller than the standard one, neglecting the top quark contributions.

MASS LIMITS for W' (A Heavy Charged Vector Boson Other Than W) in Hadron Collider Experiments

Limits are obtained when the W' couplings to quarks $g_{W'q}$ and the leptonic branching ratio $B(W' \rightarrow e\overline{\nu})$ are the same as those of the standard W, where the leptonic cross section is proportional to $(g_{W'q})^2\ B(W' \rightarrow e\overline{\nu})$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>220	90	[7] ALBAJAR	89	UA1	$p\overline{p} \rightarrow W' X$, $W' \rightarrow e\nu$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>209	90	[8] ANSARI	87D	UA2	$p\overline{p} \rightarrow W' X$, $W' \rightarrow e\nu$
>210	90	[9] ARNISON	86B	UA1	$p\overline{p} \rightarrow W' X$, $W' \rightarrow e\nu$
>170	90	[10] ARNISON	83D	UA1	$p\overline{p} \rightarrow W' X$, $W' \rightarrow e\nu$

[7] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(W')\ B(e\nu) < 4.1$ pb (90% CL).

[8] See Fig. 5 of ANSARI 87D for the excluded region in the $m(W')$–$[(g_{W'q})^2\ B(W' \rightarrow e\overline{\nu})]$ plane. Note that the quantity $(g_{W'q})^2\ B(W' \rightarrow e\overline{\nu})$ is normalized to unity for the standard W couplings.

[9] ARNISON 86B find no excess at large p_T in 148 $W \rightarrow e\nu$ events. Set limit $\sigma \times B(e\nu)$ <10 pb at CL = 90% at E_{cm} = 546 and 630 GeV.

[10] ARNISON 83B find among 47 $W \rightarrow e\nu$ candidates no event with excess p_T. Also set $\sigma\times B(e\nu)$ <30 pb with CL = 90% at E_{cm} = 540 GeV.

MASS LIMITS for Z' (Heavy Neutral Vector Boson Other Than Z)

The mass bounds depend on the quantum number and the coupling strength of Z' and neutral currents. In particular, we use the following notation for Z' associated with specific U(1) currents:

$$Z_1;\ SM\times U(1)_{Z_1}$$
$$Z_{LR};\ SU(2)_L\times SU(2)_R\times U(1) \rightarrow SM\times U(1)_{LR}$$
$$Z_\chi;\ SO(10) \rightarrow SU(5)\times U(1)_\chi$$
$$Z_\psi;\ E_6 \rightarrow SO(10)\times U(1)_\psi$$
$$Z_\eta;\ E_6 \rightarrow SM\times U(1)_\eta$$

Here SM denotes either $SU(2)_L \times U(1)_Y$ or $SU(3)_C \times SU(2)_L\times U(1)_Y$, whichever is appropriate. Typical reference coupling strengths are $g_Y = e/\cos\theta_W$ and $g_Z = g_Y/\sin\theta_W$. In particular $g_{Z_1} = g_Z$ is always assumed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>129	90	[11] COSTA	88	RVUE	$Z_\eta;\ g_\eta = g_Y$
>352	90	[12] COSTA	88	RVUE	$Z_\chi;\ g_\chi = g_Y$
>343	90	[13] AMALDI	87	RVUE	$Z_{LR};\ g_L=g_R$
>151	90	[14] AMALDI	87	RVUE	$Z_\psi;\ g_\psi=g_Y$
>180	90	[15] ANSARI	87D	UA2	$p\overline{p} \rightarrow Z_1 X\ (Z_1 \rightarrow e^+e^-)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>100	90	[11,16] HAGIWARA	90	RVUE	$Z_\eta;\ g_\eta = g_Y$
none <150 or > 363	90	[12,16,17] HAGIWARA	90	RVUE	$Z_\chi;\ g_\chi = g_Y$
>136	90	[14,16] HAGIWARA	90	RVUE	$Z_\psi;\ g_\psi = g_Y$
>208	90	[16] HAGIWARA	90	RVUE	Z_1
>173	90	[18] ALBAJAR	89	UA1	$p\overline{p} \rightarrow Z_1 X$, $Z_1 \rightarrow e^+e^-$
>280	95	[19] DORENBOS...	89	CHRM	$Z_\chi;\ g_\chi = g_Z$
>180	90	[20] COSTA	88	RVUE	Z_β with $\tan\beta = \sqrt{15}$; $g_\beta = g_Y$
>156	90	[11,21] ELLIS	88	RVUE	$Z_\eta:\ g_\eta = g_Y$
>167	90	[11,22] ELLIS	88	RVUE	$Z_\eta:\ g_\eta = g_Y$
>112	90	[11] AMALDI	87	RVUE	$Z_\eta;\ g_\eta=g_Y$
>249	90	[12] AMALDI	87	RVUE	$Z_\chi;\ g_\chi=g_Y$
>160	90	[23] ARNISON	86B	UA1	$p\overline{p} \rightarrow Z_1 X\ (Z_1 \rightarrow e^+e^-)$
>143	90	[11,22] BARGER	86B	RVUE	$Z_\eta;\ g_\eta=g_Y$
>275	90	[13] DURKIN	86	RVUE	$Z_{LR};\ g_L=g_R$
>126	90	[11] DURKIN	86	RVUE	$Z_\eta;\ g_\eta=g_Y$
>222	90	[12] DURKIN	86	RVUE	$Z_\chi;\ g_\chi=g_Y$
>114	90	[14] DURKIN	86	RVUE	$Z_\psi;\ g_\psi=g_Y$
>150	95	[24] ADEVA	85	MRKJ	Z_1; Bhabha

[11] $g_\eta=g_Y$ assumed, which implies that $E_6 \rightarrow SM\times U(1)_\eta$ in one step. $U(1)_\eta$ is defined by $Q_\eta=(3/8)^{1/2}Q_\chi-(5/8)^{1/2}Q_\psi$. $\rho = 1$ assumed.

[12] $g_\chi=g_Y$ assumed, which implies that $SO(10) \rightarrow SM\times U(1)_\chi$ in one step. $\rho = 1$ assumed.

[13] Left-right symmetry ($g_L=g_R$) assumed.

[14] $g_\psi=g_Y$ assumed, which implies that $E_6 \rightarrow SM\times U(1)\times U(1)_\psi$ in one step. $\rho = 1$ assumed.

[15] See Fig. 5 of ANSARI 87D for the excluded region in the $m(Z_1)$–$[(g_{Z_1 q})^2\ B(Z_1 \rightarrow e^+e^-)]$ plane. Note that the quantity $(g_{Z_1 q})^2 B(Z_1 \rightarrow e^+e^-)$ is normalized to unity for the standard Z couplings.

[16] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[17] $m(Z_\chi) = \infty$ is excluded at 2.7 s.d.

[18] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(Z_1)\ B(ee) < 4.2$ pb (90% CL).

[19] DORENBOSCH 89 obtain the limit $(g_\chi/g_Z)^2\cdot(m(Z)/m(Z_\chi))^2 < 0.11$ at 95% CL from the processes $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ and $\nu_\mu e \rightarrow \nu_\mu e$.

[20] $Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta$. $g_\beta = g_Y$ and $\rho = 1$ assumed.

[21] Z_η mass limits obtained by combining constraints from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider and the global analysis of neutral current data by

COSTA 88. Least favorable spectrum of three (E_6 27) generations of particles and their superpartners are assumed. The limit weakens if fourth generation of particles contribute to the Z_η width.

[22] Z_η mass limits from non-observation of an excess of $\ell^+ \ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z_η decays only into light quarks and leptons. They weaken if other particles such as exotic particles of E_6 and supersymmetry contribute to Z_η width.

[23] ARNISON 86B find no excess $e^+ e^-$ pairs among 13 pairs from Z. Set limit $\sigma \times B(e^+ e^-)$ <13 pb at CL = 90% at E_{cm} = 546 and 630 GeV.

[24] ADEVA 85 measure asymmetry of μ-pair production, following formalism of RIZZO 81.

Constraint on Coefficient (c) of Additional Neutral Current

Term in $SU(2) \times U(1)_Y \times U(1)_G$ theory. The coefficent c depends on the group G.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	95	[25] BARTEL	86C	JADE	$e^+ e^- \to \mu^+ \mu^-$, $\tau^+ \tau^-$
<0.03	95	[25] BARTEL	86C	JADE	$e^+ e^- \to e^+ e^-$
<0.05	95	[26] DERRICK	86	HRS	$e^+ e^- \to e^+ e^-$
<0.035	95	[27] ADEVA	85	MRKJ	$e^+ e^- \to \mu^+ \mu^-$
<0.05	95	[28] BERGER	85B	PLUT	$e^+ e^- \to e^+ e^-$, $\mu^+ \mu^-$

[25] E_{cm}=12–46.78 GeV. $m(Z) = 93$ GeV and $\sin^2\theta_W = 0.217$ assumed.

[26] E_{cm}=29 GeV. $m(Z) = 93$ GeV and $\sin^2\theta_W = 0.217$ assumed.

[27] ADEVA 85 measure asymmetry of μ-pair production at E_{cm} = 14–46.8 GeV. See also Adeva et al., in Phys. Rep. **109**, 133 (1984) for more details.

[28] E_{cm}=34.7 GeV. $m(Z) = 93$ GeV and $\sin^2\theta_W = 0.217$ assumed.

MASS LIMITS for a Heavy Neutral Boson Coupling to $e^+ e^-$

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 55–61		[29] ODAKA	89	VNS	$\Gamma(X^0 \to e^+ e^-) \cdot B(X^0 \to \text{hadrons}) \gtrsim 0.2$ MeV
>45	95	[30] DERRICK	86	HRS	$\Gamma(X^0 \to e^+ e^-) = 6$ MeV
>46.6	95	[31] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+ e^-) = 10$ keV
>48	95	[31] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+ e^-) = 4$ MeV
none 39.8–45.5		[32] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+ e^-) = 10$ keV
>47.8	95	[32] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+ e^-) = 4$ MeV
none 39.8–45.2		[32] BEHREND	84C	CELL	
>47	95	[32] BEHREND	84C	CELL	$\Gamma(X^0 \to e^+ e^-) = 4$ MeV

[29] ODAKA 89 looked for a narrow or wide scalar resonance in $e^+ e^- \to$ hadrons at E_{cm} = 55.0–60.8 GeV.

[30] DERRICK 86 found no deviation from the Standard Model Bhabha scattering at E_{cm} = 29 GeV and set limits on the possible scalar boson $e^+ e^-$ coupling. See their figure 4 for excluded region in the $\Gamma(X^0 \to e^+ e^-)$-$m(X^0)$ plane. Electronic chiral invariance requires a parity doublet of X^0, in which case the limit applies for $\Gamma(X^0 \to e^+ e^-) = 3$ MeV.

[31] ADEVA 85 first limit is from 2γ, $\mu^+ \mu^-$, hadrons assuming X^0 is a scalar. Second limit is from $e^+ e^-$ channel. E_{cm} = 40–47 GeV. Supercedes ADEVA 84.

[32] ADEVA 84 and BEHREND 84C have E_{cm} = 39.8–45.5 GeV. MARK-J searched X^0 in $e^+ e^- \to$ hadrons, 2γ, $\mu^+ \mu^-$, $e^+ e^-$ and CELLO in the same channels plus τ pair. No narrow or broad X^0 is found in the energy range. They also searched for the effect of X^0 with $m(X) > E_{cm}$. The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for $\Gamma(X^0 \to e^+ e^-) = 2$ MeV if X^0 is a spin-0 doublet. The second limit of BEHREND 84C was read off from their figure 2. The original papers also list limits in other channels.

Search for Leptoquarks

Mass bounds derived.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
none 5–20.8 GeV	95		[33] BARTEL	87B	JADE	Spinless-leptoquark
none 7–20.5 GeV	95	2	[34] BEHREND	86B	CELL	Spinless-leptoquark
>350 TeV			[35] DESHPANDE	83	RVUE	Pati-Salam X-boson
$>1.$TeV			[36] SHANKER	82	RVUE	PS leptoquark
>125 TeV			[36] SHANKER	82	RVUE	Vector-leptoquark

[33] BARTEL 87B limit is valid when a pair of charge 2/3 spinless leptoquarks X is produced with point coupling, and when they decay under the constraint $B(X \to c\overline{\nu}_\mu) + B(X \to s\mu^+) = 1$.

[34] BEHREND 86B assumed that a charge 2/3 spinless leptoquark, χ, decays either into $s\mu^+$ or $c\overline{\nu}$: $B(\chi \to s\mu^+) + B(\chi \to c\overline{\nu}) = 1$.

[35] DESHPANDE 83 used upper limit on $K_L^0 \to \mu e$ decay with renormalization-group equations to estimate coupling at the heavy boson mass. See also Dimopoulos et al., NP B182, 77 (1981).

[36] From $(\pi \to e\nu)/(\pi \to \mu\nu)$ ratio.

MASS LIMITS for g_A (axigluon)

Axigluons are massive color-octet gauge bosons in chiral color models and have axial-vector coupling quarks with the same coupling strength as gluons.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>65		[37] CUYPERS	89	RVUE	$\sigma(e^+ e^- \to \text{hadrons})$
no limit		[38] FALK	89	RVUE	$\sigma(e^+ e^- \to \text{hadrons})$
>29		[39] ROBINETT	89	THEO	Partial-wave unitarity
none 150–310	95	[40] ALBAJAR	88B	UA1	$\Gamma(g_A) < 0.4\, m(g_A)$
>20		BERGSTROM	88	RVUE	$p\overline{p} \to \Upsilon X$ via $g_A g$
> 9		[41] CUYPERS	88	RVUE	Υ decay
>25		[42] DONCHESKI	88B	RVUE	Υ decay

[37] CUYPERS 89 calculated axigluon corrections to $e^+ e^- \to$ hadrons and argue that a light axigluon would result in too large values of $R(e^+ e^- \to \text{hadrons})$. The listed limit is obtained by assuming "α_s(34 GeV)" (derived from R measurements) < 0.165 and $\Lambda_{\overline{MS}} = 0.1$ GeV. Use of $\Lambda = 0.2$ GeV instead gives a limit of 100 GeV. For a criticism, see FALK 89.

[38] FALK 89 argues that no limit from $e^+ e^-$ scattering can be derived for the axigluon mass.

[39] ROBINETT 89 result demands partial-wave unitarity of $J = 0$ $t\overline{t} \to t\overline{t}$ scattering amplitude and derives a limit $m(g_A) > 0.5\, m(t)$. Assumes $m(t) > 56$ GeV.

[40] ALBAJAR 88B result is from the nonobservation of a peak in two-jet invariant mass distribution. See also BAGGER 88.

[41] CUYPERS 88 requires $\Gamma(\Upsilon \to g g_A) < \Gamma(\Upsilon \to g g g)$. A similar result is obtained by DONCHESKI 88.

[42] DONCHESKI 88B requires $\Gamma(\Upsilon \to g q\overline{q})/\Gamma(\Upsilon \to g g g) < 0.25$, where the former decay proceeds via axigluon exchange. A more conservative estimate of < 0.5 leads to $m(g_A) > 21$ GeV.

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

HAGIWARA	90	PR D41 815	+Najima, Sakuda, Terunuma	(KEK, DURH, YCC, HIRO)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
CUYPERS	89	PRL 63 125	+Frampton	(UNCC)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
FALK	89	PL B230 119		(HARV)
ODAKA	89	JPSJ 58 3037	+Kondo, Abe, Amako+	(Venus Collab.)
ROBINETT	89	PR D39 834		(PSU)
ALBAJAR	88B	PL B209 127	+Albrow, Allkofer, Astbury, Aubert+	(UA1 Collab.)
BAGGER	88	PR D37 1188	+Schmidt, King	(HARV, BOST)
BALKE	88	PR D37 587	+Gidal, Jodidio+	(LBL, UCB, COLO, NWES, TRIU)
BERGSTROM	88	PL B212 386		(STOH)
COSTA	88	NP B297 244	+Ellis, Fogli, Nanopoulos+	(PADO, BARI, WISC, LBL)
CUYPERS	88	PRL 60 1237	+Frampton	(UNCC)
DONCHESKI	88	PL B206 137	+Grotch, Robinett	(PSU)
DONCHESKI	88B	PR D38 412	+Grotch, Robinett	(PSU)
ELLIS	88	PL B202 417	Ellis, Franzini, Zwirner	(CERN, UCB, LBL)
AMALDI	87	PR D36 1385	+Bohm, Durkin, Langacker+	(CERN, AACH, OSU+)
ANSARI	87D	PL B195 613	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	+Becker, Felst+	(JADE Collab.)
ARNISON	86B	EPL 1 327	+Albrow, Allkofer+	(UA1 Collab.)
BARGER	86B	PRL 56 30	+Deshpande, Whisnant	(WISC, OREG, FSU)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
BEHREND	86B	PL B178 452	+Buerger, Criegee, Fenner, Field+	(CELLO Collab.)
DERRICK	86	PL 166B 463	+Gan, Kooijman, Loos+	(HRS Collab.)
DURKIN	86	PL 166B 436	+Langacker	(PENN)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909		(UMD)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	+Deuter, Genzel+	(PLUTO Collab.)
STOKER	85	PRL 54 1887	+Balke, Carr, Gidal+	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	+Barber, Becker, Berdugo+	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	+Burger, Criegee, Fenner+	(CELLO Collab.)
ARNISON	83B	PL 122B 189	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	83D	PL 129B 273	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BERGSMA	83	PL 122B 465	+Dorenbosch, Jonker+	(CHARM Collab.)
CARR	83	PRL 51 627	+Gidal, Gobbi, Jodidio, Oram+	(LBL, NWES, TRIU)
DESHPANDE	83	PR D27 1193	+Johnson	(OREG)
BEALL	82	PRL 48 848	+Bander, Soni	(UCI, UCLA)
SHANKER	82	NP B204 375		(TRIU)
RIZZO	81	PR D24 704	+Senjanovic	(BNL)

Searches for Axions (A^0) and Other Very Light Bosons

NOTE ON AXIONS

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. Typical examples are pseudo-Goldstone bosons like axions (A^0),[1] familons,[2] and Majorons,[3] associated, respectively, with spontaneously broken Peccei-Quinn,[4] family, and lepton-number symmetries.

Peccei-Quinn symmetry gives a natural solution to the strong CP-violation problem. Axion mass and its coupling to stable particles are inversely proportional to the scale of the Peccei-Quinn symmetry breaking Λ_{PQ} ($\equiv f_A$). The original axion model[4,1] assumes $\Lambda_{PQ} = \Lambda_{EW}$, where Λ_{EW}

$= (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and has two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings are completely fixed in terms of one parameter, the ratio of the vacuum expectation values of two Higgs fields. The result of extensive experimental searches for such an axion have been negative.[5]

Observation of a narrow-peak structure in positron spectra from heavy ion collisions[6] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $\Lambda_{\rm PQ} = \Lambda_{\rm EW}$, but drop the constraints of tree-level flavor conservation, were proposed.[7] Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result.[8]

One way to avoid these experimental constraints is to make A^0 sufficiently massive. One way to achieve this is to introduce a new strong interaction (QC$'$D) with $\Lambda_{\rm QC'D} \gg \Lambda_{\rm QCD}$, whose anomaly couples to the axion.[9] A^0 can receive significant mass from the QC$'$D sector if QC$'$D colored quarks are massive.

Another way to save the Peccei-Quinn idea is to discard the proposition $\Lambda_{\rm PQ} = \Lambda_{\rm EW}$ and introduce a new scale. With $\Lambda_{\rm PQ} \gg \Lambda_{\rm EW}$, the A^0 mass becomes smaller and its coupling weaker, thus one can easily avoid all the existing experimental limits; hence such models are called invisible axion models.[10,11] Various invisible axion models can be constructed by identifying $\Lambda_{\rm PQ}$ with other large mass scales such as the Planck mass, the GUT scale, the SUSY-breaking scale, and so on. It has been found, however, that invisible axions are not completely elusive. Cosmological considerations on the matter density of our universe suggest[12] $\Lambda_{\rm PQ} < O(10^{12})$ GeV as a possible upper bound on the scale. Lower bounds of $\Lambda_{\rm PQ} > O(10^7)$ GeV are obtained from astrophysics,[13] where axion emission from the center of stellar objects can speed up their evolutionary time scales. The recent observation of the supernova SN 1987A improves the lower bound to $\Lambda_{PQ} > O(10^{10})$ GeV. Various terrestrial experiments to detect 'invisible' axions by making use of their coupling to photons have been proposed,[14] and the first result of such experiments appeared recently.

There is also a Note on "invisible" axions later in this section.

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A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

These bounds depend on model-dependent assumptions (i.e. — on a combination of axion parameters).

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.2	BARROSO	82	ASTR	Standard Axion
>0.25	[1] RAFFELT	82	ASTR	Standard Axion
>0.2	[2] DICUS	78C	ASTR	Standard Axion
	MIKAELIAN	78	ASTR	Stellar emission
>0.3	[2] SATO	78	ASTR	Standard Axion
>0.2	VYSOTSKII	78	ASTR	Standard Axion

[1] Lower bound from 5.5 MeV γ-ray line from the sun.

[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

A^0 (Axion) Searches in Stable Particle Decays

Limits are for branching ratios.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<8 \times 10^{-7}$	90		[3] BAKER	87	CALO	$K^\pm \rightarrow \pi^\pm A^0$ $(A^0 \rightarrow e^+e^-)$
$<1.3 \times 10^{-8}$	90		[4] KORENCHE...	87	SPEC	$\pi^+ \rightarrow e^+\nu A^0$ $(A^0 \rightarrow e^+e^-)$
$<1. \times 10^{-9}$	90	0	[5] EICHLER	86	SPEC	Stopped $\pi^+ \rightarrow e^+\nu A^0$
$<2. \times 10^{-5}$	90		[6] YAMAZAKI	84	SPEC	For $160<m<260$ MeV
$<(1.5–4)\times 10^{-6}$	90		[6] YAMAZAKI	84	SPEC	K decay, $m(A^0) \ll 100$ MeV
		0	[7] ASANO	82	CNTR	Stopped $K^+ \rightarrow \pi^+ A^0$
		0	[8] ASANO	81B	CNTR	Stopped $K^+ \rightarrow \pi^+ A^0$
			[9] ZHITNITSKII	79		Heavy axion

[3] BAKER 87 limit assumes that the A^0 travels much less than 1.4 cm in the lab before decaying.

[4] KORENCHENKO 87 limit assumes $m(A^0) = 1.7$ MeV, $\tau(A^0) \lesssim 10^{-12}$ s, and $B(A^0 \rightarrow e^+e^-) = 1$.

[5] EICHLER 86 looked for $\pi^+ \rightarrow e^+\nu A^0$ followed by $A^0 \rightarrow e^+e^-$. Limits on the branching fraction depend on the mass and and lifetime of A^0. The quoted limits are valid when $\tau(A^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

[6] YAMAZAKI 84 looked for a discrete line in $K^+ \rightarrow \pi^+ X$. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.

[7] ASANO 82 at KEK set limits for $B(K^+ \rightarrow \pi^+ A^0)$ for $m(A^0) <100$ MeV as BR $< 4. \times 10^{-8}$ for $\tau(A^0 \rightarrow n\gamma\text{'s}) >1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau <1. \times 10^{-9}$s.

[8] ASANO 81B is KEK experiment. Set $B(K^+ \rightarrow \pi^+ A^0) <3.8 \times 10^{-8}$ at CL = 90%.

[9] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 ($3 <m <40$ MeV) contradicts experimental muon anomalous magnetic moments.

Gauge & Higgs Boson Full Listings

Axions (A^0) and Other Very Light Bosons

A^0 (Axion) Searches in Quarkonium and Positronium Decays

Decay or transition of positronium and quarkonium. Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6.4 \times 10^{-5}$	90		[10] ORITO	89	CNTR	o-PS $\to A^0\gamma$, $m(A^0) < 30$ keV
$<5 \times 10^{-5}$	90		[11] DRUZHININ	87	ND	$\phi \to \gamma A^0$ $(A^0 \to e^+e^-)$
$<2 \times 10^{-3}$	90		[12] DRUZHININ	87	ND	$\phi \to \gamma A^0$ $(A^0 \to \gamma\gamma)$
$<7 \times 10^{-6}$	90		[13] DRUZHININ	87	ND	$\phi \to \gamma A^0$ $(A^0 \to$ missing$)$
$<3.1 \times 10^{-4}$	90	0	[14] ALBRECHT	86D	ARG	$\Upsilon(1S) \to \gamma A^0$ $(A^0 \to e^+e^-)$
$<4 \times 10^{-4}$	90	0	[14] ALBRECHT	86D	ARG	$\Upsilon(1S) \to \gamma A^0$ $(A^0 \to \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
$<8 \times 10^{-4}$	90	1	[15] ALBRECHT	86D	ARG	$\Upsilon(1S) \to \gamma A^0$
$<1.3 \times 10^{-3}$	90	0	[16] ALBRECHT	86D	ARG	$\Upsilon(1S) \to \gamma A^0$ $(A^0 \to e^+e^-, \gamma\gamma)$
$<2. \times 10^{-3}$	90		[17] BOWCOCK	86	CLEO	$\Upsilon(2S) \to \Upsilon(1S) \to A^0$
$<5. \times 10^{-3}$	90		[18] MAGERAS	86	CUSB	$\Upsilon(1S) \to A^0\gamma$
			[19] AMALDI	85	CNTR	Ortho-positronium
$<3. \times 10^{-4}$	90		[20] ALAM	83	CLEO	$\Upsilon(1S) \to A^0\gamma$
			[21] CARBONI	83	CNTR	Ortho-positronium
$<9.1 \times 10^{-4}$	90		[22] NICZYPORUK	83	LENA	$\Upsilon(1S) \to A^0\gamma$
$<1.4 \times 10^{-5}$	90		[23] EDWARDS	82	CBAL	$J/\psi \to A^0\gamma$
$<3.5 \times 10^{-4}$	90		[24] SIVERTZ	82	CUSB	$\Upsilon(1S) \to A^0\gamma$
$<1.2 \times 10^{-4}$	90		[24] SIVERTZ	82	CUSB	$\Upsilon(3S) \to A^0\gamma$

[10] ORITO 89 limit translates to $g^2_{A^0ee}/4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger $m(A^0)$: $B < 7.6 \times 10^{-6}$ at 100 keV.

[11] The first DRUZHININ 87 limit is valid when $\tau(A^0)/m(A^0) < 3 \times 10^{-13}$ s/MeV and $m(A^0) < 20$ MeV.

[12] The second DRUZHININ 87 limit is valid when $\tau(A^0)/m(A^0) < 5 \times 10^{-13}$ s/MeV and $m(A^0) < 20$ MeV.

[13] The third DRUZHININ 87 limit is valid when $\tau(A^0)/m(A^0) > 7 \times 10^{-12}$ s/MeV and $m(A^0) < 200$ MeV.

[14] $\tau(A^0) < 1 \times 10^{-13}$s and $m(A^0) < 1.5$ GeV. Applies for $A^0 \to \gamma\gamma$ when $m(A^0) < 100$ MeV.

[15] $\tau(A^0) > 1 \times 10^{-7}$s.

[16] Independent of $\tau(A^0)$.

[17] BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to A^0\gamma$. The limit for $\mathrm{BR}(\Upsilon(1S) \to A^0\gamma)\mathrm{BR}(A^0 \to e^+e^-)$ depends on $m(A^0)$ and $\tau(A^0)$. The quoted limit for $m(A^0)=1.8$ MeV is at $\tau(A^0) \sim 2. \times 10^{-12}$s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m(e) < m(A^0) < 2m(\mu)$ when the results of this experiment are combined with the results of ALAM 83.

[18] MAGERAS 86 looked for $\Upsilon(1S) \to \gamma A^0$ $(A^0 \to e^+e^-)$. The quoted branching fraction limit is for $m(A^0) = 1.7$ MeV, at $\tau(A^0) \sim 4. \times 10^{-13}$s where the limit is the worst.

[19] AMALDI 85 set limits $\mathrm{B}(A^0\gamma)$ / $\mathrm{B}(\gamma\gamma\gamma) < (1\text{–}5) \times 10^{-6}$ for $m(A^0) = 900\text{–}100$ keV which are about 1/10 of the CARBONI 83 limits.

[20] ALAM 83 is at CESR. This limit combined with limit for $\mathrm{B}(J/\psi \to A^0\gamma)$ (EDWARDS 82) excludes standard axion.

[21] CARBONI 83 looked for orthopositronium $\to A^0\gamma$. Set limit for A^0 electron coupling squared, $g(eeA^0)^2/(4\pi) < 6. \times 10^{-10}\text{–}7. \times 10^{-9}$ for $m(A^0)$ from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from $g-2$ experiments.

[22] NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of $\mathrm{B}(\Upsilon \to A^0\gamma)$ derived from $\mathrm{B}(J/\psi(1S) \to A^0\gamma)$ limit (EDWARDS 82) excludes standard axion.

[23] EDWARDS 82 looked for $J/\psi \to \gamma A^0$ decays by looking for events with a single γ [of energy $\sim 1/2$ the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

[24] SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \to \gamma A^0$, A^0 undetected. Limit for $1S$ ($3S$) is valid for $m(A^0) < 7$ GeV (4 GeV).

A^0 (Axion) Production in Hadron Collisions

Limits are for $\sigma(A^0)$ / $\sigma(\pi^0)$.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[25] FAISSNER	89	OSPK	Beam dump, $A^0 \to e^+e^-$
			[26] DEBOER	88	RVUE	$A^0 \to e^+e^-$
			[27] EL-NADI	88	EMUL	$A^0 \to e^+e^-$
			[28] FAISSNER	88	OSPK	Beam dump, $A^0 \to 2\gamma$
			[29] BADIER	86	BDMP	$A^0 \to e^+e^-$
$<2. \times 10^{-11}$	90	0	[30] BERGSMA	85	CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	[30] BERGSMA	85	CHRM	CERN beam dump
		24	[31] FAISSNER	83	OSPK	Beam dump, $A^0 \to 2\gamma$
			[32] FAISSNER	83B	RVUE	LAMPF beam dump
			[33] FRANK	83B	RVUE	LAMPF beam dump
			[34] HOFFMAN	83	CNTR	$\pi p \to nA^0$ $(A^0 \to e^+e^-)$
			[35] FETSCHER	82	RVUE	See FAISSNER 81B
		12	[36] FAISSNER	81	OSPK	CERN PS ν wideband
		15	[37] FAISSNER	81B	OSPK	Beam dump, $A^0 \to 2\gamma$
		8	[38] KIM	81	OSPK	26 GeV $pN \to A^0X$
		0	[39] FAISSNER	80	OSPK	Beam dump, $A^0 \to e^+e^-$
$<1. \times 10^{-8}$	90		[40] JACQUES	80	HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		[40] JACQUES	80	HLBC	Beam dump
			[41] SOUKAS	80	CALO	28 GeV p beam dump
			[42] BECHIS	79	CNTR	
$<1. \times 10^{-8}$	90		[43] COTEUS	79	OSPK	Beam dump
$<1. \times 10^{-3}$	95		[44] DISHAW	79	CALO	400 GeV pp
$<1. \times 10^{-8}$	90		ALIBRAN	78	HYBR	Beam dump
$<6. \times 10^{-9}$	95		ASRATYAN	78B	CALO	Beam dump
$<1.5 \times 10^{-8}$	90		[45] BELLOTTI	78	HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		[45] BELLOTTI	78	HLBC	$m(A^0)=1.5$ MeV
$<4.1 \times 10^{-9}$	90		[45] BELLOTTI	78	HLBC	$m(A^0)=1$ MeV
$<1. \times 10^{-8}$	90		[46] BOSETTI	78B	HYBR	Beam dump
			[47] DONNELLY	78		
$<0.5 \times 10^{-8}$	90		HANSL	78D	WIRE	Beam dump
			[48] MICELMAC...	78		
			[49] VYSOTSKII	78		

[25] FAISSNER 89 searched for $A^0 \to e^+e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m(e)$–20 MeV is excluded. Lower limit on f_{A^0} of $\sim 10^4$ GeV is given for $m(A^0) = 2m(e)$–20 MeV.

[26] DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass ~ 1.1, ~ 2.1, and ~ 9 MeV, lifetimes 10^{-16}–10^{-15} s decaying to e^+e^- and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. Roy. Soc. (London) **A220**, 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with π^0 Dalitz decay. DEBOER 89B is a reply which contests the criticism.

[27] EL-NADI 88 claim the existence of a neutral particle decaying into e^+e^- with mass 1.60 ± 0.59 MeV, lifetime $(0.15 \pm 0.01) \times 10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at ~ 4 GeV/c/nucleon.

[28] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \to \gamma\gamma$. A standard axion decaying to 2γ is excluded except for a region $x \sim 1$. Lower limit on f_{A^0} of 10^2–10^3 GeV is given for $m(A^0) = 0.1$–1 MeV.

[29] BADIER 86 did not find long-lived A^0 in 300 GeV π^- Beam Dump Experiment that decays into e^+e^- in the mass range $m(A^0) = (20\text{–}200)$ MeV, which excludes the A^0 decay constant $f(A^0)$ in the interval (60–600) GeV. See their figure 6 for excluded region on $f(A^0)$-$m(A^0)$ plane.

[30] BERGSMA 85 look for $A^0 \to 2\gamma$, e^+e^-, $\mu^+\mu^-$. First limit above is for $m(A^0) = 1$ MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0} - m(A^0)$ plane, where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 A^0, $m(A^0) < 180$ keV and $\tau > 0.037$ s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[31] FAISSNER 83 observed 19 1-γ and 12 2-γ events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.

[32] FAISSNER 83B extrapolate SIN γ signal to LAMPF ν experimental condition. Resulting 370 γ's are not at variance with LAMPF upper limit of 450 γ's. Derived from LAMPF limit that $[d\sigma(A^0)/d\omega$ at $90^\circ]\, m(A^0)/\tau(A^0) < 14 \times 10^{-35}$ cm^2 sr^{-1} MeV ms^{-1}. See comment on FRANK 83B.

[33] FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450 γ's. See comment on FAISSNER 83B.

[34] HOFFMAN 83 set CL = 90% limit $d\sigma/dt\, \mathrm{B}(e^+e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for $140 < m(A^0) < 160$ MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.

[35] FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2-γ peak rate remarkably decreases if iron wall is set in front of the decay region.

[36] FAISSNER 81 see excess μe events. Suggest axion interactions.

[37] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ decay of long-lived neutral penetrating particle with $m(2\gamma) \lesssim 1$ MeV. Axion interpretation with η-A^0 mixing gives $m(A^0) = 250 \pm 25$ keV, $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$ s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[38] KIM 81 analyzed 8 candidates for $A^0 \to 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is $(0.86 \sim 5.6) \times 10^{-3}$ s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[39] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \to e^+e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit 20/(A^0 mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m(A^0) < 2m(e^-)$.

[40] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events [σ(production)σ(interactaction) $< 7. \times 10^{-68}$ cm^4, CL = 90%]. Second limit is from nonobservation of axion decays into 2γ's or e^+e^-, and for axion mass a few MeV.

[41] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.

[42] BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either 2γ or e^+e^-. No signal found. CL = 90% limits for model parameter(s) are given.

[43] COTEUS 79 is a beam dump experiment at BNL.

[44] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.

[45] BELLOTTI 78 first value comes from search for $A^0 \to e^+e^-$. Second value comes from search for $A^0 \to 2\gamma$, assuming mass $< 2m(e^-)$. For any mass satisfying this, limit is above value$\times$(mass^{-4}). Third value uses data of PL 60B 401 and quotes σ(production)σ(interaction) $< 10^{-67}$ cm^4.

[46] BOSETTI 78B quotes σ(production)σ(interaction) $< 2. \times 10^{-67}$ cm^4.

[47] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.

[48] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).

[49] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

A^0 (Axion) Searches in Reactor Experiments

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
	[50] KETOV	86	SPEC	Reactor, $A^0 \to \gamma\gamma$
	[51] KOCH	86	SPEC	Reactor; $A^0 \to \gamma\gamma$
	[52] DATAR	82	CNTR	Light water reactor
	[53] VUILLEUMIER	81	CNTR	Reactor, $A^0 \to 2\gamma$

[50] KETOV 86 searched for A^0 at the Rovno nuclear power plant. They found an upper limit on the A^0 production probability of 0.8 $[100\ \text{keV}/m(A^0)]^6 \times 10^{-6}$ per fission. In the standard axion model, this corresponds to $m(A^0) > 150$ keV. Not valid for $m(A^0) \gtrsim 1$ MeV.

[51] KOCH 86 searched for $A^0 \to \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with $m(A^0) = 250$ keV gives 10^{-5} for the ratio. Not valid for $m(A^0) > 1022$ keV.

[52] DATAR 82 looked for $A^0 \to 2\gamma$ in neutron capture ($np \to dA^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $[(I=0) - (I=1)]$ result, assert nonexistence of standard A^0.

[53] VUILLEUMIER 81 is at Grenoble reactor. Set limit $m(A^0) < 280$ keV.

A^0 (Axion) and Other Light Boson (X^0) Searches in Nuclear Transitions

Limits are for branching ratio.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<(0.4\text{–}10)\times10^{-3}$	95		[54] DEBOER	90	CNTR	${}^8\text{Be}^* \to {}^8\text{Be}A^0$, $A^0 \to e^+e^-$
$<(0.2\text{–}1)\times10^{-3}$	90		[55] BINI	89	CNTR	${}^{16}\text{O}^* \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$
			[56] AVIGNONE	88	CNTR	$\text{Cu}^* \to \text{Cu}A^0$ ($A^0 \to 2\gamma$, $A^0 e \to \gamma e$, $A^0 Z \to \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[57] DATAR	88	CNTR	${}^{12}\text{C}^* \to {}^{12}\text{C}A^0$
$< 5 \times 10^{-3}$	90		[58] DEBOER	88C	CNTR	${}^{16}\text{O}^* \to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$
$< 3.4 \times 10^{-5}$	95		[59] DOEHNER	88	SPEC	${}^2\text{H}^*$, $A^0 \to e^+e^-$
$< 4 \times 10^{-4}$	95		[60] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[60] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[61] HALLIN	86	SPEC	^{6}Li isovector decay
<10.8	90		[61] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90		[61] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[62] SAVAGE	86B	CNTR	${}^{14}\text{N}^*$
			[63] ANANEV	85	CNTR	Li*, deut* $A^0 \to 2\gamma$
			[64] CAVAIGNAC	83	CNTR	${}^{97}\text{Nb}^*$, deut* transition $A^0 \to 2\gamma$
			[65] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \to 2\gamma$
			[66] LEHMANN	82	CNTR	$\text{Cu}^* \to \text{Cu}A^0$ ($A^0 \to 2\gamma$)
		0	[67] ZEHNDER	82	CNTR	Li*, Nb* decay, *n*-capt.
		0	[68] ZEHNDER	81	CNTR	$\text{Ba}^* \to \text{Ba}A^0$ ($A^0 \to 2\gamma$)
			[69] CALAPRICE	79		Carbon

[54] The DEBOER 90 limit is for the branching ratio ${}^8\text{Be}^*$ (18.15 MeV, 1^+) $\to {}^8\text{Be}A^0$, $A^0 \to e^+e^-$ for the mass range $m(A^0) = 4\text{–}15$ MeV.

[55] The BINI 89 limit is for the branching fraction of ${}^{16}\text{O}^*$ (6.05 MeV, 0^+) $\to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$ for $m(X) = 1.5\text{–}3.1$ MeV. $\tau(X^0) \lesssim 10^{-11}$ s is assumed. The spin-parity of X is restricted to 0^+ or 1^-.

[56] AVIGNONE 88 looked for the 1115 keV transition $C^* \to \text{Cu}A^0$, either from $A^0 \to 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m(A^0) < 1.1$ MeV.

[57] DATAR 88 rule out light pseudoscalar particle emission in the mass range 1.02–2.5 MeV and lifetime range $10^{-13}\text{–}10^{-8}$ s. The above limit is for $\tau = 5 \times 10^{-13}$ s and $m =$ 1.7 MeV; see the paper for the τ-m dependence of the limit.

[58] The limit is for the branching fraction of ${}^{16}\text{O}^*$ (6.05 MeV, 0^+) $\to {}^{16}\text{O}X^0$, $X^0 \to e^+e^-$ against internal pair conversion for $m(X^0) = 1.7$ MeV and $\tau(X^0) < 10^{-11}$ s. Similar limits are obtained for $m(X^0) = 1.3\text{–}3.2$ MeV. The spin parity of X^0 must be either 0^+ or 1^-. The limit at 1.7 MeV is translated into a limit for the X^0-nucleon coupling constant: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$.

[59] The DOEHNER 88 limit is for $m(A^0) = 1.7$ MeV, $\tau(A^0) < 10^{-10}$ s. Limits less than 10^{-4} are obtained for $m(A^0) = 1.2\text{–}2.2$ MeV.

[60] SAVAGE 88 looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N, 17.64 MeV state $J^P = 1^+$ in ^{8}Be, and the 18.15 MeV state $J^P = 1^+$ in ^{8}Be. This experiment constrains the isovector coupling of A^0 to hadrons, if $m(A^0) = (1.1 \to 2.2)$ MeV and the isoscalar coupling of A^0 to hadrons, if $m(A^0) = (1.1 \to 2.6)$ MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

[61] Limits are for $\Gamma(A^0(1.8\ \text{MeV}))/\Gamma(\pi M1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of e^+e^- pairs. Valid for $\tau(A^0) < 2 \times 10^{-11}$s. ^{6}Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the ^{10}B and ^{14}N isoscalar decay data strongly reject PECCEI 86 model II and III.

[62] SAVAGE 86B looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N. Limit on the branching fraction is valid if $\tau(A^0) \lesssim 1. \times 10^{-11}$s for $m(A^0) = (1.1\text{–}1.7)$ MeV. This experiment constrains the iso-vector coupling of A^0 to hadrons.

[63] ANANEV 85 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% masses below 470 keV (Li* decay) and below $2m(e)$ for deuteron* decay.

[64] CAVAIGNAC 83 at Bugey reactor exclude axion at any $m({}^{97}\text{Nb}^*$ decay) and axion with $m(A^0)$ between 275 and 288 keV (deuteron* decay).

[65] ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% mass-ranges $m(A^0) < 400$ keV (Li* decay) and 330 keV $< m(A^0) < 2.2$ MeV. (deuteron* decay).

[66] LEHMANN 82 obtained $A^0 \to 2\gamma$ rate $< 6.2 \times 10^{-5}$/s (CL = 95%) excluding $m(A^0)$ between 100 and 1000 keV.

[67] ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check A^0 production. No 2γ peak in Li*, Nb* decay (both single *p* transition) nor in *n* capture (combined with previous Ba* negative result) rules out standard A^0. Set limit $m(A^0) < 60$ keV for any A^0.

[68] ZEHNDER 81 looked for $\text{Ba}^* \to A^0\text{Ba}$ transition with $A^0 \to 2\gamma$. Obtained 2γ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding $m(A^0) > 160$ keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.

[69] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

A^0 (Axion) Limits from Its Electron Coupling

Limits are for $\tau(A^0 \to e^+e^-)$.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
		[70] BJORKEN	88	CALO	$A \to e^+e^-$ or 2γ
		[71] BLINOV	88	MD1	$e^+e^- \to e^+e^-A^0$ ($A^0 \to e^+e^-$)
none $1 \times 10^{-14}\text{–}1 \times 10^{-10}$	90	[72] RIORDAN	87	BDMP	$eN \to eA^0N$ ($A^0 \to e^+e^-$)
none $1 \times 10^{-14}\text{–}1 \times 10^{-11}$	90	[73] BROWN	86	BDMP	$eN \to eA^0N$ ($A^0 \to e^+e^-$)
none $6 \times 10^{-14}\text{–}9 \times 10^{-11}$	95	[74] DAVIER	86	BDMP	$eN \to eA^0N$ ($A^0 \to e^+e^-$)
none $3 \times 10^{-13}\text{–}1 \times 10^{-7}$	90	[75] KONAKA	86	BDMP	$eN \to eA^0N$ ($A^0 \to e^+e^-$)

[70] BJORKEN 88 reports limits on axion parameters (f_A, m_A, τ_A) for $m(A^0) < 200$ MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.

[71] BLINOV 88 assume zero spin, $m = 1.8$ MeV and lifetime $< 5\times10^{-12}$ s and find $\Gamma(A^0 \to \gamma\gamma)B(A^0 \to e^+e^-) < 2$ eV (CL=90%).

[72] Assumes $A^0\gamma\gamma$ coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for $m(A^0) < 15$ MeV.

[73] Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for $m(A^0) < 15$ MeV are shown in their figure 3.

[74] $m(A^0) = 1.8$ MeV assumed. The excluded domain in the $\tau(A^0)$–$m(A^0)$ plane extends up to $m(A^0) \approx 14$ MeV, see their figure 4.

[75] The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma$–$A^0e^+e^-$ coupling plane by assuming Primakoff production.

Search for A^0 (Axion) Resonance in Bhabha Scattering

The limit is for $[\Gamma(A^0 \to e^+e^-)]^2/\Gamma_{\text{tot}}$ ($= \Gamma_{\text{tot}}$ if only the decay channel to e^+e^- is present).

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (10^{-3} eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 5		BAUER	90	CNTR	$m(A^0) = 1.832$ MeV
< 1.9	97	[76] TSERTOS	89	CNTR	$m(A^0) = 1.82$ MeV
$<(10\text{–}40)$	97	[76] TSERTOS	89	CNTR	$m(A^0) = 1.51\text{–}1.65$ MeV
$<(1\text{–}2.5)$	97	[76] TSERTOS	89	CNTR	$m(A^0) = 1.80\text{–}1.86$ MeV
< 31	95	LORENZ	88	CNTR	$m(A^0) = 1.646$ MeV
< 94	95	LORENZ	88	CNTR	$m(A^0) = 1.726$ MeV
< 23	95	LORENZ	88	CNTR	$m(A^0) = 1.782$ MeV
< 19	95	LORENZ	88	CNTR	$m(A^0) = 1.837$ MeV
< 3.8	97	[77] TSERTOS	88	CNTR	$m(A^0) = 1.832$ MeV
		[78] VANKLINKEN	88	CNTR	
		[79] MAIER	87	CNTR	
<2500	90	MILLS	87	CNTR	$m(A^0) = 1.8$ MeV
		[80] VONWIMMER.	87	CNTR	

[76] See also TSERTOS 88B in references.

[77] The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.

[78] VANKLINKEN 88 looked for relatively long-lived resonance ($\tau = 10^{-10}\text{–}10^{-12}$ s). The sensitivity is not sufficient to exclude such a narrow resonance.

[79] MAIER 87 obtained limits $R\Gamma \lesssim 60$ eV (100 eV) at $m(A^0) \sim 1.64$ MeV (1.83 MeV) for energy resolution $\Delta E_{\text{cm}} \sim 3$ keV, where R is the resonance cross section normalized to that of Bhabha scattering, and $\Gamma = \Gamma^2_{ee}/\Gamma_{\text{tot}}$. For a discussion implying that $\Delta E_{\text{cm}} \sim$ 10 keV, see TSERTOS 89.

[80] VONWIMMERSPERG 87 measured Bhabha scattering for $E_{\text{cm}} = 1.37\text{–}1.86$ MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}} = 14.5 \pm 6.8$ keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see S.H. Connel et al., Phys. Rev. Lett. 60, 2242 (1988).

Search for A^0 (Axion) Resonance in $e^+e^- \to \gamma\gamma$

The limit is for $\Gamma(A^0 \to e^+e^-)\cdot\Gamma(A^0 \to \gamma\gamma)/\Gamma_{\rm tot}$

VALUE (10^{-3} eV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[81] FOX 89	CNTR	
< 0.11	95	[82] MINOWA 89	CNTR	$m(A^0) = 1.062$ MeV
<33	97	CONNELL 88	CNTR	$m(A^0) = 1.580$ MeV
<42	97	CONNELL 88	CNTR	$m(A^0) = 1.642$ MeV
<73	97	CONNELL 88	CNTR	$m(A^0) = 1.782$ MeV
<79	97	CONNELL 88	CNTR	$m(A^0) = 1.832$ MeV

[81] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV ($< 9 \times 10^{-5}$ of two-photon annihilation at rest).

[82] Similar limits are obtained for $m(A^0) = 1.045$–1.085 MeV.

Searches for Goldstone Bosons (X^0)

(Including Horizontal Bosons and Majorons.) Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.1 \times 10^{-9}$	90		[83] BOLTON 88	CBOX	$\mu^+ \to e^+\gamma X^0$. Familon
			[84] CHANDA 88	ASTR	Sun, Majoron
			[85] CHOI 88	ASTR	Majoron, SN 1987A
$<5 \times 10^{-6}$	90		[86] PICCIOTTO 88	CNTR	$\pi \to e\nu X^0$, Majoron
$<1.3 \times 10^{-9}$	90		[87] GOLDMAN 87	CNTR	$\mu \to e\gamma X^0$. Familon
$<3 \times 10^{-4}$	90		[88] BRYMAN 86B	RVUE	$\mu \to eX^0$. Familon
$<1. \times 10^{-10}$	90	0	[89] EICHLER 86	SPEC	$\mu^+ \to e^+X^0$. Familon
$<2.6 \times 10^{-6}$	90		[90] JODIDIO 86	SPEC	$\mu^+ \to e^+X^0$. Familon
			[91] BALTRUSAIT...85	MRK3	$\tau \to \ell X^0$. Familon
			[92] DICUS 83	COSM	ν (hvy) $\to$ ν (light) X^0

[83] BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.

[84] CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.

[85] CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling h in the range $2 \times 10^{-5} < h < 3 \times 10^{-4}$ for the interaction $L_{\rm int} = \frac{1}{2} i h \overline{\psi}^c_\nu \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

[86] PICCIOTTO 88 limit applies when $m(X^0) < 55$ MeV and $\tau(X^0) > 2$ns, and it decreases to 4×10^{-7} at $m(X^0) = 125$ MeV, beyond which no limit is obtained.

[87] GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{\rm int} = (1/F)\overline{\psi}_\mu \gamma^\mu\, (a+b\gamma_5)\, \psi_e \partial_\mu \phi_{X^0}$ with $a^2+b^2 = 1$. This is not as sensitive as the limit $F > 9.9 \times 10^9$ GeV derived from the search for $\mu^+ \to e^+X^0$ by JODIDIO 86, but does not depend on the chirality property of the coupling.

[88] Limits are for $\Gamma(\mu \to eX^0)/\Gamma(\mu \to e\nu\overline{\nu})$. Valid when $m(X^0) = 0$–93.4, 98.1–103.5 MeV.

[89] EICHLER 86 looked for $\mu^+ \to e^+X^0$ followed by $X^0 \to e^+e^-$. Limits on the branching fraction depend on the mass and and lifetime of X^0. The quoted limits are valid when $\tau(X^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

[90] JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{\rm int} = (1/F)\, \overline{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$.

[91] BALTRUSAITIS 85 search for light Goldstone boson(X^0) of broken U(1). CL = 95% limits are $B(\tau \to \mu^+X^0)/B(\tau \to \mu^+\nu\nu) < 0.125$ and $B(\tau \to e^+X^0)/B(\tau \to e^+\nu\nu) < 0.04$. Inferred limit for the symmetry breaking scale is $m > 3000$ TeV.

[92] The primordial heavy neutrino must decay into ν and familon, f_A, early so that the red-shifted decay products are below critical density, see their table. In addition, $K \to \pi f_A$ and $\mu \to e f_A$ are unseen. Combining these excludes m(heavy ν) between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and m(heavy ν) between 5×10^{-5} and 0.1 MeV (K-decay).

Majoron Searches in Neutrinoless Double β Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission.
Previous indications for neutrinoless double beta decay with majoron emission have been superceded. No experiment currently claims any such evidence. For a review, see DOI 88.

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
$> 1.4 \times 10^{21}$	90	CALDWELL 87	CNTR	^{76}Ge
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$> 1.9 \times 10^{20}$	68	BARABASH 89	CNTR	^{136}Xe
$> 1.0 \times 10^{21}$	90	FISHER 89	CNTR	^{76}Ge
$> 3.3 \times 10^{20}$	90	ALSTON-... 88	CNTR	^{100}Mo
$(6 \pm 1) \times 10^{20}$		AVIGNONE 87	CNTR	^{76}Ge
$> 4.4 \times 10^{20}$	90	ELLIOTT 87	SPEC	^{82}Se
$> 1.2 \times 10^{21}$	90	FISHER 87	CNTR	^{76}Ge
		[93] VERGADOS 82	CNTR	

[93] VERGADOS 82 sets limit $g_H < 4 \times 10^{-3}$ for (dimensionless) lepton-number violating coupling, g_H, of scalar boson (Majoron) to neutrinos, from analysis of data on double β decay of ^{48}Ca.

INVISIBLE A^0 (AXION) MASS LIMITS FROM ASTROPHYSICS AND COSMOLOGY

Limits on $m(A^0)$ are obtained from the axion coupling to electrons, nucleons, or photons. Quoted limits are often expressed in terms of the axion decay constant f_A which can be defined in terms of the mass or axion-electron coupling by $m(A^0) = 3.5 \times 10^{10} g_{Ae} \cos^{-2}\beta\,{\rm eV} = 7.2 \times 10^7 ({\rm GeV}/f_A)(N/6)\,{\rm eV}$ [using the conventions detailed in Srednicki[1]; for other conventions take $f_A \to 2f_A$ (Bardeen[2]) or $f_A \to 4f_A$ (Kaplan[3])] where N is the number of quarks with Peccei-Quinn charge (usually the number of quark flavors) and $\cos^2\beta = v_1^2/(v_1^2 + v_2^2)$ is determined by the vacuum expectation values of the two Higgs doublets coupling to up and down quarks (and charged leptons). For the coupling to photons $m(A^0) = 6.9 \times 10^9 (g_{A\gamma}/{\rm GeV}^{-1})\,{\rm eV}$ and for the coupling to nucleons $m(A^0) = 7.7 \times 10^7 g_{AN}/c_{AN}\,{\rm eV}$ where c_{AN} depends on the details of the coupling of axions to nucleons. These couplings are defined by

$$\mathcal{L}_{\rm int} = -\frac{1}{4} g_{A\gamma}\, \phi_A F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{A\gamma}\, \phi_A \mathbf{E}\cdot\mathbf{B} \ ,$$

$$\mathcal{L}_{\rm int} = i g_{Ae}\, \phi_A \overline{\psi}_e \gamma_5 \psi_e \ , \qquad \text{and}$$

$$\mathcal{L}_{\rm int} = i g_{AN}\, \phi_A \overline{\psi}_N \gamma_5 \psi_N \ .$$

The factors in these equations are model dependent, in particular $g_{Ae} = 0$ in the KSVZ[4] models. In the comment for each limit below, D indicates that the limit is specific to DFSZ[5] axions, K to KSVZ axions (The limits quoted assume $N = 6$ and $v_1 = v_2$.)

References

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2. W. Bardeen and H. Tye, Phys. Lett. **74B**, 229 (1978).
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Invisible A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

$v_1 = v_2$ is usually assumed (v_i = vacuum expectation values).

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$< 1 \times 10^{-3}$	[94] BURROWS 89	ASTR	D,K, SN 1987A
$<(1.4$–$10) \times 10^{-3}$	[95] ERICSON 89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[96] MAYLE 89	ASTR	D,K, SN 1987A
<12	CHANDA 88	ASTR	D, Sun
$< 1 \times 10^{-3}$	RAFFELT 88	ASTR	D,K, SN 1987A
	[97] RAFFELT 88B	ASTR	red giant
< 0.07	FRIEMAN 87	ASTR	D, red giant
< 0.7	[98] RAFFELT 87	ASTR	K, red giant
< 2–5	TURNER 87	COSM	K, thermal production
< 0.01	[99] DEARBORN 86	ASTR	D, red giant
< 0.06	RAFFELT 86	ASTR	D, red giant
< 0.7	[100] RAFFELT 86	ASTR	K, red giant
< 0.03	RAFFELT 86B	ASTR	D, white dwarf
< 1	[101] KAPLAN 85	ASTR	K, red giant
< 0.003–0.02	IWAMOTO 84	ASTR	D, K, neutron star
$> 1 \times 10^{-5}$	ABBOTT 83	COSM	D,K, mass density of the universe
$> 1 \times 10^{-5}$	DINE 83	COSM	D,K, mass density of the universe

< 0.04		ELLIS 83B	ASTR	D, red giant
$> 1 \times 10^{-5}$		PRESKILL 83	COSM	D,K, mass density of the universe
< 0.1		BARROSO 82	ASTR	D, red giant
< 1		[102] FUKUGITA 82	ASTR	D, stellar cooling
< 0.07		FUKUGITA 82B	ASTR	D, red giant

[94] The region $m(A^0) \gtrsim 2$ eV is also allowed.

[95] ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.

[96] MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.

[97] RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars $\epsilon < 100$ erg $\mathrm{g}^{-1}\ \mathrm{s}^{-1}$, which gives a firmer basis for the axion limits based on red giant cooling.

[98] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}\ \mathrm{GeV}^{-1}$.

[99] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}\ \mathrm{GeV}^{-1}$.

[100] RAFFELT 86 gives a limit $g_{A\gamma} < 1.1\times10^{-10}\ \mathrm{GeV}^{-1}$ from red giants and $< 2.4\times10^{-9}\ \mathrm{GeV}^{-1}$ from the sun.

[101] KAPLAN 85 says $m(A^0) < 23$ eV is allowed for a special choice of model parameters.

[102] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}\ \mathrm{GeV}^{-1}$.

Search for Invisible Axions

Limits are for $[G_{A\gamma\gamma}/m(A^0)]^2\rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\mathrm{int}} = \frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\tilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$, and ρ_A is the axion energy density near the earth.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.3 \times 10^{-42}$	95	[103] WUENSCH 89	CNTR	$m(A^0) = (4.5\text{–}10.2)10^{-6}$ eV
$<2 \times 10^{-41}$	95	[103] WUENSCH 89	CNTR	$m(A^0) = (11.3\text{–}16.3)10^{-6}$ eV

[103] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m(A^0)]^2 = 1.1 \times 10^{-16}\ \mathrm{MeV}^{-4}$ (the three generation DFSZ model) and $\rho_A = 300\ \mathrm{MeV/cm}^3$ that makes up galactic halos gives $(G_{A\gamma\gamma}/m(A^0))^2\ \rho_A = 2.3 \times 10^{-46}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

REFERENCES FOR Searches for Axions (A^0) and Other Very Light Bosons

BAUER	90	NIM B50 300	+Briggmann, Carstanjen, Connell, et al	(STUT, PSI, GSI)
DEBOER	90	JP G16 L1	de Boer, Lehmann, Steyaert	(LVLN)
BARABASH	89	PL B223 273	+Kuzminov, Lobashev, Novikov+	(ITEP, INRM)
BINI	89	PL B221 99	+Fazzini, Giannatiempo, Poggi, Sona+	(FIRZ, CERN, AARH)
BURROWS	89	PR D39 1020	+Turner, Brinkmann	(ARIZ, CHIC, FNAL, BOCH)
Also	88	PRL 60 1797	Turner	(FNAL, EFI)
DEBOER	89B	PRL 62 2639	de Boer, van Dantzig	(ANIK)
ERICSON	89	PL B219 507	+Mathiot	(CERN, IPN)
FAISSNER	89	ZPHY C44 557	+Heinrigs, Preussger, Reitz, Samm+	(AACH, BERL, PSI)
FISHER	89	PL B218 257	+Boehm, Bovet, Egger+	(CIT, NEUC, PSI)
FOX	89	PR C39 288	+Kemper, Cottle, Zingarelli	(FSU)
MAYLE	89	PL B219 515	+Wilson, Ellis+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
Also	88	PL B203 188	Mayle, Wilson+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
MINOWA	89	PRL 62 1091	+Orito, Tlsuchiaki, Tlsukamoto	(TOKY)
ORITO	89	PRL 63 597	+Yoshimura, Haga, Minowa, Tsuchiaki	(TOKY)
PERKINS	89	PRL 62 2638		(OXF)
TSERTOS	89	PR D40 1397	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
WUENSCH	89	PR D40 3153	+De Panfilis-Wuensch, Semertzidis+	(ROCH, BNL, FNAL)
Also	87	PRL 59 839	De Panfilis, Melissinos, Moskowitz+	(ROCH, BNL, FNAL)
ALSTON-...	88	PRL 60 1928	Alston-Garnjost, Dougherty+	(LBL, MTHO, UNM)
AVIGNONE	88	PR D37 618	+Baktash, Barker, Calaprice+	(PRIN, USCR, ORNL, WASH)
BJORKEN	88	PR D38 3375	+Ecklund, Nelson, Abashian+	(FNAL, SLAC, VPI)
BLINOV	88	SJNP 47 563	+Bondar, Bukin, Vorobyev, Groshev+	(NOVO)
		Translated from YAF 47 889.		
BOLTON	88	PR D38 2077	+Cooper, Frank, Hallin+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 56 2461	Bolton, Bowman, Cooper+	(LANL, STAN, CHIC, TEMP)
Also	86	PRL 57 3241	Grosnick, Wright, Bolton+	(CHIC, LANL, STAN, TEMP)
CHANDA	88	PR D37 2714	+Nieves, Pal	(UMD, UPR, MASA)
CHOI	88	PR D37 3225	+Kim, Kim, Lam	(JHU)
CONNELL	88	PRL 60 2242	+Fearick, Hoernle, Sideras-Haddad, Sellschop	(WITW)
DATAR	88	PR C37 250	+Fortier, Gales, Hourani+	(IPN)
DEBOER	88	PRL 61 1274	de Boer, van Dantzig	(ANIK)
Also	89	PRL 62 2644 erratum	de Boer, van Dantzig	(ANIK)
Also	89	PRL 62 2638	Perkins	(OXF)
Also	89B	PRL 62 2639	de Boer, van Dantzig	(ANIK)
DEBOER	88C	JP G14 L131	de Boer, Deutsch, Lehmann, Prieels, Steyaert	(LVLN)
DOEHNER	88	PR D38 2722	+Last, Arnold, Freedman, Dubbers	(HEID, ANL, ILLG)
DOI	88	PR D37 2575	+Kotani, Takasugi	(OSAK)
EL-NADI	88	PRL 61 1271	+Badawy	(CAIR)
FAISSNER	88	ZPHY C37 231	+Heinrigs, Preussger, Reitz, Samm+	(AACH, BERL, SIN)
HATSUDA	88B	PL B203 469	+Yoshimura	(KEK)
LORENZ	88	PL B214 10	+Mageras, Stiegler, Huszar	(MPIM, PSI)
MAYLE	88	PL B203 188	+Wilson+	(LLL, CERN, MINN, FNAL, CHIC, OSU)
PICCIOTTO	88	PR D37 1131	+Ahmad, Britton, Bryman, Clifford+	(TRIU, CNRC)
RAFFELT	88	PRL 60 1793	+Seckel	(UCB, LLL, UCSC)
RAFFELT	88B	PR D37 549	+Dearborn	(UCB, LLL)
SAVAGE	88	PR D37 1134	+Filippone, Mitchell	(CIT)
TSERTOS	88	PL B207 273	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
TSERTOS	88B	ZPHY A331 103	+Kozhuharov, Armbruster, Kienle+	(GSI, ILLG)
VANKLINKEN	88	PL B205 223	van Klinken, Meiring, de Boer, Schaafsma+	(GRON, GSI)
VANKLINKEN	88B	PRL 60 2442	van Klinken	(GRON)
VONWIMMER...	88	PRL 60 2443	von Wimmersperg	(BNL)
AVIGNONE	87	AIP Conf. 1987	+Brodzinski, Miley, Reeves	(SCUC, PNL)
AIP Conf.	Proc.	Salt Lake City, UT		
BAKER	87	PRL 59 2832	+Gordon, Lazarus+	(BNL, SIN, WASH, YALE)
Also	88	PRL 60 472 erratum	Baker, Gordon+	(BNL, SIN, WASH, YALE)
CALDWELL	87	PRL 59 419	+Eisberg, Grumm, Witherell+	(UCSB, LBL)
DRUZHININ	87	ZPHY C37 1	+Dubrovin, Eidelman, Golubev+	(NOVO)
ELLIOTT	87	PRL 59 1649	+Hahn, Moe	(UCI)
FISHER	87	PL B192 460	+Boehm, Bovet, Egger+	(CIT, NEUC, SIN)
FRIEMAN	87	PR D36 2201	+Dimopoulos, Turner	(SLAC, STAN, FNAL, EFI)
GOLDMAN	87	PR D36 1543	+Hallin, Hoffman+	(LANL, CHIC, STAN, TEMP)
KORENCHE...	87	SJNP 46 192	Korenchenko, Kostin, Mzhaviya+	(JINR)
		Translated from YAF 46 313.		
MAIER	87	ZPHY A326 527	+Bauer, Briggmann, Carstanjen+	(STUT, GSI)
MILLS	87	PR D36 707	+Levy	(BELL)
RAFFELT	87	PR D36 2211	+Dearborn	(LLL, UCB)
RIORDAN	87	PRL 59 755	+Krasny, Lang, Barbaro, Bodek+	(ROCH, CIT+)
TURNER	87	PRL 59 2489		(FNAL, EFI)
VONWIMMER...	87	PRL 59 266	von Wimmersperg, Connell, Hoernle, Sideras-Haddad	(WITW)
ALBRECHT	86D	PL B179 403	+Binder, Boeckmann+	(ARGUS Collab.)
BADIER	86	ZPHY C31 21	+Bemporad, Boucrot, Callot+	(NA3 Collab.)
BOWCOCK	86	PRL 56 2676	+Giles, Hassard, Kinoshita+	(CLEO Collab.)
BROWN	86	PRL 57 2101	+	(FNAL, WASH, KYOT, KEK, COLU, STON, SACL)
BRYMAN	86B	PRL 57 2787	+Clifford	(TRIU)
DAVIER	86	PL B180 295	+Jeanjean, Nguyen Ngoc	(LALO)
DEARBORN	86	PRL 56 26	+Schramm, Steigman	(LLL, CHIC, FNAL, BART)
EICHLER	86	PL B175 101	+Felawka, Kraus, Niebuhr+	(SINDRUM Collab.)
HALLIN	86	PRL 57 2105	+Calparice, Dunford, McDonald	(PRIN)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
KETOV	86	JETPL 44 146	+Klimov, Nikolaev, Mikaelyan+	(KIAE)
		Translated from ZETFP 44 114.		
KOCH	86	NC 96A 182	+Schult	(JULI)
KONAKA	86	PRL 57 659	+Imai, Kobayashi, Masaike, Miyake+	(KYOT, KEK)
MAGERAS	86	PRL 56 2672	+Franzini, Tuts, Youssef+	(MPIM, COLU, STON)
PECCEI	86	PL B172 435	+Wu, Yanagida	(DESY)
RAFFELT	86	PR D33 897		(MPIM)
RAFFELT	86B	PL 166B 402		(MPIM)
SAVAGE	86B	PRL 57 178	+McKeown, Filippone, Mitchell	(CIT)
AMALDI	85	PL 153B 444	+Carboni, Jonson, Thun	(CERN)
ANANEV	85	SJNP 41 585	+Kalinina, Lushchikov, Olshevskii+	(JINR)
		Translated from YAF 41 912.		
BALTRUSAIT...	85	PRL 55 1842	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BERGSMA	85	PL 157B 458	+Dorenbosch, Allaby, Amaldi+	(CHARM Collab.)
KAPLAN	85	NP B260 215		(HARV)
IWAMOTO	84	PRL 53 1198		(UCSB, WUSL)
YAMAZAKI	84	PRL 52 1089	+Ishikawa, Taniguchi, Yamanaka+	(TOKY, KEK)
ABBOTT	83	PL 120B 133	+Sikivie	(BRAN, FLOR)
ALAM	83	PR D27 1665	+	(VAND, CORN, ITHA, HARV, OHIO, ROCH+)
CARBONI	83	PL 123B 349	+Dahme	(CERN, MUNI)
CAVAIGNAC	83	PL 121B 193	+Hoummada, Koang, Ost+	(ISNG, LAPP)
DICUS	83	PR D28 1778	+Teplitz	(TEXA, UMD)
DINE	83	PL 120B 137	+Fischler	(IAS, PENN)
ELLIS	83B	NP B223 252	+Olive	(CERN)
FAISSNER	83	PR D28 1198	+Heinrigs, Preussger, Samm	(AACH)
FAISSNER	83B	PR D28 1787	+Frenzel, Heinrigs, Preussger+	(AACH)
FRANK	83B	PR D28 1790	+	(LANL, YALE, LBL, MIT, SACL, SIN, CNRC, BERN)
HOFFMAN	83	PR D28 660	+Frank, Mischke, Moir, Schardt	(LANL, ARZS)
NICZYPORUK	83	ZPHY C17 197	+Jakubowski, Zeludziewicz+	(LENA Collab.)
PRESKILL	83	PL 120B 127	+Wise, Wilczek	(HARV, UCSB)
SIKIVIE	83	PRL 51 1415		(FLOR)
Also	84	PRL 52 695 (erratum)	Sikivie	(FLOR)
ALEKSEEV	82	JETP 55 591	+Kartamyshev, Makarin+	(KIAE)
		Translated from ZETF 82 1007.		
ALEKSEEV	82B	JETPL 36 116	+Kalinina, Kruglov, Kulikov+	(MOSU, JINR)
		Translated from ZETFP 36 94.		
ASANO	82	PL 113B 195	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, OSAK)
BARROSO	82	PL 116B 247	+Branco	(LISB)
DATAR	82	PL 114B 63	+Baba, Betigeri, Singh	(BHAB)
EDWARDS	82	PRL 48 903	+Partridge, Peck, Porter+	(Crystal Ball Collab.)
FETSCHER	82	JP G8 L147		(ETH)
FUKUGITA	82	PRL 48 1522	+Watamura, Yoshimura	(KEK)
FUKUGITA	82B	PR D26 1840	+Watamura, Yoshimura	(KEK)
LEHMANN	82	PL 115B 270	+Lesquoy, Muller, Zylberajch	(SACL)
RAFFELT	82	PL 119B 323	+Stodolsky	(MPIM)
SIVERTZ	82	PR D26 717	+Lee-Franzini, Horstkotte+	(CUSB Collab.)
VERGADOS	*82*	*PL 109B 96*		*(CERN)*
ZEHNDER	82	PL 110B 419	+Gabathuler, Vuilleumier	(ETH, SIN, CIT)
ASANO	81B	PL 107B 159	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, OSAK)
BARROSO	81	PL 106B 91	+Mukhopadhyay	(SIN)
FAISSNER	81	ZPHY C10 95	+Frenzel, Grimm, Hansl, Hoffman+	(AACH)
FAISSNER	81B	PL 103B 234	+Frenzel, Heinrigs, Preussger+	(AACH)
KIM	81	PL 105B 55	+Stamm	(AACH)
VUILLEUMIER	81	PL 101B 341	+Boehm, Hahn, Kwon+	(CIT, MUNI)
ZEHNDER	*81*	*PL 104B 494*		*(ETH)*
FAISSNER	80	PL 96B 201	+Frenzel, Heinrigs, Preussger, Samm+	(AACH)
JACQUES	80	PR D21 1206	+Kalelkar, Miller, Plano+	(RUTG, STEV, COLU)
SOUKAS	80	PRL 44 564	+Wanderer, Weng+	(BNL, HARV, ORNL, PENN)
BECHIS	79	PRL 42 1511	+Dombeck+	(UMD, COLU, AFRR)
CALAPRICE	79	PR D20 2708	+Dunford, Kouzes, Miller+	(PRIN)
COTEUS	79	PRL 42 1438	+Diesburg, Fine, Lee, Sokolsky+	(COLU, ILL, BNL)
DISHAW	79	PL 85B 142	+Diamant-Berger, Faessler, Liu+	(SLAC, CIT)
ZHITNITSKII	79	SJNP 29 517	+Skovpen	(NOVO)
		Translated from YAF 29 1001.		
ALIBRAN	78	PL 74B 134	+Armenise, Arnold, Bartley	(Gargamelle Collab.)
ASRATYAN	78B	PL 79B 497	+Epstein, Fakhrutdinov+	(ITEP, SERP)
BELLOTTI	78	PL 76B 223	+Fiorini, Zanotti	(MILA)
BOSETTI	78B	PL 74B 143	+Deden, Deutschmann, Fritze+	(BEBC Collab.)
DICUS	78C	PR D18 1829	+Kolb, Teplitz, Wagoner	(TEXA, VPI, STAN)
DONNELLY	78	PR D18 1607	+Freedman, Lytel, Peccei, Schwartz	(STAN)
Also	76	PRL 37 315	Reines, Gurr, Sobel	(UCI)
Also	74	PRL 33 179	Gurr, Reines, Sobel	(UCI)
HANSL	78D	PL 74B 139	+Holder, Knobloch, May, Paar+	(CDHS Collab.)
MICELMAC...	78	LNC 21 441	Micelmacher, Pontecorvo	(JINR)
MIKAELIAN	78	PR D18 3605		(FNAL, NWES)
SATO	78	PTP 60 1942		(KYOT)
VYSOTSKII	78	JETPL 27 502	+Zeldovich, Khlopov, Chechetkin	(ASCI)
		Translated from ZETFP 27 533.		
YANG	78	PRL 41 523		(MASA)
PECCEI	77	PR D16 1791	+Quinn	(STAN, SLAC)
Also	77B	PRL 38 1440	Peccei, Quinn	(STAN, SLAC)
REINES	76	PRL 37 315	+Gurr, Sobel	(UCI)
GURR	74	PRL 33 179	+Reines, Sobel	(UCI)

OTHER RELATED PAPERS

SREDNICKI	85	NP B260 689		(UCSB)
BARDEEN	78	PL 74B 229	+Tye	(FNAL)

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u}-d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

NOTE ON PSEUDOSCALAR–MESON DECAY CONSTANTS

The decay constant f_P for pseudoscalar meson P is defined by

$$\langle 0|A_\mu(0)|P(\mathbf{q})\rangle = if_P\, q_\mu \ ,$$

where A_μ is the axial-vector part of the charged weak current after a Cabibbo-Kobayashi-Maskawa mixing-matrix element $V_{qq'}$ has been removed. The state vector is normalized by $\langle P(\mathbf{q})|P(\mathbf{q}')\rangle = (2\pi)^3 2E_q\, \delta(\mathbf{q}-\mathbf{q}')$, and its phase is chosen to make f_P real and positive. Note, however, that in many theoretical papers our $f_P/\sqrt{2}$ is denoted by f_P and called the pseudoscalar decay constant.

In determining f_P experimentally, radiative corrections must in principle be taken into account. Since the photon-loop correction introduces an infrared divergence that is canceled by soft-photon emission, we can determine f_P only from the combined rate for $P^\pm \to \ell^\pm\nu$ and $P^\pm \to \ell^\pm\nu\gamma$. This rate is given by

$$\Gamma\left[P \to \ell\nu(+\ell\nu\gamma)\right] =$$

$$\frac{G_F^2 |V_{qq'}{}^2|}{8\pi} f_P^2\, m_\ell^2\, m_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 \left[1 + \frac{\alpha}{2\pi}(B + B_{\rm SD})\right] \ .$$

The term of order α consists of the inner bremsstrahlung part B, which does not depend on the structure of the meson,[1,2] and the structure-dependent part $B_{\rm SD}$.[3] Although the latter involves a substantial theoretical ambiguity and grows with m_P, it is, in the case of the muonic decays, much smaller than the unambiguous inner bremsstrahlung part. Since we determine f_π, f_K, and f_D from muonic decays, we keep only the inner bremsstrahlung part, given by[4]

$$B = 4\left[\left(\frac{x^2+1}{x^2-1}\right)\ln x - 1\right]\left[\ln(x^2-1) - 2\ln x - \frac{3}{4}\right]$$

$$+4\left(\frac{x^2+1}{x^2-1}\right)L\left(1 - \frac{1}{x^2}\right) - \ln x - \frac{3}{4}$$

$$+\frac{(10x^2-7)}{(x^2-1)^2}\ln x + \frac{(15x^2-21)}{4(x^2-1)} \ ,$$

where

$$L(z) = \int_0^z \ln(1-t)\frac{dt}{t} \ , \text{ and } x = m_P/m_\ell \ .$$

B is -1.35 for $\pi \to \mu\nu$ and -6.44 for $K \to \mu\nu$.

We use the experimental values of $|V_{qq'}|$ given in Eqs. (5), (7), and (8) of the "Cabibbo-Kobayashi-Maskawa Mixing Matrix" section and our current best values of branching ratios, lifetimes, and masses to obtain the following values:

$$f_\pi = (131.74 \pm 0.15) \text{ MeV} \ ,$$

$$f_K = (160.6 \pm 1.4) \text{ MeV} \ ,$$

$$f_D < 310 \text{ MeV} \ \ (\text{CL} = 90\%) \ .$$

References

1. S. Berman, Phys. Rev. Lett. **1**, 468 (1958).
2. T. Kinoshita, Phys. Rev. Lett. **2**, 477 (1959).
3. T. Goldman and W.J. Wilson, Phys. Rev. **D15**, 709 (1977).
4. A. Sirlin, Phys. Rev. **D5**, 436 (1972).

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition (Physics Letters B204).

$\pi^{\pm}$ MASS

The fit uses the $\pi^\pm$, π^0, and $\mu^\pm$ mass and mass difference measurements. Measurements with an error > 0.005 MeV have been omitted from this Listing.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
139.5675±0.0004 OUR FIT	Error includes scale factor of 1.2.				
139.56737±0.00033 OUR AVERAGE					
139.56752±0.00037	[1] JECKELMAN	86	CNTR	−	Mesonic atoms
139.5664 ±0.0009	[2] LU	80	CNTR	−	Mesonic atoms
139.5686 ±0.0020	CARTER	76	CNTR	−	Mesonic atoms
139.5660 ±0.0024	[2,3] MARUSHEN...	76	CNTR	−	Mesonic atoms
• • • We do not use the following data for averages, fits, limits, etc. • • •					
139.5704 ±0.0011	[4] ABELA	84	SPEC	+	$\pi^+ \to \mu^+\nu$

[1] JECKELMAN 86 gives $m(\pi)/m(e) = 273.12677(71)$. We use $m(e) = 0.51099906(15)$ MeV from COHEN 87.

[2] Value
scaled with a new wavelength-energy conversion factor $V\lambda = 1.23984244(37)\times10^{-6}$ eV m from COHEN 87.

[3] This MARUSHENKO 76 value used at the authors' request to use the accepted set of calibration γ energies. Error increased from 0.0017 MeV to include QED calculation error of 0.0017 MeV (12 ppm).

[4] The ABELA 84 value depends on assumed μ^+ mass $= 105.65932 \pm 0.00029$ MeV. ABELA 84 enters our fit via the π–μ mass difference below, which is independent of $m(\mu)$.

$\pi^+ - \mu^+$ MASS DIFFERENCE

The fit uses the $\pi^\pm$, π^0, and $\mu^\pm$ mass and mass difference measurements. Measurements with an error > 0.05 MeV have been omitted from this Listing.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
33.9092±0.0004 OUR FIT	Error includes scale factor of 1.2.					
33.9111±0.0011		ABELA	84	SPEC		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
33.925 ±0.025		BOOTH	70	CNTR	+	Magnetic spect.
33.881 ±0.035	145	HYMAN	67	HEBC	+	K^- He

$[m(\pi^+) - m(\pi^-)]$ / AVERAGE m

A test of *CPT* invariance.

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*
2±5	AYRES	71	CNTR

$\pi^{\pm}$ MEAN LIFE

Measurements with an error > 0.02×10^{-8} s have been omitted.

VALUE (10^{-8} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.6030±0.0024 OUR AVERAGE				
2.609 ±0.008	DUNAITSEV	73	CNTR	+
2.602 ±0.004	AYRES	71	CNTR	±
2.604 ±0.005	NORDBERG	67	CNTR	+
2.602 ±0.004	ECKHAUSE	65	CNTR	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.640 ±0.008	[5] KINSEY	66	CNTR	+

[5] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

$[\tau(\pi^+) - \tau(\pi^-)]$ / AVERAGE τ

A test of *CPT* invariance.

VALUE (units 10^{-4})	DOCUMENT ID		TECN
5.5± 7.1	AYRES	71	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−14 ±29	PETRUKHIN	68	CNTR
40 ±70	BARDON	66	CNTR
23 ±40	[6] LOBKOWICZ	66	CNTR

[6] This is the most conservative value given by LOBKOWICZ 66.

π^+ DECAY MODES

π^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+\nu_\mu$		(99.98782 ± 0.00014) %	
Γ_2	$e^+\nu_e$		$(1.218\pm0.014)\times10^{-4}$	
Γ_3	$\mu^+\nu_\mu\gamma$	[a]	$(1.24\pm0.25)\times10^{-4}$	
Γ_4	$e^+\nu_e\gamma$	[a]	$(5.6\pm0.7)\times10^{-8}$	
Γ_5	$e^+\nu_e\pi^0$		$(1.025\pm0.034)\times10^{-8}$	
Γ_6	$e^+\nu_e e^+ e^-$		$(3.2\pm0.5)\times10^{-9}$	
Γ_7	$e^+\nu_e\nu\overline{\nu}$		$<5\times10^{-6}$	90%
Lepton number (*L*) or Lepton Family number (*LF*) violating modes				
Γ_8	$\mu^+\overline{\nu}_e$	*L*	$<1.5\times10^{-3}$	90%
Γ_9	$\mu^+\nu_e$	*LF*	$<8.0\times10^{-3}$	90%
Γ_{10}	$\mu^-e^+e^+\nu$	*LF*	$<7.7\times10^{-6}$	90%

[a] See the Listings below for the energy range used in this measurement; low-energy γ's are not included. See also the note to the next block of data.

π^+ BRANCHING RATIOS

$\Gamma(e^+\nu_e)/\Gamma_{\text{total}}$ Γ_2/Γ

See the next block of data. Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\text{total}} = 100\%$.

VALUE (units 10^{-4})	DOCUMENT ID
1.218±0.014 OUR EVALUATION	

$[\Gamma(e^+\nu_e) + \Gamma(e^+\nu_e\gamma)]/[\Gamma(\mu^+\nu_\mu) + \Gamma(\mu^+\nu_\mu\gamma)]$ $(\Gamma_2+\Gamma_4)/(\Gamma_1+\Gamma_3)$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.218±0.014	32k	BRYMAN	86	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.218±0.014	32k	BRYMAN	83	CNTR	See BRYMAN 86
1.273±0.028	11k	[7] DICAPUA	64	CNTR	
1.21 ±0.07		ANDERSON	60	CNTR	

[7] DICAPUA 64 updated using current mean life.

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.24±0.25	26	CASTAGNOLI	58	EMUL	$\text{KE}_\mu < 3.38$ MeV

$\Gamma(e^+\nu_e\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
5.6±0.7	226	[8] STETZ	78	SPEC	$P_e > 56$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.0	143	DEPOMMIER	63B	CNTR	$(\text{KE})_{e^+\gamma} > 48$ MeV

[8] STETZ 78 is for an $e^-\gamma$ opening angle > 132°. Obtains 3.7 when using same cutoffs as DEPOMMIER 63B.

$\Gamma(e^+\nu_e\pi^0)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.025±0.034 OUR AVERAGE						
1.026±0.039	1224	[9] MCFARLANE	85	CNTR	+	Decay in flight
$1.00\ {}^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[10] BACASTOW	65	OSPK	+	
1.10 ±0.26		[10] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[10] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[10] BARTLETT	64	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.15 ±0.22	52	[10] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

[9] Combines a measured rate (0.394 ± 0.015)/s with 1982 PDG mean life.

[10] DEPOMMIER 68 says the result of DEPOMMIER 63 is at least 10% too large because of a systematic error in the π^0 detection efficiency, and that this may be true of all the previous measurements (also V. Soergel, private communication, 1972).

$\Gamma(e^+\nu_e e^+ e^-)/\Gamma(\mu^+\nu_\mu)$ Γ_6/Γ_1

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.2±0.5±0.2		98	EGLI	89	SPEC		Uses $R_{\text{PCAC}} = 0.068\pm0.004$
• • • We do not use the following data for averages, fits, limits, etc. • • •							
seen		79	EGLI	86	SPEC	+	See EGLI 89
< 4.8	90		KORENCHE...	76B	SPEC	+	
<34	90		KORENCHE...	71	OSPK	+	

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<5	90	PICCIOTTO	88	SPEC

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_8/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ Γ_9/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8.0	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\mu^-e^+e^+\nu)/\Gamma_{\text{total}}$ Γ_{10}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
<7.7	90	KORENCHE...	87	SPEC	+

π^+ — POLARIZATION OF EMITTED μ^+

$\pi^+ \to \mu^+\nu$

Tests the Lorentz structure of leptonic charged weak interactions.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<(−0.9959)	90	[11] FETSCHER	84	RVUE	+	
−0.99±0.16		[12] ABELA	83	SPEC	−	μ *X*-rays

[11] FETSCHER 84 uses only the measurement of CARR 83.

[12] Sign of measurement reversed in ABELA 83 to compare with μ^+ measurements.

NOTE ON $\pi^\pm \to \ell^\pm\nu\gamma$ AND $K^\pm \to \ell^\pm\nu\gamma$ FORM FACTORS

(by H.S. Pruys, Zürich University)

In the radiative decay $P^\pm \to \ell^\pm\nu\gamma$, where P stands for π or K, ℓ for e or μ, and γ for a real or virtual photon (e^+e^- pair), both the vector and the axial-vector weak hadronic currents contribute to the decay amplitude. The vector current only gives a structure-dependent term (SD_V), but the axial-vector current gives two contributions, one for inner bremsstrahlung (IB) from the lepton and meson, and one for structure-dependent radiation (SD_A) from virtual hadronic states. The IB amplitudes are determined by the meson decay constants f_π and f_K.[1] The SD_V and SD_A amplitudes are parameterized by the vector form factor F_V and the axial-vector form factors F_A and R.[1–4]

$$M(\text{SD}_V) = \frac{-eG_F V_{qq'}}{\sqrt{2}\, m_P} \epsilon^\mu\, \ell^\nu\, F_V\, \epsilon_{\mu\nu\sigma\tau}\, k^\sigma\, q^\tau \ ,$$

$$M(\text{SD}_A) = \frac{-ie\, G_F V_{qq'}}{\sqrt{2}\, m_P}\, \epsilon^\mu\, \ell^\nu \left\{F_A\left[(s-t)g_{\mu\nu} - q_\mu\, k_\nu\right] + Rtg_{\mu\nu}\right\} \ .$$

Here $V_{qq'}$ is the Cabibbo-Kobayashi-Maskawa mixing-matrix element; ϵ^μ is the polarization vector of the real photon or the e^+e^- current, $\epsilon^\mu = (e/t)\overline{u}(p_-)\gamma^\mu v(p_+)$; ℓ^ν is the lepton-neutrino current, $\ell^\nu = \overline{u}(p_\nu)\gamma^\nu(1-\gamma_5)v(p_\ell)$; q and k are the meson and photon four-momenta; and $s = q\cdot k$ and $t = k^2$. The s and t dependence of the form factors is neglected, which is a good approximation for pions,[2] but not for kaons.[4] For pions, the vector form factor F_V^π is related via CVC to the

π^0 lifetime, $|F_V^{\pi}| = (1/\alpha)\sqrt{2\Gamma_{\pi^0}/\pi m_{\pi^0}}$.[1] PCAC relates R to the electromagnetic radius of the meson,[2,4] $R^P = \frac{1}{3} m_P f_P \langle r_P^2 \rangle$. The calculation of the other form factors, F_A^{π}, F_V^K, and F_A^K, is model dependent.[1,4]

For the decay $P^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ with a real photon, the partial decay rate can be given analytically,[1,5]

$$\frac{d^2\Gamma_{P\rightarrow\ell\nu\gamma}}{dxdy} = \frac{d^2\Gamma_{\rm IB}}{dxdy} + \frac{d^2\Gamma_{\rm SD}}{dxdy} + \frac{d^2\Gamma_{\rm INT}}{dxdy} ,$$

$$\frac{d^2\Gamma_{\rm SD}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{P\rightarrow\ell\nu}\,\frac{1}{r(1-r)^2}\left(\frac{m_P}{f_P}\right)^2$$
$$\times\left[(F_V+F_A)^2\,{\rm SD}^+ + (F_V-F_A)^2\,{\rm SD}^-\right] ,$$

where

$${\rm SD}^+ = (x+y-1-r)\left[(x+y-1)(1-x)-r\right] ,$$
$${\rm SD}^- = (1-y+r)\left[(1-x)(1-y)+r\right] .$$

Here $x = 2E_\gamma/m_P$, $y = 2E_\ell/m_P$, and $r = (m_\ell/m_P)^2$. $\Gamma_{\rm IB}, \Gamma_{\rm SD}$, and $\Gamma_{\rm INT}$ are the contributions from inner brems-strahlung, structure-dependent radiation, and their interference.

In $\pi^{\pm} \rightarrow e^{\pm}\nu\gamma$ and $K^{\pm} \rightarrow e^{\pm}\nu\gamma$ decays, the interference terms are small, and thus only the absolute values $|F_A + F_V|$ and $|F_A - F_V|$ can be obtained. In $K^{\pm} \rightarrow \mu^{\pm}\nu\gamma$ decay, the interference term is important and thus the signs of F_V and F_A can be obtained. In $\pi^{\pm} \rightarrow \mu^{\pm}\nu\gamma$ decay, bremsstrahlung completely dominates. In $\pi^{\pm} \rightarrow e^{\pm}\nu e^+e^-$ and $K^{\pm} \rightarrow \ell^{\pm}\nu e^+e^-$ decays, all three form factors, F_V, F_A, and R, can be determined.

We list the $\pi^{\pm}$ form factors F_V, F_A, and R below. In the $K^{\pm}$ branching ratio section of the Full Listings, we list measurements of $\Gamma_{{\rm SD}^+}$ and combinations of the interference terms and $\Gamma_{{\rm SD}^-}$ for $K^{\pm} \rightarrow \mu^{\pm}\nu\gamma$, and $\Gamma_{{\rm SD}^+}$ and $\Gamma_{{\rm SD}^-}$ for $K^{\pm} \rightarrow e^{\pm}\nu\gamma$.

References

1. D.A. Bryman et al., Phys. Rep. **88**, 151 (1982). See also the "Note on Pseudoscalar-Meson Decay Constants," above.
2. A. Kersch and F. Scheck, Nucl. Phys. **B263**, 475 (1986).
3. W.T. Chu et al., Phys. Rev. **166**, 1577 (1968).
4. D.Yu. Bardin and E.A. Ivanov, Sov. J. Part. Nucl. **7**, 286 (1976).
5. S.G. Brown and S.A. Bludman, Phys. Rev. **136**, B1160 (1964).

$\pi^{\pm}$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.023^{+0.015}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+\nu_e e^+ e^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.029^{+0.019}_{-0.014}$		EGLI	86	SPEC	See EGLI 89

F_A, AXIAL-VECTOR FORM FACTOR

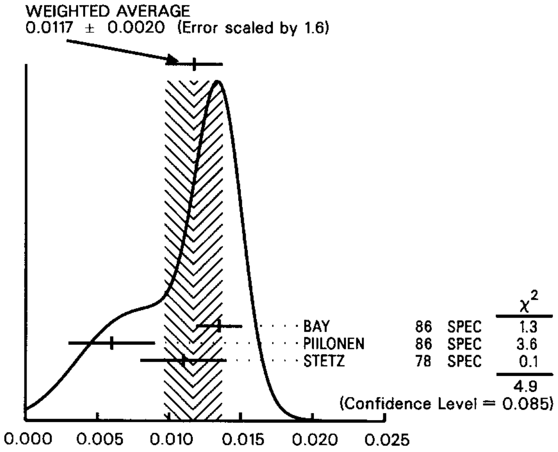
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0117±0.0020 OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.			
0.0135±0.0016		[13] BAY	86	SPEC	$\pi^+ \rightarrow e^+\nu\gamma$
0.006 ±0.003		[13] PIILONEN	86	SPEC	$\pi^+ \rightarrow e^+\nu\gamma$
0.011 ±0.003		[13,14] STETZ	78	SPEC	$\pi^+ \rightarrow e^+\nu\gamma$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.021\ ^{+0.011}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+\nu_e e^+ e^-$
$0.018\ ^{+0.015}_{-0.012}$		EGLI	86	SPEC	See EGLI 89

[13] Using the vector form factor from CVC prediction F_V = 0.0259 ± 0.0005. Only the absolute value of F_A is determined.

[14] The result of STETZ 78 has a two-fold ambiguity. We take the solution compatible with later determinations.



$\pi^{\pm}$ axial-vector form factor

R, SECOND AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.059^{+0.009}_{-0.008}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+\nu_e e^+ e^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.063^{+0.026}_{-0.016}$		EGLI	86	SPEC	See EGLI 89

REFERENCES FOR $\pi^{\pm}$

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition (Physics Letters **B204**).

EGLI 89 PL B222 533 +Engfer, Grab, Hermes, Kraus+ (SINDRUM Collab.)
PICCIOTTO 88 PR D37 1131 +Ahmad, Britton, Bryman, Clifford+ (TRIU, CNRC)
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
KORENCHE... 87 SJNP 46 192 Korenchenko, Kostin, Mzhaviya+ (JINR)
Translated from YAF 46 313.
BAY 86 PL B174 445 +Ruegger, Gabioud, Joseph, Loude+ (LAUS, ZURI)
BRYMAN 86 PR D33 1211 +Dubois, Macdonald, Numao+ (TRIU, CNRC)
EGLI 86 PL B175 97 +Engfer, Grab, Hermes+ (AACH, ETH, SIN, ZURI)
JECKELMAN 86 PRL 56 1444 +Nakada, Beer+ (ETH, FRIB)
PIILONEN 86 PRL 57 1402 +Bolton, Cooper, Frank+ (LANL, TEMP, CHIC)
MCFARLANE 85 PR D32 547 +Auerbach, Gaille+ (TEMP, LANL)
ABELA 84 PL 146B 431 +Daum, Eaton, Frosch, Jost, Kettle+ (SIN)
Also 78 PL 74B 126 Daum, Eaton, Frosch, Hirschmann+ (SIN)
Also 79 PR D20 2692 Daum, Eaton, Frosch, Hirschmann+ (SIN)
FETSCHER 84 PL 140B 117 (ETH)
ABELA 83 NP A395 413 +Backenstoss, Kunold, Simons+ (BASL, KARL)
BRYMAN 83 PRL 50 7 +Dubois, Numao, Olaniya+ (TRIU, CNRC)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
LU 80 PRL 45 1066 +Delker, Dugan, Wu, Caffrey+ (YALE, COLU, JHU)
STETZ 78 NP B138 285 +Carroll, Ortendahl, Perez-Mendez+ (LBL, UCLA)
CARTER 76 PRL 37 1380 +Dixit, Sundaresan+ (CARL, CNRC, CHIC, CIT)
KORENCHE... 76B JETP 44 35 Korenchenko, Kostin, Micelmacher+ (JINR)
Translated from ZETF 71 69.
MARUSHEN... 76 JETPL 23 72 Marushenko, Mezentsev, Petrunin+ (LENI)
Translated from ZETFP 23 80.
Also 76 Private Comm. Shafer (FNAL)
Also 78 Private Comm. Smirnov (LENI)
DUNAITSEV 73 SJNP 16 292 +Prokoshkin, Razuvaev+ (SERP)
Translated from YAF 16 524.
AYRES 71 PR D3 1051 +Cormack, Greenberg, Kenney+ (LRL, UCSB)
Also 67 PR 157 1288 Ayres, Caldwell, Greenberg, Kenney, Kurz+ (LRL)
Also 68 PRL 21 261 Ayres, Cormack, Greenberg+ (LRL, UCSB)
Also 69 UCRL 18369 Thesis Ayres (LRL)
Also 69 PRL 23 1267 Greenberg, Ayres, Cormack+ (LRL, UCSB)
KORENCHE... 71 SJNP 13 189 Korenchenko, Kostin, Micelmacher+ (JINR)
Translated from YAF 13 339.

Meson Full Listings

BOOTH 70 PL 32B 723 +Johnson, Williams, Wormald (LIVP)
DEPOMMIER 68 NP B4 189 +Duclos, Heintze, Kleinknecht+ (CERN)
PETRUKHIN 68 JINR P1 3862 +Rykalin, Khazins, Cisek (JINR)
HYMAN 67 PL 25B 376 +Loken, Pewitt, McKenzie+ (ANL, CMU, NWES)
NORDBERG 67 PL 24B 594 +Lobkowicz, Burman (ROCH)
BARDON 66 PRL 16 775 +Dore, Dorfan, Krieger+ (COLU)
KINSEY 66 PR 144 1132 +Lobkowicz, Nordberg (ROCH)
LOBKOWICZ 66 PRL 17 548 +Melissinos, Nagashima+ (ROCH, BNL)
BACASTOW 65 PR 139B 407 +Ghesquiere, Wiegand, Larsen (LRL, SLAC)
BERTRAM 65 PR 139B 617 +Meyer, Carrigan+ (MICH, CMU)
DUNAITSEV 65 JETP 20 58 +Petrukhin, Prokoshkin+ (JINR)
Translated from ZETF 47 84.
ECKHAUSE 65 PL 19 348 +Harris, Shuler+ (WILL)
BARTLETT 64 PR 136B 1452 +Devons, Meyer, Rosen (COLU)
DICAPUA 64 PR 133B 1333 +Garland, Pondrom, Strelzoff (COLU)
Also 86 Private Comm. Pondrom (WISC)
DEPOMMIER 63 PL 5 61 +Heintze, Rubbia, Soergel (CERN)
DEPOMMIER 63B PL 7 285 +Heintze, Rubbia, Soergel (CERN)
ANDERSON 60 PR 119 2050 +Fujii, Miller+ (EFI)
CASTAGNOLI 58 PR 112 1779 +Muchnik (ROMA)

OTHER RELATED PAPERS

BRYMAN 82B PRPL 88 151 +Depommier, Leroy (TRIU, MONT, LVLN)
DEPOMMIER 80 NP A335 97 (MONT)
WILKIN 80 JP G6 L5 (LOUC) P
BRYMAN 75 PR D11 1337 +Picciotto (VICT)
CARRIGAN 68 NP B6 662 (CMU) J
CZIRR 63 PR 130 341 (LRL)
MERRISON 62 ADVP 11 1 (LIVP)
SHAPIRO 62 PR 125 1022 +Lederman (COLU)
CARTWRIGHT 53 PR 91 677 +Richman, Whitehead, Wilcox (LRL) J

$\boxed{\pi^0}$

$I^G(J^{PC}) = 1^-(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition (Physics Letters B204).

π^0 MASS

The fit uses the $\pi^{\pm}$, π^0, and $\mu^{\pm}$ mass and mass difference measurements.

VALUE (MeV)	*DOCUMENT ID*
134.9739±0.0006 OUR FIT	Error includes scale factor of 1.1.

$\pi^{\pm} - \pi^0$ MASS DIFFERENCE

The fit uses the $\pi^{\pm}$, π^0, and $\mu^{\pm}$ mass and mass difference measurements. Measurements with an error > 0.01 MeV have been omitted from this Listing.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
4.5937 ±0.0005 OUR FIT				
4.59366±0.00048	CRAWFORD	88B	CNTR	$\pi^- p \to \pi^0 n$, n TOF

• • • We do not use the following data for averages, fits, limits, etc. • • •

4.5930 ±0.0013	CRAWFORD	86	CNTR	See CRAWFORD 88B
4.6034 ±0.0052	VASILEVSKY	66	CNTR	
4.6056 ±0.0055	CZIRR	63	CNTR	

π^0 MEAN LIFE

Measurements with an error > 1 × 10^{-17} s have been omitted.

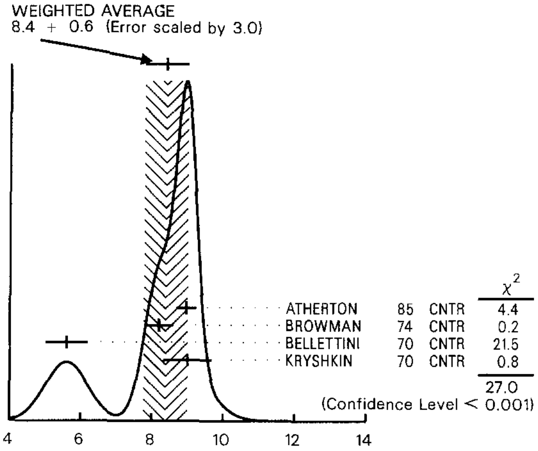
VALUE (10^{-17} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
8.4 ±0.6 OUR AVERAGE		Error includes scale factor of 3.0. See the ideogram below.			
8.97±0.22±0.17		ATHERTON	85	CNTR	
8.2 ±0.4		[1] BROWMAN	74	CNTR	Primakoff effect
5.6 ±0.6		BELLETTINI	70	CNTR	Primakoff effect
9 ±0.68		KRYSHKIN	70	CNTR	Primakoff effect

• • • We do not use the following data for averages, fits, limits, etc. • • •

8.4 ±0.5 ±0.5	1182	[2] WILLIAMS	88	CBAL	$e^+ e^- \to e^+ e^- \pi^0$

[1] BROWMAN 74 gives a π^0 width Γ = 8.02 ± 0.42 eV. The mean life is $\hbar/\Gamma$.

[2] WILLIAMS 88 gives $\Gamma(\gamma\gamma)$ = 7.7 ± 0.5 ± 0.5 eV. We give here $\tau = \hbar/\Gamma(\text{total})$.



π^0 mean life (10^{-17} s)

π^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ		(98.798±0.032) %	S=1.1
Γ_2	$e^+ e^- \gamma$		(1.198±0.032) %	S=1.1
Γ_3	$e^+ e^+ e^- e^-$		(3.14 ±0.30) × 10^{-5}	
Γ_4	$e^+ e^-$		< 1.3 × 10^{-7}	CL=90%
Γ_5	4γ		< 2 × 10^{-8}	CL=90%
Γ_6	$\nu \overline{\nu}$		< 6.5 × 10^{-6}	CL=90%
Γ_7	$\nu_e \overline{\nu}_e$		< 1.7 × 10^{-6}	CL=90%
Γ_8	$\nu_\mu \overline{\nu}_\mu$		< 3.1 × 10^{-6}	CL=90%
Γ_9	$\nu_\tau \overline{\nu}_\tau$		< 2.1 × 10^{-6}	CL=90%
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
Γ_{10}	3γ	*C*	< 3.1 × 10^{-8}	CL=90%
Γ_{11}	$\mu^+ e^-$	*LF*	< 1.6 × 10^{-8}	CL=90%
Γ_{12}	$\mu^+ e^- + e^- \mu^+$	*LF*		

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a χ^2 = 1.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ccc} x_2 & -100 & \\ x_3 & -1 & 0 \\ & x_1 & x_2 \end{array}$$

π^0 BRANCHING RATIOS

$\Gamma(e^+ e^- \gamma)/\Gamma(2\gamma)$ Γ_2/Γ_1

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.213±0.033 OUR FIT		Error includes scale factor of 1.1.			
1.213±0.030 OUR AVERAGE					
1.25 ±0.04		SCHARDT	81	SPEC	$\pi^- p \to n \pi^0$
1.166±0.047	3071	[3] SAMIOS	61	HBC	$\pi^- p \to n \pi^0$
1.17 ±0.15	27	BUDAGOV	60	HBC	

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.196		JOSEPH	60	THEO	QED calculation

[3] SAMIOS 61 value uses a Panofsky ratio = 1.62.

$\Gamma(e^+ e^+ e^- e^-)/\Gamma(2\gamma)$ Γ_3/Γ_1

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3.18±0.30 OUR FIT					
3.18±0.30	146	[4] SAMIOS	62B	HBC	

• • • We do not use the following data for averages, fits, limits, etc. • • •

3.28		MIYAZAKI	73	THEO	QED calculation

[4] SAMIOS 62B value uses a Panofsky ratio = 1.62.

$\Gamma(e^+e^-)/\Gamma(2\gamma)$ Γ_4/Γ_1

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.3	90		NIEBUHR 89	SPEC	$\pi^- p \to \pi^0 n$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.3	90		ZEPHAT 87	SPEC	$\pi^- p \to \pi^0 n$ 0.3 GeV/c
1.7 ±0.6 ±0.3		59	FRANK 83	SPEC	$\pi^- p \to n\pi^0$
1.8 ±0.6		58	MISCHKE 82	SPEC	See FRANK 83
$2.23^{+2.40}_{-1.10}$	90	8	FISCHER 78B	SPRK	$K^+ \to \pi^+\pi^0$

$\Gamma(4\gamma)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 2	90		MCDONOUGH 88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<160	90		BOLOTOV 86C	CALO	
<440	90	0	AUERBACH 80	CNTR	

$\Gamma(\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 6.5	90		DORENBOS... 88	CHRM	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<24	90	0	[5] HERCZEG 81	RVUE	$K^+ \to \pi^+\nu\nu'$

[5] This limit applies to all possible $\nu\nu'$ states as well as to other massless, weakly interacting states.

$\Gamma(\nu_e\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<1.7	90	DORENBOS... 88	CHRM	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.1	90	[6] HOFFMAN 88	RVUE	Beam dump, prompt ν

[6] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\mu\overline{\nu}_\mu)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<3.1	90	[7] HOFFMAN 88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7.8	90	DORENBOS... 88	CHRM	Beam dump, prompt ν

[7] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\tau\overline{\nu}_\tau)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<2.1	90	[8] HOFFMAN 88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.1	90	DORENBOS... 88	CHRM	Beam dump, prompt ν

[8] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(3\gamma)/\Gamma_{\text{total}}$ Γ_{10}/Γ

Forbidden by C invariance.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 3.1	90		MCDONOUGH 88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 38	90	0	HIGHLAND 80	CNTR	
<150	90	0	AUERBACH 78	CNTR	
<490	90	0	[9] DUCLOS 65	CNTR	
<490	90		[9] KUTIN 65	CNTR	

[9] These experiments give $B(3\gamma/2\gamma) < 5.0 \times 10^{-6}$.

$\Gamma(\mu^+e^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-8})	CL%	DOCUMENT ID	TECN	COMMENT
<1.6	90	LEE 90	SPEC	$K^+ \to \pi^+\mu^+e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7.8	90	CAMPAGNARI 88	SPEC	See LEE 90

$[\Gamma(\mu^+e^-) + \Gamma(e^-\mu^+)]/\Gamma_{\text{total}}$ Γ_{12}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-8})	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<14		HERCZEG 84	RVUE	$K^+ \to \pi^+\mu e$
< 2×10^{-7}		HERCZEG 84	THEO	$\mu^- \to e^-$ conversion
< 7	90	BRYMAN 82	RVUE	$K^+ \to \pi^+\mu e$

π^0 ELECTROMAGNETIC FORM FACTOR

The amplitude for the process $\pi^0 \to e^+e^-\gamma$ contains a form factor $F(x)$ at the $\pi^0\gamma\gamma$ vertex, where $x = [m(e^+e^-)/m(\pi^0)]^2$. The parameter a in the linear expansion $F(x) = 1 + ax$ is listed below.

LINEAR COEFFICIENT OF π^0 ELECTROMAGNETIC FORM FACTOR

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.11±0.03±0.08	32k	FONVIEILLE 89	SPEC	Radiation corr.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.12^{+0.05}_{-0.04}$		[10] TUPPER 83	THEO	FISCHER 78 data
+0.10±0.03	30k	[11] FISCHER 78	SPEC	Radiation corr.
+0.01±0.11	2200	DEVONS 69	OSPK	No radiation corr.
−0.15±0.10		KOBRAK 61	HBC	No radiation corr.
−0.24±0.16	3071	SAMIOS 61	HBC	No radiation corr.

[10] TUPPER 83 is a theoretical analysis of FISCHER 78 including 2-photon exchange in the corrections.

[11] The FISCHER 78 error is statistical only. The result without radiation corrections is +0.05 ± 0.03.

REFERENCES FOR π^0

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition (Physics Letters **B204**).

LEE	90	PRL 64 165	+Alliegro, Campagnari+	(BNL, FNAL, PSI, WASH, YALE)
FONVIEILLE	89	PL B233 65	+Bensayah, Berthot, Bertin+	(PASC, CBER, SACL)
NIEBUHR	89	PR D40 2796	+Eichler, Felawka, Kozlowski+	(SINDRUM Collab.)
CAMPAGNARI	88	PRL 61 2062	+Alliegro, Chaloupka+	(BNL, FNAL, PSI, WASH, YALE)
CRAWFORD	88B	PL B213 391	+Daum, Frosch, Jost, Kettle, Marshall+	(PSI, VIRG)
DORENBOS...	88	ZPHY C40 497	Dorenbosch, Allaby, Amaldi, Barbiellini+	(CHARM Collab.)
HOFFMAN	88	PL B208 149		(LANL)
MCDONOUGH	88	PR D38 2121	+Highland, McFarlane, Bolton+	(TEMP, LANL, CHIC)
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ZEPHAT	87	JP G13 1375	+Playfer, van Doesburg, Bressani+	(OMICRON Collab.)
BOLOTOV	86C	JETPL 43 520 Translated from ZETFP 43 405.	+Gninenko, Dzhilkibaev, Isakov	(INRM)
CRAWFORD	86	PRL 56 1043	+Daum, Frosch, Jost, Kettle+	(SIN, VIRG)
ATHERTON	85	PL 158B 81	+Bovet, Coet+	(CERN, ISU, LUND, LPTP, EFI)
HERCZEG	84	PR D29 1954	+Hoffman	(LANL)
FRANK	83	PR D28 423	+Hoffman, Mischke, Moir+	(LANL, ARZS)
TUPPER	83	PR D28 2905	+Grose, Samuel	(OKSU)
BRYMAN	82	PR D26 2538		(TRIU)
MISCHKE	82	PRL 48 1153	+Frank, Hoffman, Moir, Sarracino+	(LANL, ARZS)
HERCZEG	81	PL 100B 347	+Hoffman	(LANL)
SCHARDT	81	PR D23 639	+Frank, Hoffmann, Mischke, Moir+	(ARZS, LANL)
AUERBACH	80	PL 90B 317	+Haik, Highland, McFarlane, Macek+	(TEMP, LASL)
HIGHLAND	80	PRL 44 628	+Auerbach, Haik, McFarlane, Macek+	(TEMP, LASL)
AUERBACH	78	PRL 41 275	+Highland, Johnson+	(TEMP, LASL)
FISCHER	78	PL 73B 359	+Extermann, Guisan, Mermod+	(GEVA, SACL)
FISCHER	78B	PL 73B 364	+Extermann, Guisan, Mermod+	(GEVA, SACL)
BROWMAN	74	PRL 33 1400	+Dewire, Gittelman, Hanson+	(CORN, BING)
MIYAZAKI	73	PR D8 2051	+Takasugi	(TOKY)
BELLETTINI	70	NC 66A 243	+Bemporad, Lubelsmey+	(PISA, BONN)
KRYSHKIN	70	JETP 30 1037 Translated from ZETF 57 1917.	+Sterligov, Usov	(TMSK)
DEVONS	69	PR 184 1356	+Nemethy, Nissim-Sabat, Capua+	(COLU, ROMA)
VASILEVSKY	66	PL 23 281	+Vishnyakov, Dunaitsev+	(JINR)
DUCLOS	65	PL 19 253	+Freytag, Heintze+	(CERN, HEID)
KUTIN	65	JETPL 2 243 Translated from unknown journal.	+Petrukhin, Prokoshkin	(JINR)
CZIRR	63	PR 130 341		(LRL)
SAMIOS	62B	PR 126 1844	+Plano, Prodell+	(COLU, BNL)
KOBRAK	61	NC 20 1115		(EFI)
SAMIOS	61	PR 121 275		(COLU, BNL)
BUDAGOV	60	JETP 11 755 Translated from ZETF 38 1047.	+Viktor, Dzhelepov, Ermolov+	(JINR)
JOSEPH	60	NC 16 997		(EFI)

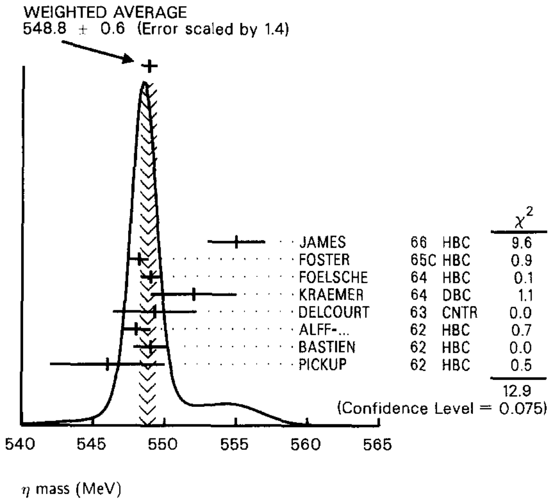
$\boxed{\eta}$

$I^G(J^{PC}) = 0^+(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition (Physics Letters B204).

η MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN
548.8±0.6 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.	
555.0±2.0	250	JAMES 66	HBC
548.2±0.65		FOSTER 65C	HBC
549.0±0.7	148	FOELSCHE 64	HBC
552.0±3.0	325	KRAEMER 64	DBC
549.3±2.9		DELCOURT 63	CNTR
548.0±1.0	91	ALFF-... 62	HBC
549.0±1.2	53	BASTIEN 62	HBC
546.0±4.0	35	PICKUP 62	HBC



η WIDTH

This is the partial decay rate $\Gamma(\eta \to \gamma\gamma)$ divided by the fitted branching fraction for that mode. See the Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$, below.

VALUE (keV)	*DOCUMENT ID*
1.19±0.12 OUR FIT	Error includes scale factor of 2.0.

η DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	neutral modes		(70.8 ± 0.8) %	S=1.2
Γ_2	2γ	[a]	(38.9 ± 0.5) %	S=1.2
Γ_3	$3\pi^0$		(31.9 ± 0.4) %	S=1.2
Γ_4	$\pi^0 2\gamma$		$(7.1 \pm 1.4) \times 10^{-4}$	
Γ_5	charged modes		(29.2 ± 0.8) %	S=1.2
Γ_6	$\pi^+\pi^-\pi^0$		(23.6 ± 0.6) %	S=1.2
Γ_7	$\pi^+\pi^-\gamma$		(4.88 ± 0.15) %	S=1.2
Γ_8	$e^+e^-\gamma$		$(5.0 \pm 1.2) \times 10^{-3}$	
Γ_9	$\mu^+\mu^-\gamma$		$(3.1 \pm 0.4) \times 10^{-4}$	
Γ_{10}	e^+e^-		$< 3 \times 10^{-4}$	CL=90%
Γ_{11}	$\mu^+\mu^-$		$(6.5 \pm 2.1) \times 10^{-6}$	
Γ_{12}	$\pi^+\pi^-e^+e^-$		$(1.3 {}^{+1.3}_{-0.8}) \times 10^{-3}$	
Γ_{13}	$\pi^+\pi^-2\gamma$		$< 2.1 \times 10^{-3}$	
Γ_{14}	$\pi^+\pi^-\pi^0\gamma$		$< 6 \times 10^{-4}$	CL=90%
Γ_{15}	$\pi^0\mu^+\mu^-\gamma$		$< 3 \times 10^{-6}$	CL=90%

Charge conjugation (*C*), Parity (*P*), or Charge conjugation × Parity (*CP*) violating modes

Γ_{16}	3γ	*C*	$< 5 \times 10^{-4}$	
Γ_{17}	$\pi^+\pi^-$	*P,CP*	$< 1.5 \times 10^{-3}$	
Γ_{18}	$\pi^0 e^+e^-$	*C*	$< 4 \times 10^{-5}$	CL=90%
Γ_{19}	$\pi^0\mu^+\mu^-$	*C*	$< 5 \times 10^{-6}$	CL=90%

[a] See the Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$, below.

CONSTRAINED FIT INFORMATION

An overall fit to a partial width and 14 branching ratios uses 38 measurements and one constraint to determine 9 parameters. The overall fit has a $\chi^2 = 30.7$ for 30 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	57							
x_4	3	3						
x_6	−88	−84	−5					
x_7	−77	−74	−5	81				
x_8	−11	−10	−1	−3	−4			
x_9	0	0	0	0	0	0		
x_{12}	−3	−3	0	−13	−10	−2	0	
Γ	−12	−7	0	10	9	1	0	0
	x_2	x_3	x_4	x_6	x_7	x_8	x_9	x_{12}

	Mode		Rate (keV)	Scale factor
Γ_2	2γ	[a]	0.46 ± 0.05	2.1
Γ_3	$3\pi^0$		0.38 ± 0.04	2.0
Γ_4	$\pi^0 2\gamma$		$(8.4 \pm 1.9) \times 10^{-4}$	1.1
Γ_6	$\pi^+\pi^-\pi^0$		0.282 ± 0.032	1.9
Γ_7	$\pi^+\pi^-\gamma$		0.058 ± 0.007	1.9
Γ_8	$e^+e^-\gamma$		0.0059 ± 0.0016	1.1
Γ_9	$\mu^+\mu^-\gamma$		$(3.7 \pm 0.6) \times 10^{-4}$	1.2
Γ_{12}	$\pi^+\pi^-e^+e^-$		$0.0016^{+0.0015}_{-0.0010}$	

NOTE ON THE DECAY WIDTH $\Gamma(\eta \to \gamma\gamma)$

(by N.A. Roe, Lawrence Berkeley Laboratory)

In the measurements of $\Gamma(\eta \to \gamma\gamma)$ listed below, the results from two-photon production disagree with those from Primakoff production. Since the 1988 edition, new two-photon measurements from the Crystal Ball and ASP groups, consistent with previous two-photon results and having somewhat smaller errors, have exacerbated the disagreement with the Primakoff results. The weighted average of the two-photon measurements is 0.510 ± 0.027 keV, to be compared with the Primakoff-production measurement of BROWMAN 74B, 0.324 ± 0.046 keV.

In the two-photon measurements, η's are produced in the QED process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\eta$. The calculation of the rate is believed to be well understood. The uncertainty due to the virtual photon form factor is small; WILLIAMS 88 quotes an uncertainty of 0.2% from this source. Backgrounds to the η signal from beam-gas interactions and other two-photon interactions with missing particles are also small.

In the Primakoff experiments, η's are produced by the interaction of a real photon with a virtual photon in the Coulomb field of the nucleus. There is coherent background from strong production of η's in the nuclear hadronic field, and interference between the strong and Primakoff production amplitudes. The angular dependences of the Primakoff signal and the background are different, allowing $\Gamma(\eta \to \gamma\gamma)$ to be extracted from a fit to the angular distribution. In the best fit to their data, BEMPORAD 67 found the coherent hadronic background to be consistent with zero. BROWMAN 74B had a wider range of photon energies, a higher maximum energy, better angular resolution, and higher statistics. They found a significant contribution from the hadronic background, especially at lower energies. BROWMAN 74B also reanalyzed the data of BEMPORAD 67 and found that it was compatible with their fit, including background terms. This suggests that the background was underestimated by BEMPORAD 67, and we consider their result to be superseded by that of BROWMAN 74B.

There remains the disagreement between the two-photon results and the result of BROWMAN 74B. The errors assigned by BROWMAN 74B include a 5.3% statistical error, a 12.2% systematic error for uncertainty in the accepted photon spectrum, and a 2.5% systematic error for uncertainty in the nuclear parameters used in the calculation of the Primakoff and nuclear form factors. The Primakoff form factor F_C is a function of the momentum transfer q and the production angle θ. As $q^2 \to 0$, the uncertainty in F_C due to the q^2 dependence vanishes. The minimum q^2 in this experiment ranged from -680 MeV^2 at the lowest energy to -174 MeV^2 at the highest. In this range, the result is sensitive to details in the calculation of F_C, but it is difficult to estimate the systematic error of this dependence. Another possible source of systematic error is in the phase of the interference term, ϕ. This was a free parameter in the fit, but was not well determined by the data because the interference contribution peaks in the same angular region as the Primakoff signal and so cannot be unambiguously separated by an angular fit. A reanalysis of the data would be necessary to determine whether any of these factors was overlooked in the determination of the systematic error.

Using the same apparatus, Browman et al.[1] measured $\Gamma(\pi^0 \to \gamma\gamma)$ to be 7.92 ± 0.42 eV, in good agreement with our world average of 7.7 ± 0.6 eV. (Our average includes the measurement of Browman et al., but is dominated by a decay-length measurement by Atherton et al.[2] The error on the average involves a scale factor S=3.0 due to one outlying measurement.) However, the uncertainty due to F_C is reduced at lower momentum transfers, and q^2 was on the order of 100 times smaller in the π^0 measurement. The signal-to-background ratio is also larger, making the fit less sensitive to nuclear production.

A possible source of common systematic error in the two-photon experiments is the calculation of the two-photon luminosity function. However, WILLIAMS 88 measured the two-photon width of the π^0 as well as of the η, and their result, $7.7 \pm 0.5 \pm 0.5$ eV, is consistent with the world average quoted above.

To summarize, the two-photon measurements seem more reliable than the best Primakoff-production measurement. However, we include the latter in our average as there is no compelling reason to exclude it. The result, $\Gamma(\eta \to \gamma\gamma) = 0.46 \pm 0.05$ keV, is one standard deviation from the average using only the two-photon measurements, 0.510 ± 0.027 keV, and the error is twice as large, due to the scale factor.

References

1. A. Browman et al., Phys. Rev. Lett. **33**, 1400 (1974).
2. H.W. Atherton et al., Phys. Lett. **158B**, 81 (1985).

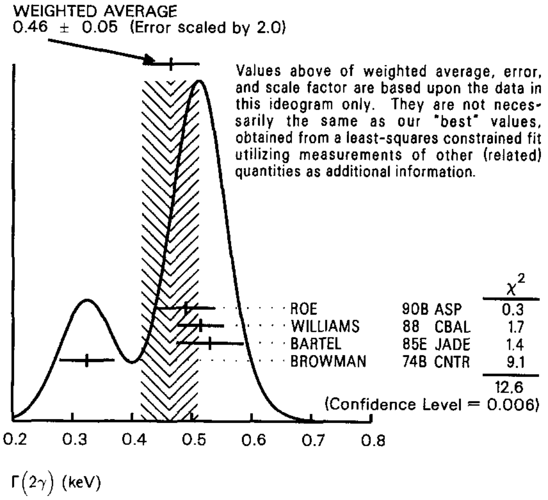
η DECAY RATES

$\Gamma(2\gamma)$ Γ_2

See the above Note on the Decay Rate $\Gamma(\eta \to \gamma\gamma)$.

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
0.46 ±0.05 OUR FIT	Error includes scale factor of 2.1.			
0.46 ±0.05 OUR AVERAGE	Error includes scale factor of 2.0. See the ideogram below.			
0.490±0.010±0.048	2287	ROE 90B	ASP	$e^+e^- \to e^+e^-\eta$
0.514±0.017±0.035	1295	WILLIAMS 88	CBAL	$e^+e^- \to e^+e^-\eta$
0.53 ±0.04 ±0.04		BARTEL 85E	JADE	$e^+e^- \to e^+e^-\eta$
0.324±0.046		BROWMAN 74B	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64 ±0.14 ±0.13		AIHARA 86	TPC	$e^+e^- \to e^+e^-\eta$
0.56 ±0.16	56	WEINSTEIN 83	CBAL	$e^+e^- \to e^+e^-\eta$
1.00 ±0.22		[1] BEMPORAD 67	CNTR	Primakoff effect

[1] BEMPORAD 67 gives $\Gamma(2\gamma) = 1.21 \pm 0.26$ keV assuming $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.314$. Bemporad private communication gives $\Gamma(2\gamma)^2/\Gamma(\text{total}) = 0.380 \pm 0.083$. We evaluate this using $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.38 \pm 0.01$. Not included in average because the uncertainty resulting from the separation of the coulomb and nuclear amplitudes has apparently been underestimated.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(2\gamma)$ (keV)

η BRANCHING RATIOS

$\Gamma(\text{neutral modes})/\Gamma_{\text{total}}$ $(\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.708±0.008 OUR FIT	Error includes scale factor of 1.2.			
0.705±0.008	16k	BASILE 71D	CNTR	MM spectrometer
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.79 ±0.08		BUNIATOV 67	OSPK	

$\Gamma(2\gamma)/\Gamma(\text{neutral modes})$ $\Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.5491±0.0028 OUR FIT				
0.549 ±0.004 OUR AVERAGE				
0.549 ±0.004		ALDE 84	GAM2	
0.535 ±0.018		BUTTRAM 70	OSPK	
0.59 ±0.033		BUNIATOV 67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.52 ±0.09	88	ABROSIMOV 80	HLBC	
0.60 ±0.14	113	KENDALL 74	OSPK	
0.57 ±0.09		STRUGALSKI 71	HLBC	
0.579 ±0.052		FELDMAN 67	OSPK	
0.416 ±0.044		DIGIUGNO 66	CNTR	Error doubled
0.44 ±0.07		GRUNHAUS 66	OSPK	
0.39 ±0.06		[2] JONES 66	CNTR	

[2] This result from combining cross sections from two different experiments.

$\Gamma(3\pi^0)/\Gamma(\text{neutral modes})$ $\Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.4499±0.0028 OUR FIT				
0.450 ±0.004 OUR AVERAGE				
0.450 ±0.004		ALDE 84	GAM2	
0.439 ±0.024		BUTTRAM 70	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ±0.08	75	ABROSIMOV 80	HLBC	
0.32 ±0.09		STRUGALSKI 71	HLBC	
0.41 ±0.033		BUNIATOV 67	OSPK	Not indep. of $\Gamma(2\gamma)$ / $\Gamma(\text{neutral modes})$
0.177 ±0.035		FELDMAN 67	OSPK	
0.209 ±0.054		DIGIUGNO 66	CNTR	Error doubled
0.29 ±0.10		GRUNHAUS 66	OSPK	

$\Gamma(3\pi^0)/\Gamma(2\gamma)$ Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.819±0.009 OUR FIT			
0.84 ±0.06 OUR AVERAGE			
0.91 ±0.14	COX 70B	HBC	
0.75 ±0.09	DEVONS 70	OSPK	
0.88 ±0.16	BALTAY 67D	DBC	
1.1 ±0.2	CENCE 67	OSPK	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN	COMMENT
1.25 ±0.39	BACCI 63	CNTR	Inverse BR reported

$\Gamma(\pi^0 2\gamma)/\Gamma(\text{neutral modes})$ $\Gamma_4/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID	TECN
0.00100±0.00020 OUR FIT		
0.0010 ±0.0002	ALDE 84	GAM2

$\Gamma(\pi^0 2\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

These results are summarized in the review by LANDSBERG 85.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
7.1±1.4 OUR FIT					

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
7.1±1.7			[3] ALDE 84	GAM2	$\pi^- p \to \eta n$
9.5±2.3		70	BINON 82	GAM2	See ALDE 84
<30	90	0	DAVYDOV 81	GAM2	$\pi^- p \to \eta n$

[3] Not independent of the ALDE 84 result $\Gamma(\pi^0 2\gamma)/\Gamma(\text{neutral modes})$.

$\Gamma(\text{neutral modes})/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^+\pi^-\gamma)+\Gamma(e^+e^-\gamma)]$ $(\Gamma_2+\Gamma_3+\Gamma_4)/(\Gamma_6+\Gamma_7+\Gamma_8)$

VALUE	EVTS	DOCUMENT ID	TECN
2.44±0.09 OUR FIT Error includes scale factor of 1.2.			
2.64±0.23		BALTAY 67B	DBC

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN
4.5 ±1.0	280	[4] JAMES 66	HBC
3.20±1.26	53	[4] BASTIEN 62	HBC
2.5 ±1.0	10	[4] PICKUP 62	HBC

[4] These experiments not used in the averages as they do not separate clearly $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ from each other. The reported values thus probably contain some unknown fraction of $\eta \to \pi^+\pi^-\gamma$.

$\Gamma(2\gamma)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^+\pi^-\gamma)+\Gamma(e^+e^-\gamma)]$ $\Gamma_2/(\Gamma_6+\Gamma_7+\Gamma_8)$

VALUE	EVTS	DOCUMENT ID	TECN
1.34±0.05 OUR FIT Error includes scale factor of 1.2.			
1.1 ±0.4 OUR AVERAGE			
1.51±0.93	75	KENDALL 74	OSPK
0.99±0.48		CRAWFORD 63	HBC

$\Gamma(\text{neutral modes})/\Gamma(\pi^+\pi^-\pi^0)$ $(\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma_6$

VALUE	EVTS	DOCUMENT ID	TECN
2.99±0.11 OUR FIT Error includes scale factor of 1.2.			
3.26±0.30 OUR AVERAGE			
2.54±1.89	74	KENDALL 74	OSPK
3.4 ±1.1	29	AGUILAR-... 72B	HBC
2.83±0.80	70	[5] BLOODWO... 72B	HBC
3.6 ±0.6	244	FLATTE 67B	HBC
2.89±0.56		ALFF-... 66	HBC
3.6 ±0.8	50	KRAEMER 64	DBC
3.8 ±1.1		PAULI 64	DBC

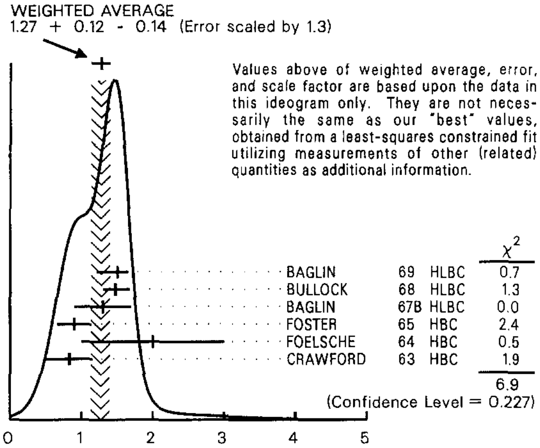
[5] Error increased from published value 0.5 by Bloodworth (private communication).

$\Gamma(2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_2/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN
1.64±0.06 OUR FIT Error includes scale factor of 1.2.			
1.69±0.21 OUR AVERAGE			
1.72±0.25	401	BAGLIN 69	HLBC
1.61±0.39		FOSTER 65	HBC

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN
1.35±0.05 OUR FIT Error includes scale factor of 1.2.			
$1.27^{+0.12}_{-0.14}$ OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.			
$1.50^{+0.15}_{-0.29}$	199	BAGLIN 69	HLBC
$1.47^{+0.20}_{-0.17}$		BULLOCK 68	HLBC
1.3 ±0.4		BAGLIN 67B	HLBC
0.90±0.24		FOSTER 65	HBC
2.0 ±1.0		FOELSCHE 64	HBC
0.83±0.32		CRAWFORD 63	HBC



$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_7/Γ_6

VALUE	EVTS	DOCUMENT ID	TECN
0.207±0.004 OUR FIT Error includes scale factor of 1.1.			
0.207±0.004 OUR AVERAGE Error includes scale factor of 1.1.			
0.209±0.004	18k	THALER 73	ASPK
0.201±0.006	7250	GORMLEY 70	ASPK

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN
0.28 ±0.04		BALTAY 67B	DBC
0.25 ±0.035		LITCHFIELD 67	DBC
0.30 ±0.06		CRAWFORD 66	HBC
0.196±0.041		FOSTER 65C	HBC

$\Gamma(e^+e^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_8/Γ_6

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
2.1±0.5 OUR FIT				
2.1±0.5	80	JANE 75B	OSPK	See the erratum

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
3.1±0.4 OUR FIT				
3.1±0.4	600	DZHELYADIN 80	SPEC	$\pi^- p \to \eta n$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
1.5±0.75	100	BUSHNIN 78	SPEC	See DZHELYADIN 80

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<3	90	DAVIES 74	RVUE	Uses ESTEN 67

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.65±0.21		27	DZHELYADIN 80B	SPEC	$\pi^- p \to \eta n$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<2	95	0	WEHMANN 68	OSPK	

$\Gamma(\mu^+\mu^-)/\Gamma(2\gamma)$ Γ_{11}/Γ_2

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-5})	DOCUMENT ID	TECN
5.9±2.2	HYAMS 69	OSPK

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma(\pi^+\pi^-\gamma)$ Γ_{12}/Γ_7

VALUE	EVTS	DOCUMENT ID	TECN
$0.027^{+0.026}_{-0.017}$ OUR FIT			
0.026±0.026	1	GROSSMAN 66	HBC

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN
$0.13^{+0.13}_{-0.08}$ OUR FIT		

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (units 10^{-2})	DOCUMENT ID	TECN
<0.7	RITTENBERG 65	HBC

$\Gamma(\pi^+\pi^-2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{13}/Γ_6

VALUE	CL%	DOCUMENT ID	TECN
<0.009		PRICE 67	HBC

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN
<0.016	95	BALTAY 67B	DBC

$\Gamma(\pi^+\pi^-\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{14}/Γ_6

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN
<0.24	90	0	THALER 73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	90		ARNOLD 68	HLBC
<1.6	95		BALTAY 67B	DBC
<7.0			FLATTE 67	HBC
<0.9			PRICE 67	HBC

$\Gamma(\pi^0\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<3	90	DZHELYADIN 81	SPEC	$\pi^- p \to \eta n$

$\Gamma(3\gamma)/\Gamma(\text{neutral modes})$ $\Gamma_{16}/(\Gamma_2+\Gamma_3+\Gamma_4)$

Forbidden by C invariance.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
<7	95	ALDE 84	GAM2

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

Violates P and CP invariance.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
<0.15	0	THALER 73	ASPK

$\Gamma(\pi^0 e^+ e^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{18}/Γ_6

A single photon process forbidden by C parity.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN
< 1.9	90		JANE 75	OSPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 42	90		BAGLIN 67	HLBC
< 16	90	0	BILLING 67	HLBC
< 77		0	FOSTER 65B	HBC
<110			PRICE 65	HBC

$\Gamma(\pi^0 e^+ e^-)/\Gamma_{\text{total}}$ Γ_{18}/Γ

A single photon process forbidden by C parity.

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.016	90	0	MARTYNOV 76	HLBC
<0.084	90		BAZIN 68	DBC
<0.7			RITTENBERG 65	HBC

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{19}/Γ

A single photon process forbidden by C parity.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	DZHELYADIN 81	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5		WEHMANN 68	OSPK	

NOTE ON η DECAY PARAMETERS

C violation in η decays

A number of experiments have looked for charge asymmetries in $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ decays. Any difference between the π^+ and π^- spectra in either decay would indicate C violation in electromagnetic interactions. In sections that follow this Note, we list measurements of the following parameters:

(a) The left-right asymmetry

$$A = (N^+ - N^-)/(N^+ + N^-) ,$$

where N^+ is the number of events in which the π^+ energy in the η rest frame is greater than the π^- energy, etc.

(b) For the decay $\eta \to \pi^+\pi^-\pi^0$, the sextant asymmetry

$$A_s = \frac{N_1 + N_3 + N_5 - N_2 - N_4 - N_6}{N_1 + N_2 + N_3 + N_4 + N_5 + N_6} ,$$

where the N_i are the numbers of events in sextants of the Dalitz plot; see, for example, Layter et al.[1] A_s is sensitive to an I=0 C-violating final state.

(c) For the decay $\eta \to \pi^+\pi^-\pi^0$, the quadrant asymmetry

$$A_q = \frac{N_1 + N_3 - N_2 - N_4}{N_1 + N_2 + N_3 + N_4} ,$$

where the N_i are numbers of events in quadrants of the Dalitz plot. A_q is sensitive to an I=2 C-violating final state.

(d) For the decay $\eta \to \pi^+\pi^-\gamma$, evidence for a D-wave contribution to the C-violating amplitude. The upper limit for this contribution is measured by the parameter β, defined by

$$dN/d\,|\cos\theta\,| \propto \sin^2\theta\,(1 + \beta\,\cos^2\theta) ,$$

where θ is the angle between the π^+ and the γ in the dipion center of mass. A term proportional to $\cos^2\theta$ could also come from P- and F-wave interference.

Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$

The Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$ decay may be fit to the distribution

$$|\,M(x,y)|^2 \propto (1 + ay + by^2 + cx + dx^2 + exy) .$$

Here

$$x = \sqrt{3}\,(T_+ - T_-)/Q ,$$

$$y = (3T_0/Q) - 1 ,$$

where T_+ , T_- , and T_0 are the kinetic energies of the π^+, π^-, and π^0 in the η rest frame, and $Q = T_+ + T_0 + T_-$. The coefficient of the term linear in x is sensitive to C violation due to an I=0 or I=2 final state. In a section below, we list papers that measured a, b, c, and d, but do not tabulate values of these parameters because the assumptions made by different authors are not compatible and do not allow comparison of the numerical values.

Dalitz plot for $\eta \to \pi^0\pi^0\pi^0$

The Dalitz plot for the decay $\eta \to \pi^0\pi^0\pi^0$ may be fit to

$$|\,M\,|^2 \propto 1 + 2\alpha z ,$$

where

$$z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - m_\eta}{m_\eta - 3m_{\pi^0}}\right)^2 = \frac{\rho^2}{\rho^2_{\max}} .$$

Here E_i is the energy of the i^{th} pion in the η rest frame, and ρ is the distance from the center of the Dalitz plot. We list measurements of the parameter α in a section below.

Reference

1. J.G. Layter et al., Phys. Rev. Lett. **29**, 316 (1972).

η C-NONCONSERVING DECAY PARAMETERS

$\pi^+\pi^-\pi^0$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error > 1.0×10^{-2} have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
0.09±0.17 OUR AVERAGE			
0.28±0.26	165k	JANE 74	OSPK
−0.05±0.22	220k	LAYTER 72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.5 ±0.5	37k	[6] GORMLEY 68C	ASPK

[6] The GORMLEY 68C asymmetry is probably due to unmeasured (E × B) spark chamber effects. New experiments with (E × B) controls don't observe an asymmetry.

$\pi^+\pi^-\pi^0$ SEXTANT ASYMMETRY PARAMETER

Measurements with an error > 2.0×10^{-2} have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
0.18±0.16 OUR AVERAGE			
0.20±0.25	165k	JANE 74	OSPK
0.10±0.22	220k	LAYTER 72	ASPK
0.5 ±0.5	37k	GORMLEY 68C	WIRE

$\pi^+\pi^-\pi^0$ QUADRANT ASYMMETRY PARAMETER

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
-0.17 ± 0.17 OUR AVERAGE			
-0.30 ± 0.25	165k	JANE 74	OSPK
-0.07 ± 0.22	220k	LAYTER 72	ASPK

$\pi^+\pi^-\gamma$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error $> 2.0\times10^{-2}$ have been omitted.

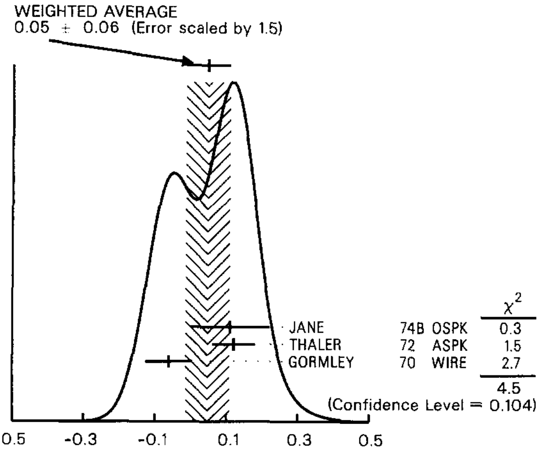
VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
$0.9\ \pm0.4$ OUR AVERAGE			
$1.2\ \pm0.6$	35k	JANE 74B	OSPK
$0.5\ \pm0.6$	36k	THALER 72	ASPK
1.22 ± 1.56	7257	GORMLEY 70	ASPK

$\pi^+\pi^-\gamma$ PARAMETER β

Sensitive to a *D*-wave contribution: $dN/d\cos\theta = \sin^2\theta\ (1+\beta\ \cos^2\theta)$

VALUE	EVTS	DOCUMENT ID	TECN
$0.05\ \pm0.06$ OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.		
$0.11\ \pm0.11$	35k	JANE 74B	OSPK
$0.12\ \pm0.06$		[7] THALER 72	ASPK
-0.060 ± 0.065	7250	GORMLEY 70	WIRE

[7] The authors don't believe this indicates *D*-wave because the dependence of β on the γ energy is inconsistent with theoretical prediction. A $\cos^2\theta$ dependence may also come from *P*- and *F*-wave interference.



β for $\eta \to \pi^+\pi^-\gamma$

ENERGY DEPENDENCE OF $\eta \to \pi^+\pi^-\pi^0$ DALITZ PLOT

See the Note on η Decay Parameters above. The following experiments fit to one or more of the coefficients *a*, *b*, *c*, *d*, or *e* for $|\text{matrix element}|^2 = 1 + ay + by^2 + cx + dx^2 + exy$.

VALUE	EVTS	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	81k	LAYTER 73	ASPK
	220k	LAYTER 72	ASPK
	1138	CARPENTER 70	HBC
	349	DANBURG 70	DBC
	7250	GORMLEY 70	WIRE
	526	BAGLIN 69	HLBC
	7170	CNOPS 68	OSPK
	37k	GORMLEY 68C	WIRE
	1300	CLPWY 66	HBC
	705	LARRIBE 66	HBC

α PARAMETER FOR $\eta \to 3\pi^0$

See the Note on η Decay Parameters above. The value here is of α in $|\text{matrix element}|^2 = 1 + 2\alpha z$.

VALUE	EVTS	DOCUMENT ID	TECN
-0.022 ± 0.023	50k	ALDE 84	GAM2
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$-0.32\ \pm0.37$	192	BAGLIN 70	HLBC

REFERENCES FOR η

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition (Physics Letters **B204**).

ROE	90B	PR D41 17	+Bartha, Burke, Garbincius+	(ASP Collab.)
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
AIHARA	86	PR D33 844	+Alston-Garnjost+	(TPC-2γ Collab.)
BARTEL	85E	PL 160B 421	+Becker, Cords, Felst+	(JADE Collab.)
LANDSBERG	85	PRPL 128 310		(SERP)
ALDE	84	ZPHY C25 225	+Binon, Bricman, Donskov+	(SERP, BELG, LAPP)
Also	84B	SJNP 40 918	Alde, Binon, Bricman+	(SERP, BELG, LAPP)
		Translated from YAF 40 1447.		
WEINSTEIN	83	PR D28 2896	+Antreasyan, Gu, Kollman+	(Crystal Ball Collab.)
BINON	82	SJNP 36 391	+Bricman, Gouanere+	(SERP, BELG, LAPP, CERN)
		Translated from YAF 36 670.		
Also	82B	NC 71A 497	Binon, Bricman+	(SERP, BELG, LAPP, CERN)
DAVYDOV	81	LNC 32 45	+Donskov, Inyakin+	(SERP, BELG, LAPP, CERN)
Also	81B	SJNP 33 825	Davydov, Binon+	(SERP, BELG, LAPP, CERN)
		Translated from YAF 33 1534.		
DZHELYADIN	81	PL 105B 239	+Golovkin, Konstantinov, Kubarovski+	(SERP)
Also	81C	SJNP 33 822	Dzhelyadin, Viktorov, Golovkin+	(SERP)
		Translated from YAF 33 1529.		
ABROSIMOV	80	SJNP 31 195	+Ilina, Niszcz, Okhrimenko+	(JINR)
		Translated from YAF 31 371.		
DZHELYADIN	80	PL 94B 548	+Viktorov, Golovkin+	(SERP)
Also	80C	SJNP 32 516	Dzhelyadin, Golovkin, Kachanov+	(SERP)
		Translated from YAF 32 998.		
DZHELYADIN	80B	PL 97B 471	+Viktorov, Golovkin+	(SERP)
Also	80D	SJNP 32 518	Dzhelyadin, Golovkin, Kachanov+	(SERP)
		Translated from YAF 32 1002.		
BUSHNIN	78	PL 79B 147	+Dzhelyadin, Golovkin, Gritsuk+	(SERP)
Also	78B	SJNP 28 775	Bushnin, Golovkin, Gritsuk, Dzhelyadin+	(SERP)
		Translated from YAF 28 1507.		
MARTYNOV	76	SJNP 23 48	+Saltykov, Tarasov, Uzhinskii	(JINR)
		Translated from YAF 23 93.		
JANE	75	PL 59B 99	+Grannis, Jones, Lipman, Owen+	(RHEL, LOWC)
JANE	75B	PL 59B 103	+Grannis, Jones, Lipman, Owen+	(RHEL, LOWC)
Also	78B	PL 73B 503	Jane	
Erratum in private communication.				
BROWMAN	74B	PRL 32 1067	+Dewire, Gittelman, Hanson, Loh+	(CORN, BING)
DAVIES	74	NC 24A 324	+Guy, Zia	(BIRM, RHEL, SHMP)
JANE	74	PL 48B 260	+Jones, Lipman, Owen+	(RHEL, LOWC, SUSS)
JANE	74B	PL 48B 265	+Jones, Lipman, Owen+	(RHEL, LOWC, SUSS)
KENDALL	74	NC 21A 387	+Lanou, Massimo, Shapiro+	(BROW, BARI, MIT)
LAYTER	73	PR D7 2565	+Appel, Kotlewski, Lee, Stein, Thaler	(COLU)
THALER	73	PR D7 2569	+Appel, Kotlewski, Layter, Lee, Stein	(COLU)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
BLOODWO...	72B	NP B39 525	Bloodworth, Jackson, Prentice, Yoon	(TNTO)
LAYTER	72	PRL 29 316	+Appel, Kotlewski, Lee, Stein, Thaler	(COLU)
THALER	72	PRL 29 313	+Appel, Kotlewski, Layter, Lee, Stein	(COLU)
BASILE	71D	NC 3A 796	+Bollini, Dalpiaz, Frabetti+	(CERN, BGNA, STRB)
STRUGALSKI	71	NP B27 429	+Chuvilo, Gemesy, Ivanovskaya+	(JINR)
BAGLIN	70	NP B22 66	+Bezaguet, Degrange+	(EPOL, MADR, STRB)
BUTTRAM	70	PRL 25 1358	+Kreisler, Mischke	(PRIN)
CARPENTER	70	PR D1 1303	+Binkley, Chapman, Cox, Dagan+	(DUKE)
COX	70B	PRL 24 534	+Fortney, Golson	(DUKE)
DANBURG	70	PR D2 2564	+Abolins, Dahl, Davies, Hoch, Kirz+	(LRL)
DEVONS	70	PR D1 1936	+Grunhaus, Kozlowski, Nemethy+	(COLU, SYRA)
GORMLEY	70	PR D2 501	+Hyman, Lee, Nash, Peoples+	(COLU, BNL)
Also	70B	Nevis 181 Thesis	Gormley	(COLU)
BAGLIN	69	PL 29B 445	+Bezaguet+	(EPOL, UCB, MADR, STRB)
Also	70	NP B22 66	Baglin, Bezaguet, Degrange+	(EPOL, MADR, STRB)
HYAMS	69	PL 29B 128	+Koch, Potter, VonLindern+	(CERN, MPIM)
ARNOLD	68	PL 27B 466	+Paty, Baglin, Bingham+	(STRB, MADR, EPOL, UCB)
BAZIN	68	PRL 20 895	+Goshaw, Zacher+	(PRIN, QUKI)
BULLOCK	68	PL 27B 402	+Esten, Fleming, Govan, Henderson+	(LOUC)
CNOPS	68	PRL 21 1609	+Hough, Cohn+	(BNL, ORNL, UCND, TENN, PENN)
GORMLEY	68C	PRL 21 402	+Hyman, Lee, Nash, Peoples+	(COLU, BNL)
WEHMANN	68	PRL 20 748	+Engels+	(HARV, CASE, SLAC, CORN, MCGI)
BAGLIN	67	PL 24B 637	+Bezaguet, Degrange+	(EPOL, UCB)
BAGLIN	67B	BAPS 12 567	+Bezaguet, Degrange+	(EPOL, UCB)
BALTAY	67B	PRL 19 1498	+Franzini, Kim, Newman+	(COLU, STON)
BALTAY	67D	PRL 19 1495	+Franzini, Kim, Newman+	(COLU, BRAN)
BEMPORAD	67	PL 25B 380	+Braccini, Foa, Lubelsmey+	(PISA, BONN)
Also	67	Private Comm.	Ion	
BILLING	67	PL 25B 435	+Bullock, Esten, Govan+	(LOUC, OXF)
BUNIATOV	67	PL 25B 560	+Zavattini, Deinet+	(CERN, KARL)
CENCE	67	PRL 19 1393	+Peterson, Stenger, Chiu+	(HAWA, LRL)
ESTEN	67	PL 24B 115	+Govan, Knight, Miller, Tovey+	(LOUC, OXF)
FELDMAN	67	PRL 18 868	+Frati, Gleeson, Halpern+	(PENN)
FLATTE	67	PRL 18 976		(LRL)
FLATTE	67B	PR 163 1441	+Wohl	(LRL)
LITCHFIELD	67	PL 24B 486	+Rangan, Segar, Smith+	(RHEL, SACL)
PRICE	67	PRL 18 1207	+Crawford	(LRL)
ALFF-...	66	PR 145 1072	Alff-Steinberger, Berley+	(COLU, RUTG)
CLPWY	66	PR 149 1044		(SCUC, LRL, PURD, WISC, YALE)
CRAWFORD	66	PRL 16 333	+Price	(LRL)
DIGIUGNO	66	PRL 16 767	+Giorgi, Silvestri+	(NAPL, TRST, FRAS)
GROSSMAN	66	PR 146 993	+Price, Crawford	(LRL)
GRUNHAUS	66	Thesis		(COLU)
JAMES	66	PR 142 896	+Kraybill	(YALE, BNL)
JONES	66	PL 23 597	+Binnie, Duane, Horsey, Mason+	(LOIC, RHEL)
LARRIBE	66	PL 23 600	+Leveque, Muller, Pauli+	(SACL, RHEL)
FOSTER	65	PR 138B 652	+Peters, Meer, Loeffler+	(WISC, PURD)
FOSTER	65B	Athens Conf.	+Good, Meer	(WISC)
FOSTER	65C	Thesis		(WISC)
PRICE	65	PRL 15 123	+Crawford	(LRL)
RITTENBERG	65	PRL 15 556	+Kalbfleisch	(LRL, BNL)
FOELSCHE	64	PR 134B 1138	+Kraybill	(YALE)
KRAEMER	64	PR 136B 496	+Madansky, Fields+	(JHU, NWES, WOOD)
PAULI	64	PL 13 351	+Muller	(SACL)
BACCI	63	PRL 11 37	+Penso, Salvini+	(ROMA, FRAS)
CRAWFORD	63	PRL 10 546	+Lloyd, Fowler	(LRL, DUKE)
Also	66B	PRL 16 907	Crawford, Lloyd, Fowler	(LRL, DUKE)
DELCOURT	63	PL 7 215	+Lefrancois, Perez-y-Jorba+	(ORSA)
ALFF-...	62	PRL 9 322	Alff-Steinberger, Berley, Colley+	(COLU, RUTG)
BASTIEN	62	PRL 8 114	+Berge, Dahl, Ferro-Luzzi+	(LRL)
PICKUP	62	PRL 8 329	+Robinson, Salant	(CNRC, BNL)

OTHER RELATED PAPERS

BOWEN	67	PL 24B 206	+Cnops, Finocchiaro+	(CERN, ETH, SACL)
CARMONY	62	PRL 8 117	+Rosenfeld, VanDeWalle	(LRL)
ROSENFELD	62	PRL 8 293	+Carmony, VanDeWalle	(LRL)
PEVSNER	61	PRL 7 421	+Kraemer, Nussbaum, Richardson+	(JHU)

$\rho(770)$

$I^G(J^{PC}) = 1^+(1^{--})$

Our latest mini-review on this particle can be found in the 1984 edition.

$\rho(770)$ MASS

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
768.3±0.5 OUR AVERAGE		Includes data from the 2 datablocks that follow this one.				
767 ±3	2935	[1] CAPRARO	87	SPEC	−	$200\ \pi^- \mathrm{Cu} \to \pi^-\pi^0\mathrm{Cu}$
761 ±5	967	[1] CAPRARO	87	SPEC	−	$200\ \pi^- \mathrm{Pb} \to \pi^-\pi^0\mathrm{Pb}$
771 ±4		HUSTON	86	SPEC	+	$202\ \pi^+ A \to \pi^+\pi^0 A$
766 ±7	6500	[2] BYERLY	73	OSPK	−	$5\ \pi^- p$
766.8±1.5	9650	[3] PISUT	68	RVUE	−	$1.7–3.2\ \pi^- p,\ t < 10$
767 ±6	900	[1] EISNER	67	HBC	−	$4.2\ \pi^- p,\ t < 10$

NEUTRAL ONLY, PHOTOPRODUCED

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
768.1± 1.3 OUR AVERAGE						
767.6± 2.7		BARTALUCCI	78	CNTR	0	$\gamma p \to e^+ e^- p$
775 ± 5		GLADDING	73	CNTR	0	$2.9–4.7\ \gamma p$
767.0± 4.0	1930	BALLAM	72	HBC	0	$2.8\ \gamma p$
770.0± 4.0	2430	BALLAM	72	HBC	0	$4.7\ \gamma p$
765.0±10.0		ALVENSLEBEN	70	CNTR	0	$\gamma A,\ t < 0.01$
767.7± 1.9	140k	BIGGS	70	CNTR	0	$<4.1\ \gamma C \to \pi^+\pi^- C$
765 ± 5.0	4000	ASBURY	67B	CNTR	0	$\gamma + \mathrm{Pb}$

NEUTRAL ONLY, OTHER REACTIONS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
768.7±0.7 OUR AVERAGE		Error includes scale factor of 1.2.				
768 ±1		[4] GESHKENBEIN	89	RVUE		π form factor
768.0±4.0		[5,6] BOHACIK	80	RVUE	0	
769.0±3.0		[2] WICKLUND	78	ASPK	0	$3,4,6\ \pi^\pm N$
768.0±1.0	76000	DEUTSCH...	76	HBC	0	$16\ \pi^+ p$
767 ±4	4100	ENGLER	74	DBC	0	$6\ \pi^+ n \to \pi^+\pi^- p$
775.0±4.0	32000	[5] PROTOPOP...	73	HBC	0	$7.1\ \pi^+ p,\ t < 0.4$
764.0±3.0	6800	RATCLIFF	72	ASPK	0	$15\ \pi^- p,\ t < 0.3$
774.0±3.0	1700	REYNOLDS	69	HBC	0	$2.26\ \pi^- p$
775.0±3.0	2250	HYAMS	68	OSPK	0	$11.2\ \pi^- p$
769.2±1.5	13300	[7] PISUT	68	RVUE	0	$1.7–3.2\ \pi^- p,\ t < 10$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
775.9±1.1		[8] BARKOV	85	OLYA	0	π form factor
777.4±2.0		[9] CHABAUD	83	ASPK	0	$17\ \pi^- p$ polarized
770 ±2		[10] HEYN	80	RVUE		Pion form factor
769.5±0.7		[5,6] LANG	79	RVUE	0	
770 ±9		[6] ESTABROOKS	74	RVUE	0	$17\ \pi^- p \to \pi^+\pi^- n$
773.5±1.7	11200	[1] JACOBS	72	HBC	0	$2.8\ \pi^- p$

[1] Mass errors enlarged by us to $\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[2] Phase shift analysis. Systematic errors added corresponding to spread of different fits.

[3] From fit of 3-parameter relativistic P-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.

[4] Includes BARKOV 85 data. Model-dependent width definition.

[5] From pole extrapolation.

[6] From phase shift analysis of GRAYER 74 data.

[7] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.

[8] From the Gounaris-Sakurai parametrization of the pion form factor.

[9] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.

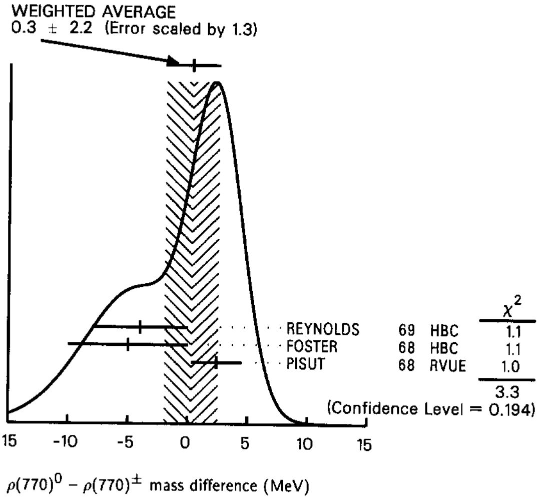
[10] HEYN 80 includes all spacelike and timelike F_π values until 1978.

$\rho(770)^0 - \rho(770)^\pm$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.3±2.2 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.				
−4.0±4.0	3000	[11] REYNOLDS	69	HBC	−0	$2.26\ \pi^- p$
−5 ±5	3600	[11] FOSTER	68	HBC	±0	$0.0\ \bar{p}p$
2.4±2.1	22950	[12] PISUT	68	RVUE		$\pi N \to \rho N$

[11] From quoted masses of charged and neutral modes.

[12] Includes MALAMUD 69, ARMENISE 68, BATON 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65, CARMONY 64, GOLDHABER 64, ABOLINS 63.



$\rho(770)$ RANGE PARAMETER

The range parameter R enters an energy-dependent correction to the width, of the form $(1 + q_r^2 R^2) / (1 + q^2 R^2)$, where q is the momentum of one of the pions in the $\pi\pi$ rest system. At resonance, $q = q_r$.

VALUE (GeV^{-1})	DOCUMENT ID		TECN	CHG	COMMENT
$5.3^{+0.9}_{-0.7}$	CHABAUD	83	ASPK	0	$17\ \pi^- p$ polarized

$\rho(770)$ WIDTH

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
149.1± 2.9 OUR FIT						
151.5± 1.2 OUR AVERAGE		Includes data from the 2 datablocks that follow this one.				
155 ±11	2935	[13] CAPRARO	87	SPEC	−	$200\ \pi^- \mathrm{Cu} \to \pi^-\pi^0\mathrm{Cu}$
154 ±20	967	[13] CAPRARO	87	SPEC	−	$200\ \pi^- \mathrm{Pb} \to \pi^-\pi^0\mathrm{Pb}$
150 ± 5		HUSTON	86	SPEC	+	$202\ \pi^+ A \to \pi^+\pi^0 A$
146 ±12	6500	[14] BYERLY	73	OSPK	−	$5\ \pi^- p$
148.2± 4.1	9650	[15] PISUT	68	RVUE	−	$1.7–3.2\ \pi^- p,\ t < 10$
146 ±13	900	EISNER	67	HBC	−	$4.2\ \pi^- p,\ t < 10$

NEUTRAL ONLY, PHOTOPRODUCED

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
150.9± 3.0		BARTALUCCI	78	CNTR	0	$\gamma p \to e^+ e^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
147 ±11		GLADDING	73	CNTR	0	$2.9–4.7\ \gamma p$
155.0±12.0	2430	BALLAM	72	HBC	0	$4.7\ \gamma p$
145.0±13.0	1930	BALLAM	72	HBC	0	$2.8\ \gamma p$
140.0± 5.0		ALVENSLEBEN	70	CNTR	0	$\gamma A,\ t < 0.01$
146.1± 2.9	140k	BIGGS	70	CNTR	0	$<4.1\ \gamma C \to \pi^+\pi^- C$
160.0±10.0		LANZEROTTI	68	CNTR	0	γp
130 ± 5	4000	ASBURY	67B	CNTR	0	$\gamma + \mathrm{Pb}$

NEUTRAL ONLY, OTHER REACTIONS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
152.4± 1.5 OUR FIT						
152.4± 1.5 OUR AVERAGE						
150.5± 3.0		[16] BARKOV	85	OLYA	0	π form factor
148.0± 6.0		[17,18] BOHACIK	80	RVUE	0	
152.0± 9.0		[14] WICKLUND	78	ASPK	0	$3,4,6\ \pi^\pm pN$
154.0± 2.0	76000	DEUTSCH...	76	HBC	0	$16\ \pi^+ p$
157.0± 8.0	6800	RATCLIFF	72	ASPK	0	$15\ \pi^- p,\ t < 0.3$
143.0± 8.0	1700	REYNOLDS	69	HBC	0	$2.26\ \pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

138 ± 1		[19] GESHKENBEIN	89	RVUE		π form factor
$160.0^{+4.1}_{-4.0}$		[20] CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized
155 ± 1		[21] HEYN	80	RVUE	0	π form factor
148.0 ± 1.3		[17,18] LANG	79	RVUE	0	
146 ± 14	4100	ENGLER	74	DBC	0	6 $\pi^+ n \rightarrow \pi^+\pi^- p$
143 ± 13		[18] ESTABROOKS	74	RVUE	0	17 $\pi^- p \rightarrow \pi^+\pi^- n$
160.0 ± 10.0	32000	[17] PROTOPOP...	73	HBC	0	7.1 $\pi^+ p$, $t < 0.4$
145.0 ± 12.0	2250	[13] HYAMS	68	OSPK	0	11.2 $\pi^- p$
163.0 ± 15.0	13300	[22] PISUT	68	RVUE	0	1.7–3.2 $\pi^- p$, $t < 10$

[13] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[14] Phase shift analysis. Systematic errors added corresponding to spread of different fits.

[15] From fit of 3-parameter relativistic P-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.

[16] From the Gounaris-Sakurai parametrization of the pion form factor.

[17] From pole extrapolation.

[18] From phase shift analysis of GRAYER 74 data.

[19] Includes BARKOV 85 data. Model-dependent width definition.

[20] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.

[21] HEYN 80 includes all spacelike and timelike F_π values until 1978.

[22] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.

$\rho(770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	$\sim$ 100 %	
	$\rho(770)^\pm$ decays		
Γ_2	$\pi^\pm\pi^0$	$\sim$ 100 %	
Γ_3	$\pi^\pm\gamma$	$(4.5 \pm 0.5) \times 10^{-4}$	S=2.2
Γ_4	$\pi^\pm\eta$	$< 8 \times 10^{-3}$	CL=84%
Γ_5	$\pi^\pm\pi^+\pi^-\pi^0$	$< 2.0 \times 10^{-3}$	CL=84%
	$\rho(770)^0$ decays		
Γ_6	$\pi^+\pi^-$	$\sim$ 100 %	
Γ_7	$\pi^+\pi^-\gamma$	(1.11 ± 0.14) %	
Γ_8	$\pi^0\gamma$	$(7.9 \pm 2.0) \times 10^{-4}$	
Γ_9	$\eta\gamma$	$(3.8 \pm 0.7) \times 10^{-4}$	
Γ_{10}	$\mu^+\mu^-$	[a] $(4.60 \pm 0.28) \times 10^{-5}$	
Γ_{11}	e^+e^-	[a] $(4.44 \pm 0.21) \times 10^{-5}$	
Γ_{12}	$\pi^+\pi^-\pi^0$	$< 1.2 \times 10^{-4}$	CL=90%
Γ_{13}	$\pi^+\pi^-\pi^+\pi^-$	$< 2 \times 10^{-4}$	CL=90%
Γ_{14}	$\pi^+\pi^-\pi^0\pi^0$	$< 2 \times 10^{-4}$	CL=90%

[a] The e^+e^- branching fraction is from $e^+e^- \rightarrow \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \rightarrow \mu^+\mu^-) = \Gamma(\rho^0 \rightarrow e^+e^-) \times 0.99785$.

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 9 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 10.2$ for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ccc} x_3 & -100 & \\ \Gamma & 18 & -18 \\ & x_2 & x_3 \end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_2	$\pi^\pm\pi^0$	149.1 ± 2.9	
Γ_3	$\pi^\pm\gamma$	0.068 ± 0.007	2.3

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and a branching ratio uses 8 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 = 3.3$ for 5 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

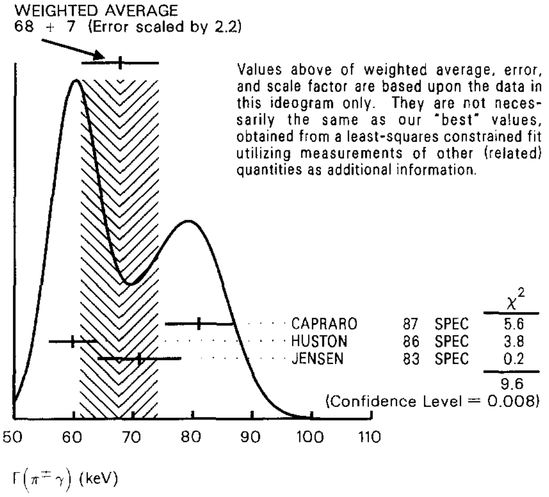
$$\begin{array}{cccc} x_{10} & -80 & & \\ x_{11} & -60 & 0 & \\ \Gamma & 13 & 0 & -21 \\ & x_6 & x_{10} & x_{11} \end{array}$$

	Mode	Rate (MeV)
Γ_6	$\pi^+\pi^-$	152.4 ± 1.5
Γ_{10}	$\mu^+\mu^-$	[a] 0.0070 ± 0.0004
Γ_{11}	e^+e^-	[a] 0.00677 ± 0.00032

$\rho(770)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ Γ_3

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
68 ± 7 OUR FIT Error includes scale factor of 2.3.					
68 ± 7 OUR AVERAGE Error includes scale factor of 2.2. See the ideogram below.					
81.0 ± 4.0 ± 4.0	CAPRARO	87	SPEC	−	200 $\pi^- A \rightarrow \pi^-\pi^0 A$
59.8 ± 4.0	HUSTON	86	SPEC	+	202 $\pi^+ A \rightarrow \pi^+\pi^0 A$
71.0 ± 7.0	JENSEN	83	SPEC	−	156–260 $\pi^- A \rightarrow \pi^-\pi^0 A$



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(e^+e^-)$ Γ_{11}

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
6.77 ± 0.32 OUR FIT				
6.77 ± 0.10 ± 0.30	BARKOV	85	OLYA	$e^+e^- \rightarrow \pi^+\pi^-$

$\Gamma(\pi^0\gamma)$ Γ_8

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
121 ± 31	DOLINSKY	89	ND	$e^+e^- \rightarrow \pi^0\gamma$

$\Gamma(\eta\gamma)$ Γ_9

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62 ± 17	[23] DOLINSKY	89	ND	$e^+e^- \rightarrow \eta\gamma$
111 ± 22	[24] DOLINSKY	89	ND	$e^+e^- \rightarrow \eta\gamma$

[23] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.

[24] Solution corresponding to destructive ρ-ω interference.

$\rho(770)$ BRANCHING RATIOS

$\Gamma(\pi^\pm\eta)/\Gamma(\pi\pi)$ Γ_4/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<80	84	FERBEL	66	HBC	±	$\pi^\pm p$ above 2.5

$\Gamma(\pi^\pm\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ Γ_5/Γ_1

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<20	84	FERBEL 66	HBC	±	$\pi^\pm p$ above 2.5
• • • We do not use the following data for averages, fits, limits, etc. • • •					
35±40		JAMES 66	HBC	+	2.1 $\pi^+ p$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ Γ_{10}/Γ_6

VALUE (units 10^{-5})	*DOCUMENT ID*	*TECN*	*COMMENT*
4.60±0.28 OUR FIT			
4.6 ±0.2 ±0.2	ANTIPOV 89	SIGM	$\pi^- \text{Cu} \to \mu^+\mu^-\pi^- \text{Cu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$8.2\ ^{+1.6}_{-3.6}$	[25] ROTHWELL 69	CNTR	Photoproduction
5.6 ±1.5	[26] WEHMANN 69	OSPK	12 π^- C, Fe
$9.7\ ^{+3.1}_{-3.3}$	[27] HYAMS 67	OSPK	11 π^- Li, H

[25] Possibly large ρ-ω interference leads us to increase the minus error.

[26] Result contains 11 ± 11% correction using SU(3) for central value. The error on the correction takes account of possible ρ-ω interference and the upper limit agrees with the upper limit of $\omega \to \mu^+\mu^-$ from this experiment.

[27] HYAMS 67's mass resolution is 20 MeV. The ω region was excluded.

$\Gamma(e^+e^-)/\Gamma(\pi\pi)$ Γ_{11}/Γ_1

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
0.41±0.05	BENAKSAS 72	OSPK	e^+e^-

$\Gamma(\eta\gamma)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
3.8±0.7 OUR AVERAGE				
4.0±1.1	[28] DOLINSKY 89	ND		e^+e^-
3.6±0.9	[28] ANDREWS 77	CNTR	0	6.7–10 γCu
• • • We do not use the following data for averages, fits, limits, etc. • • •				
7.3±1.5	[29] DOLINSKY 89	ND		e^+e^-
5.4±1.1	[29] ANDREWS 77	CNTR	0	6.7–10 γCu

[28] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.

[29] Solution corresponding to destructive ω-ρ interference.

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<2	90	KURDADZE 88	OLYA	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma(\pi\pi)$ Γ_{13}/Γ_1

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<15	90	ERBE 69	HBC	0	2.5–5.8 γp
<20		CHUNG 68	HBC	0	3.2,4.2 $\pi^- p$
<20	90	HUSON 68	HLBC	0	16.0 $\pi^- p$
<80		JAMES 66	HBC	0	2.1 $\pi^+ p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.2	90	VASSERMAN 88B	ND	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ Γ_{12}/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 0.01		BRAMON 86	RVUE	0	$J/\psi \to \omega\pi^0$
<0.01	84	[30] ABRAMS 71	HBC	0	3.7 $\pi^+ p$

[30] Model dependent, assumes $I = 1$, 2, or 3 for the 3π system.

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<2	90	KURDADZE 86	OLYA	0	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0111±0.0014	[31] VASSERMAN 88	ND	$e^+e^- \to \pi^+\pi^-\gamma$

[31] For Photon energy greater than 50 MeV/c.

$\Gamma(\pi^0\gamma)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
7.9±2.0	DOLINSKY 89	ND	e^+e^-

$\rho(770)$ REFERENCES

ANTIPOV	89	ZPHY C42 185	+Batarin+	(SERP, JINR, BGNA, MILA, TBLI)
DOLINSKY	89	ZPHY C42 511	+Druzhinin, Dubrovin, Golubev+	(NOVO)
GESHKENBEIN	89	ZPHY 45 351		(ITEP)
KURDADZE	88	JETPL 47 512	+Leltchouk, Pakhtusova, Sidorov+	(NOVO)
		Translated from ZETFP 47 432.		
VASSERMAN	88	SJNP 47 1035	+Golubev, Dolinsky+	(NOVO)
		Translated from YAF 47 1635.		
VASSERMAN	88B	SJNP 48 480	+Golubev, Dolinsky+	(NOVO)
		Translated from YAF 48 753.		
CAPRARO	87	NP B288 659	+Levy+	(CLER, FRAS, MILA, PISA, LCGT, TRST+)
BRAMON	86	PL B173 97	+Casulleras	(BARC)
HUSTON	86	PR 33 3199	+Berg, Collick, Jonckheere+	(ROCH, FNAL, MINN)
KURDADZE	86	JETPL 43 643	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)
		Translated from ZETFP 43 497.		
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
CHABAUD	83	NP B223 1	+Gorlich, Cerrada+	(CERN, CRAC, MPIM)
JENSEN	83	PR D27 26	+Berg, Biel, Collick+	(ROCH, FNAL, MINN)
BOHACIK	80	PR D21 1342	+Kuhnelt	(SLOV, WIEN)
HEYN	80	ZPHY C7 169	+Lang	(GRAZ)
LANG	79	PR D19 956	+Mas-Parareda	(GRAZ)
BARTALUCCI	78	NC 44A 587	+Basini, Bertolucci+	(DESY, FRAS)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
ANDREWS	77	PRL 38 198	+Fukushima, Harvey, Lobkowicz, May+	(ROCH)
DEUTSCH...	76	NP B103 426	Deutschmann+	(AACH, BERL, BONN, CERN+)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)
ESTABROOKS	74	NP B79 301	+Martin	(DURH)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
BYERLY	73	PR D7 637	+Anthony, Coffin, Meanley, Meyer, Rice+	(MICH)
GLADDING	73	PR D8 3721	+Russell, Tannenbaum, Weiss, Thomson	(HARV)
PROTOPOP...	73	PR D7 1280	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)
BALLAM	72	PR D5 545	+Chadwick, Bingham, Milburn+	(SLAC, LBL, TUFT)
BENAKSAS	72	PL 39B 289	+Cosme, Jean-Marie, Jullian, Laplanche+	(ORSA)
JACOBS	72	PR D6 1291		(SACL)
RATCLIFF	72	PL 38B 345	+Bulos, Carnegie, Kluge, Leith, Lynch+	(SLAC)
ABRAMS	71	PR D4 653	+Barnham, Butler, Coyne, Goldhaber, Hall+	(LBL)
ALVENSLEBEN	70	PRL 24 786	+Becker, Bertram, Chen, Cohen	(DESY)
BIGGS	70	PRL 24 1197	+Braben, Clifft, Gabathuler, Kitching+	(DARE)
ERBE	69	PR 188 2060	+Hilpert+	(German Bubble Chamber Collab.)
MALAMUD	69	Argonne Conf. 93	+Schlein	(UCLA)
REYNOLDS	69	PR 184 1424	+Albright, Bradley, Brucker, Harms+	(FSU)
ROTHWELL	69	PRL 23 1521	+Chase, Earles, Gettner, Glass, Weinstein+	(NEAS)
WEHMANN	69	PR 178 2095	+	(HARV, CASE, SLAC, CORN, MCGI)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSA)
BATON	68	PR 176 1574	+Laurens	(SACL)
CHUNG	68	PR 165 1491	+Dahl, Kirz, Miller	(LRL)
FOSTER	68	NP B6 107	+Gavillet, Labrosse, Montanet+	(CERN, CDEF)
HUSON	68	PL 28B 208	+Lubatti, Six, Veillet+	(ORSA, MILA, UCLA)
HYAMS	68	NP B7 1	+Koch, Potter, Wilson, VonLindern+	(CERN, MPIM)
LANZEROTTI	68	PR 166 1365	+Blumenthal, Ehn, Faissler+	(HARV)
PISUT	68	NP B6 325	+Roos	(CERN)
ASBURY	67B	PRL 19 865	+Becker, Bertram, Joos, Jordan+	(DESY, COLU)
BACON	67	PR 157 1263	+Fickinger, Hill, Hopkins, Robinson+	(BNL)
EISNER	67	PR 164 1699	+Johnson, Klein, Peters, Sahni, Yen+	(PURD)
HUWE	67	PL 24B 252	+Marquit, Oppenheimer, Schultz, Wilson	(COLU)
HYAMS	67	PL 24B 634	+Koch, Pellett, Potter, VonLindern+	(CERN, MPIM)
MILLER	67B	PR 153 1423	+Gutay, Johnson, Loeffler+	(PURD)
ALFF-...	66	PR 145 1072	Alff-Steinberger, Berley+	(COLU, RUTG)
FERBEL	66	PL 21 111		(ROCH)
HAGOPIAN	66	PR 145 1128	+Selove, Alitti, Baton+	(PENN, SACL)
HAGOPIAN	66B	PR 152 1183	+Pan	(PENN, LRL)
JACOBS	66B	UCRL 16877		(LRL)
JAMES	66	PR 142 896	+Kraybill	(YALE, BNL)
WEST	66	PR 149 1089	+Boyd, Erwin, Walker	(WISC)
BLIEDEN	65	PL 19 444	+Freytag, Geibel+	(CERN Missing Mass Spect. Collab.)
CARMONY	64	PRL 12 254	+Lander, Rindfleisch, Xuong, Yager	(UCB)
GOLDHABER	64	PRL 12 336	+Brown, Kadyk, Shen+	(LRL, UCB)
ABOLINS	63	PRL 11 381	+Lander, Mehlhop, Nguyen, Yager	(UCSD)

OTHER RELATED PAPERS

ERKAL	85	ZPHY C29 485	+Olsson	(WISC)
RYBICKI	85	ZPHY C28 65	+Sakrejda	(CRAC)
KURDADZE	83	JETPL 37 733	+Lelchuk, Pakhtusova+	(NOVO)
		Translated from ZETFP 37 613.		
ALEKSEEV	82	JETP 55 591	+Kartamyshev, Makarin+	(KIAE)
		Translated from ZETF 82 1007.		
BERG	80	PRL 44 706	+Chandlee, Biel+	(ROCH, FNAL, MINN)
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)
QUENZER	78	PL 76B 512	+Ribes, Rumpf, Bertrand, Bizot, Chase+	(LALO)
MONTONEN	75	LNC 12 627	+Roos, Tornqvist	(HELS)
CARROLL	74B	PR D10 1430	+Matthews, Walker+	(SLAC, DUKE, WISC, TNTO)
HABER	74	PR D10 1387	+Hodous, Hulsizer, Kistiakowsky, Levy+	(MIT)
NORDBERG	74	PL 51B 106	+Abramson, Andrews, Harvey+	(CORN, ROCH)
SPITAL	74	PR D9 126	+Yennie	(CORN)
CHARLESW...	73	NP B65 253	Charlesworth, Emms, Bell+	(RHEL, BIRM, DURH)
BAILLON	72	PL 38B 555	+Carnegie, Kluge, Leith, Lynch, Ratcliff+	(SLAC)
BASDEVANT	72	PL 41B 178	+Froggatt, Petersen	(CERN)
DRIVER	72	NP B38 1	+Heinloth, Hohne, Hofmann, Rathje+	(DESY, HAMB)
EISENBERG	72	PR D5 15	+Ballam, Dagan+	(REHO, SLAC, TELA)
GRAYER	72	NP B50 29	+Hyams, Jones, Weilhammer, Blum+	(CERN, MPIM)
GRAYER	72B	Phil. Conf. 5	+Hyams, Jones, Schlein+	(CERN, MPIM)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHO, PENN, NDAM, ANL)
BLOODWO...	71	NP B35 133	Bloodworth, Jackson, Prentice, Yoon	(TNTO)
DEERY	71	PR D3 635	+Biswas, Cason, Groves, Johnson+	(NDAM)
BINGHAM	70	PRL 24 955	+Fretter, Moffeit, Ballam+	(LRL, SLAC, TUFT)
GALLOWAY	70	PR D1 3077	+Mott, Alyea, Lee, Martin, Prickett	(IND)
AUGUSTIN	69B	LNC 2 214	+Lefrancois, Lehmann, Marin+	(ORSA)
AUGUSTIN	69C	PL 28B 508	+Bizot, Buon, Haissinski, Lalanne+	(ORSA)
HAISSINSKI	69	Argonne Conf. 373		(ORSA)
JUHALA	69	PR 184 1461	+Leacock, Rhode, Kopelman, Libby+	(ISU, COLO)
MILLER	69	PR 178 2061	+Lichtman, Willmann	(PURD)
MOTT	69	PR 177 1966	+Ammar, Davis, Kropac, Slate+	(NWES, ANL)
ROOS	69	NP B10 563	+Pisut	(CERN, CMNS)
SCHARENG...	69	Argonne Conf. 306	Scharenguivel	(PURD)
BLECHSCH...	68	NC 53A 1045	Blechschmidt, Dowd, Elsner+	(DESY, MCHS)
Also	67	NC 52A 1348	Blechschmidt	
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
DONALD	68C	NP B6 174	+Edwards, Frodesen, Bettini+	(LIVP, OSLO, PADO)
JOHNSON	68	PR 176 1651	+Poirier, Biswas, Gutay+	(NDAM, PURD, SLAC)
JONES	68	PR 166 1405	+Bleuler, Caldwell, Elsner, Harting+	(CERN)
KEY	68	PR 166 1430	+Prentice, Cooper, Manner+	(TNTO, ANL, WISC)
LAMSA	68	PR 166 1395	+Cason, Biswas, Derado, Groves+	(NDAM)
MARATECK	68	PRL 21 1613	+Hagopian+	(PENN, LRL, COLO, PURD, TNTO+)
ALLES-...	67B	NC 50A 776	Alles-Borelli, French, Frisk+	(CERN, BONN)
BANNER	67	PL 25B 300	+Fayoux, Hamel, Zsembery, Cheze+	(SACL, CAEN)

BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
BATON	67	PL 25B 419	+Laurens, Reignier	(SACL)
Also	67B	NP B3 349	Baton, Laurens, Reignier	(SACL)
CLEAR	67	NC 49A 399	+Johnston, Cooper, Manner+	(TNTO, ANL, WISC)
DANYSZ	67B	NC 51A 801	+French, Simak	(CERN)
FRENCH	67	NC 52A 438	+Kinson, McDonald, Riddiford+	(CERN, BIRM)
POIRIER	67	PR 163 1462	+Biswas, Cason, Derado, Kenney+	(NDAM, PENN)
ACCENSI	66	PL 20 557	+Alles-Borelli, French, Frisk+	(CERN)
BALTAY	66B	PR 145 1103	+Franzini, Lutjens, Severiens, Tycko+	(COLU)
CAMBRIDGE	66	PR 146 994		(Cambridge Bubble Chamber Collab.)
CASON	66	PR 148 1282		(WISC)
DEUTSCH...	66	PL 20 82	Deutschmann, Steinberg+	(AACH, BERL, CERN)
ALYEA	65	PL 15 82	+Crittenden, Martin, Rhode+	(IND)
ARMENISE	65	NC 37 361		(SACL, ORSA, BARI, BGNA)
CLARK	65	PR 139B 1556	+Christenson, Cronin, Turlay	(PRIN)
GUTAY	65	NC 39 381	+Lannutti, Tuli	(FSU)
ZDANIS	65	PRL 14 721	+Madansky, Kraemer+	(JHU, BNL)
BONDAR	64	NC 31 729	+	(AACH, BIRM, BONN, DESY, LOIC, MPIM)
GUIRAGOS...	63	PRL 11 85	Guiragossian	(LRL)
SACLAY	63	Siena Conf. 1 239		(SACL, ORSA, BARI, BGNA)
KENNEY	62	PR 126 736	+Shephard, Gall	(KNTY)
SAMIOS	62	PRL 9 139	+Bachman, Lea+	(BNL, CUNY, COLU, KNTY)
XUONG	62	PR 128 1849	+Lynch	(LRL)
ANDERSON	61	PRL 6 365	+Bang, Burke, Carmony, Schmitz	(LRL)
ERWIN	61	PRL 6 628	+March, Walker, West	(WISC)

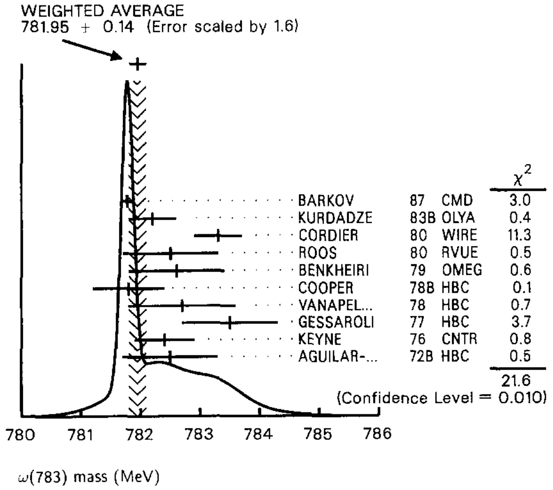
$\boxed{\omega(783)}$

$I^G(J^{PC}) = 0^-(1^{--})$

$\omega(783)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
781.95±0.14 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			
781.78±0.10		BARKOV	87 CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
782.2 ±0.4		KURDADZE	83B OLYA	e^+e^-
783.3 ±0.4		CORDIER	80 WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
782.5 ±0.8	33260	ROOS	80 RVUE	0.0–3.6 $\overline{p}p$
782.6 ±0.8	3000	BENKHEIRI	79 OMEG	9–12 $\pi^\pm p$
781.8 ±0.6	1430	COOPER	78B HBC	0.7–0.8 $\overline{p}p \to 5\pi$
782.7 ±0.9	535	VANAPEL...	78 HBC	7.2 $\overline{p}p \to \overline{p}p\omega$
783.5 ±0.8	2100	GESSAROLI	77 HBC	11 $\pi^-p \to \omega\pi$
782.4 ±0.5	7000	[1] KEYNE	76 CNTR	$\pi^-p \to \omega n$
782.5 ±0.8	418	AGUILAR-...	72B HBC	3.9,4.6 K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •				
783.4 ±1.0	248	BIZZARRI	71 HBC	0.0 $p\overline{p} \to K^+K^-\omega$
781.0 ±0.6	510	BIZZARRI	71 HBC	0.0 $p\overline{p} \to K_1K_1\omega$
783.7 ±1.0		[2] COYNE	71 HBC	3.7 π^+p
784.1 ±1.2	750	ABRAMOVI...	70 HBC	3.9 π^-p
783.2 ±1.6		[3] BIGGS	70B CNTR	<4.1 $\gamma C \to \pi^+\pi^-C$
782.4 ±0.5	2400	BIZZARRI	69 HBC	0.0 $\overline{p}p$

[1] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.
[2] From best-resolution sample of COYNE 71.
[3] From ω-ρ interference in the $\pi^+\pi^-$ mass spectrum assuming ω width 12.6 MeV.



$\omega(783)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$8.43^{+0.10}_{-0.09}$ OUR AVERAGE				
8.4 ±0.1		[4] AULCHENKO	87 ND	$e^+e^-, \pi^+\pi^-\pi^0$
8.30±0.40		BARKOV	87 CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
9.8 ±0.9		KURDADZE	83B OLYA	e^+e^-
9.0 ±0.8		CORDIER	80 WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
9.1 ±0.8		BENAKSAS	72B OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
12.0 ±2.0	1430	COOPER	78B HBC	0.7–0.8 $\overline{p}p \to 5\pi$
9.4 ±2.5	2100	GESSAROLI	77 HBC	11 $\pi^-p \to \omega\pi$
10.22±0.43	20000	[5] KEYNE	76 CNTR	$\pi^-p \to \omega n$
13.3 ±2	418	AGUILAR-...	72B HBC	3.9,4.6 K^-p
10.5 ±1.5		BORENSTEIN	72 HBC	2.18 K^-p
7.70±0.9 ±1.15	940	BROWN	72 MMS	2.5 $\pi^-p \to n$ MM
10.3 ±1.4	510	BIZZARRI	71 HBC	0.0 $p\overline{p} \to K_1K_1\omega$
12.8 ±3.0	248	BIZZARRI	71 HBC	0.0 $p\overline{p} \to K^+K^-\omega$
9.5 ±1.0	4270	COYNE	71 HBC	3.7 π^+p

[4] Relativistic Breit-Wigner includes radiative corrections.
[5] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.

$\omega(783)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\pi^0$	(88.8 ±0.6) %	
Γ_2	$\pi^0\gamma$	(8.5 ±0.5) %	
Γ_3	$\pi^+\pi^-$	(2.21±0.30) %	
Γ_4	neutrals (excluding $\pi^0\gamma$)	$(4.4 ^{+7.9}_{-2.9}) \times 10^{-3}$	
Γ_5	$\pi^0e^+e^-$	$(5.9 \pm 1.9) \times 10^{-4}$	
Γ_6	$\eta\gamma$	$(4.7 ^{+2.2}_{-1.8}) \times 10^{-4}$	S=1.1
Γ_7	$\pi^0\mu^+\mu^-$	$(9.6 \pm 2.3) \times 10^{-5}$	
Γ_8	e^+e^-	$(7.07 \pm 0.19) \times 10^{-5}$	S=1.1
Γ_9	$\pi^+\pi^-\pi^0\pi^0$	< 2 %	CL=90%
Γ_{10}	$\pi^+\pi^-\gamma$	$< 4 \times 10^{-3}$	CL=95%
Γ_{11}	$\pi^+\pi^-\pi^+\pi^-$	$< 1 \times 10^{-3}$	CL=90%
Γ_{12}	$\pi^0\pi^0\gamma$	$< 4 \times 10^{-4}$	CL=90%
Γ_{13}	$\mu^+\mu^-$	$< 1.8 \times 10^{-4}$	CL=90%
Γ_{14}	$\eta\pi^0$		

CONSTRAINED FIT INFORMATION

An overall fit to 6 branching ratios uses 22 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 11.3 for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{cccc} x_2 & 12 & & \\ x_3 & -44 & -5 & \\ x_4 & -69 & -71 & 0 \\ & x_1 & x_2 & x_3 \end{array}$$

$\omega(783)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_8

VALUE (keV)	DOCUMENT ID
0.60±0.02 OUR EVALUATION	Error includes scale factor of 1.1.

$\omega(783)$ BRANCHING RATIOS

$\Gamma(\text{neutrals})/\Gamma(\pi^+\pi^-\pi^0)$ $(\Gamma_2+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.101±0.007 OUR FIT	Error includes scale factor of 1.1.			
0.105±0.009 OUR AVERAGE				
0.15 ±0.04	46	AGUILAR-...	72B HBC	3.9,4.6 K^-p
0.10 ±0.03	19	BARASH	67B HBC	0.0 $\overline{p}p$
0.134±0.026	850	DIGIUGNO	66B CNTR	1.4 π^-p
0.097±0.016	348	FLATTE	66 HBC	1.8 K^-p
$0.06 ^{+0.05}_{-0.02}$		JAMES	66 HBC	2.1 π^+p
0.08 ±0.03	35	KRAEMER	64 DBC	1.2 π^+d
0.11 ±0.02	20	BUSCHBECK	63 HBC	1.5 K^-p

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_3/Γ_1

See also $\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$.

VALUE	DOCUMENT ID	TECN	COMMENT
0.0249±0.0035 OUR FIT			
0.026 ±0.005 OUR AVERAGE			
$0.021 ^{+0.028}_{-0.009}$	[6] RATCLIFF	72 ASPK	15 $\pi^-p \to n2\pi$
0.028 ±0.006	BEHREND	71 ASPK	Photoproduction
$0.022 ^{+0.009}_{-0.01}$	[7] ROOS	70 RVUE	

[6] Significant interference effect observed. NB of $\omega \to 3\pi$ comes from an extrapolation.
[7] ROOS 70 combines ABRAMOVICH 70 and BIZZARRI 70.

$\Gamma(\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.096±0.006 OUR FIT			
0.096±0.006 OUR AVERAGE			
0.099±0.007	DOLINSKY 89	ND	$e^+e^-\to\pi^0\gamma$
0.084±0.013	KEYNE 76	CNTR	$\pi^-p\to\omega n$
0.109±0.025	BENAKSAS 72C	OSPK	e^+e^-
0.081±0.020	BALDIN 71	HLBC	2.9 π^+p
0.13 ±0.04	JACQUET 69B	HLBC	

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{10}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.066	90	KALBFLEISCH 75	HBC	2.2 K^-p
<0.05	90	FLATTE 66	HBC	1.8 K^-p

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.004	95	BITYUKOV 88B	SPEC	32 $\pi^-p\to\pi^+\pi^-\gamma X$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1\times10^{-3}$	90	KURDADZE 88	OLYA	$e^+e^-\to\pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{total}$ Γ_9/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<2	90	KURDADZE 86	OLYA	0	$e^+e^-\to\pi^+\pi^-\pi^0\pi^0$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{13}/Γ_1

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.2	90	WILSON 69	OSPK	12 $\pi^-C\to$ Fe
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	74	FLATTE 66	HBC	1.8 K^-p
<1.2		BARBARO-... 65	HBC	2.7 K^-p

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^0\gamma)$ Γ_{12}/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.005	90	DOLINSKY 89	ND	e^+e^-
<0.18	95	KEYNE 76	CNTR	$\pi^-p\to\omega n$
<0.15	90	BENAKSAS 72C	OSPK	e^+e^-
<0.14		BALDIN 71	HLBC	2.9 π^+p
<0.1	90	BARMIN 64	HLBC	1.3–2.8 π^-p

$[\Gamma(\eta\gamma)+\Gamma(\eta\pi^0)]/\Gamma(\pi^+\pi^-\pi^0)$ $(\Gamma_6+\Gamma_{14})/\Gamma_1$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.017	90	FLATTE 66	HBC	1.8 K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.045	95	JACQUET 69B	HLBC	

Γ(neutrals)$/\Gamma$(charged particles) $(\Gamma_2+\Gamma_4)/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.098±0.007 OUR FIT Error includes scale factor of 1.1.			
0.124±0.021	FELDMAN 67C	OSPK	1.2 π^-p

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{12}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00045	90	DOLINSKY 89	ND	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	95	JACQUET 69B	HLBC	

$\Gamma(\eta\gamma)/\Gamma(\pi^0\gamma)$ Γ_6/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.0082±0.0033 OUR AVERAGE			
0.0082±0.0033	[8] DOLINSKY 89	ND	e^+e^-
0.010 ±0.045	APEL 72B	OSPK	4–8 $\pi^-p\to n3\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.039 ±0.007	[9] DOLINSKY 89	ND	e^+e^-

[8] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.

[9] Solution corresponding to destructive ρ-ω interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
0.96±0.23	DZHELYADIN 81B	CNTR	25–33 $\pi^-p\to\omega n$

$\Gamma(\pi^0e^+e^-)/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
5.9±1.9	43	DOLINSKY 88	ND	$e^+e^-\to\pi^0e^+e^-$

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
0.707±0.019 OUR AVERAGE Error includes scale factor of 1.1.				
0.714±0.036		DOLINSKY 89	ND	e^+e^-
0.72 ±0.03		BARKOV 87	CMD	$e^+e^-\to\pi^+\pi^-\pi^0$
0.64 ±0.04		KURDADZE 83B	OLYA	e^+e^-
0.675±0.069		CORDIER 80	WIRE	$e^+e^-\to3\pi$
0.83 ±0.10		BENAKSAS 72B	OSPK	$e^+e^-\to3\pi$
0.77 ±0.06		[10] AUGUSTIN 69D	OSPK	$e^+e^-\to2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.65 ±0.13	33	[11] ASTVACAT... 68	OSPK	Assume SU(3)+mixing

[10] Rescaled by us to correspond to ω width 8.4 MeV.

[11] Not resolved from ρ decay. Error statistical only.

Γ(neutrals)$/\Gamma_{total}$ $(\Gamma_2+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.089±0.006 OUR FIT Error includes scale factor of 1.1.				
0.079±0.009 OUR AVERAGE				
0.073±0.018	42	BASILE 72B	CNTR	1.67 π^-p
0.075±0.025		BIZZARRI 71	HBC	0.0 $p\bar{p}$
0.079±0.019		DEINET 69B	OSPK	1.5 π^-p
0.084±0.015		BOLLINI 68C	CNTR	2.1 π^-p

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ Γ_3/Γ

See also $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$.

VALUE	DOCUMENT ID	TECN	COMMENT
0.0221±0.0030 OUR FIT			
0.021 ±0.004 OUR AVERAGE			
0.023 ±0.005	BARKOV 85	OLYA	e^+e^-
$0.016\,^{+0.009}_{-0.007}$	QUENZER 78	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.010 ±0.001	[12] WICKLUND 78	ASPK	3,4,6 $\pi^\pm N$
0.0122±0.0030	ALVENSLEBEN 71C	CNTR	Photoproduction
$0.013\,^{+0.012}_{-0.009}$	MOFFEIT 71	HBC	2.8,4.7 γp
$0.0080\,^{+0.0028}_{-0.002}$	[13] BIGGS 70B	CNTR	$4.2\gamma C\to\pi^+\pi^-C$

[12] From a model-dependent analysis assuming complete coherence.

[13] Re-evaluated under $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ by BEHREND 71 using more accurate $\omega\to\rho$ photoproduction cross-section ratio.

$\Gamma(\pi^0\pi^0\gamma)/\Gamma$(neutrals) $\Gamma_{12}/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.07		[14] DAKIN 72	OSPK	1.4 $\pi^-p\to n$ MM
<0.19	90	DEINET 69B	OSPK	

[14] See $\Gamma(\pi^0\gamma)/\Gamma$(neutrals) .

$\Gamma(\pi^0\gamma)/\Gamma$(neutrals) $\Gamma_2/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.78±0.07		[15] DAKIN 72	OSPK	1.4 $\pi^-p\to n$ MM
>0.81	90	DEINET 69B	OSPK	

[15] Error statistical only. Authors obtain good fit also assuming $\pi^0\gamma$ as the only neutral decay.

$\Gamma(\eta\gamma)/\Gamma_{total}$ Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
$4.7\,^{+2.2}_{-1.8}$ **OUR AVERAGE** Error includes scale factor of 1.1.			
7.3±2.9	[16] DOLINSKY 89	ND	e^+e^-
$3.0\,^{+2.5}_{-1.8}$	[16] ANDREWS 77	CNTR	6.7–10 γCu
• • • We do not use the following data for averages, fits, limits, etc. • • •			
35 ±5	[17] DOLINSKY 89	ND	e^+e^-
29.0±7.0	[17] ANDREWS 77	CNTR	6.7–10 γCu

[16] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.

[17] Solution corresponding to destructive ω-ρ interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma(\mu^+\mu^-)$ Γ_7/Γ_{13}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2±0.6	30	[18] DZHELYADIN 79	CNTR	25–33 π^-p

[18] Superseded by DZHELYADIN 81B result above.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.8942±0.0062	DOLINSKY 89	ND	e^+e^-

$\omega(783)$ REFERENCES

DOLINSKY 89 ZPHY C42 511 +Druzhinin, Dubrovin, Golubev+ (NOVO)
BITYUKOV 88B YAF 47 1258 +Borisov, Viktorov, Golovkin+ (SERP)
DOLINSKY 88 YAF 48 442 +Druzhinin, Dubrovin, Golubev+ (NOVO)
KURDADZE 88 JETPL 47 512 +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
Translated from ZETFP 47 432.
AULCHENKO 87 PL B186 432 +Dolinsky, Druzhinin, Dubrovin+ (NOVO)
BARKOV 87 JETPL 46 164 +Vasserman, Vorobev, Ivanov (NOVO)
Translated from ZETFP 46 132.
KURDADZE 86 JETPL 43 643 +Lelchuk, Pakhtusova, Sidorov, Skrinskii+ (NOVO)
Translated from ZETFP 43 497.
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
KURDADZE 83B JETPL 36 274 +Pakhtusova, Sidorov+ (NOVO)
Translated from ZETFP 36 221.
DZHELYADIN 81B PL 102B 296 +Golovkin, Konstantinov+ (SERP)
CORDIER 80 NP B172 13 +Delcourt, Eschstruth, Fulda+ (LALO)
ROOS 80 LNC 27 321 +Pellinen (HELS)
BENKHEIRI 79 NP B150 268 +Eisenstein+ (EPOL, CERN, CDEF, LALO)
DZHELYADIN 79 PL 84B 143 +Golovkin, Gritsuk+ (SERP)
COOPER 78B NP B146 1 +Gurtu+ (TATA, CERN, CDEF, MADR)
QUENZER 78 PL 76B 512 +Ribes, Rumpf, Bertrand, Bizot, Chase+ (LALO)
VANAPEL... 78 NP B133 245 VanApeldoorn, Grundeman, Harting+ (ZEEM)
WICKLUND 78 PR D17 1197 +Ayres, Diebold, Greene, Kramer, Pawlicki (ANL)
ANDREWS 77 PRL 38 198 +Fukushima, Harvey, Lobkowicz, May+ (ROCH)
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
KEYNE 76 PR D14 28 +Binnie, Carr, Debenham, Garbutt+ (LOIC, SHMP)
Also 73B PR D8 2789 Binnie, Carr, Debenham, Duane+ (LOIC, SHMP)
KALBFLEISCH 75 PR D11 987 +Strand, Chapman (BNL, MICH)
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
APEL 72B PL 41B 234 +Auslander, Muller, Bertolucci+ (KARL, PISA)
BASILE 72B Phil. Conf. 153 +Bollini, Broglin, Dalpiaz, Frabetti+ (CERN)
BENAKSAS 72B PL 42B 507 +Cosme, Jean-Marie, Jullian (ORSA)
BENAKSAS 72C PL 42B 511 +Cosme, Jean-Marie, Jullian, Laplanche+ (ORSA)
BORENSTEIN 72 PR D5 1559 +Danburg, Kalbfleisch+ (BNL, MICH)
BROWN 72 PL 42B 117 +Downing, Holloway, Huld, Bernstein+ (ILL, ILLC)
DAKIN 72 PR D6 2321 +Hauser, Kreisler, Mischke (PRIN)
RATCLIFF 72 PL 38B 345 +Bulos, Carnegie, Kluge, Leith, Lynch+ (SLAC)
ALVENSLEBEN 71C PRL 27 888 +Becker, Busza, Chen, Cohen+ (DESY)
BALDIN 71 SJNP 13 758 +Yergakov, Trebukhovsky, Shishov (ITEP)
Translated from YAF 13 1318.
BEHREND 71 PRL 27 61 +Lee, Nordberg, Wehmann+ (ROCH, CORN, FNAL)
BIZZARRI 71 NP B27 140 +Montanet, Nilsson, D'Andlau+ (CERN, CDEF)
COYNE 71 NP B32 333 +Butler, Fang-Landau, MacNaughton (LRL)
MOFFEIT 71 NP B29 349 +Bingham, Fretter+ (LRL, UCB, SLAC, TUFT)
ABRAMOVI... 70 NP B20 209 Abramovich, Blumenfeld, Bruyant+ (CERN)
BIGGS 70B PRL 24 1201 +Clifft, Gabathuler, Kitching, Rand (DARE)
BIZZARRI 70 PRL 25 1385 +Ciapetti, Dore, Gaspero, Guidoni+ (ROMA, SYRA)
ROOS 70 DNPL/R7 173 (CERN)
Proc. Daresbury Study Weekend No. 1.
AUGUSTIN 69D PL 28B 513 +Benaksas, Buon, Gracco, Haissinski+ (ORSA)
BIZZARRI 69 NP B14 169 +Foster, Gavillet, Montanet+ (CERN, CDEF)
DEINET 69B PL 30B 426 +Menzione, Muller, Buniatov+ (KARL, CERN)
JACQUET 69B NC 63A 743 +Nguyen-Khac, Haatuft, Halsteinslid (EPOL, BERG)
WILSON 69 Private Comm. (HARV)
Also 69 PR 178 2095 Wehmann+ (HARV, CASE, SLAC, CORN, MCGI)
ASTVACAT... 68 PL 27B 45 Astvacaturov, Azimov, Baldin+ (JINR, MOSU)
BOLLINI 68C NC 56A 531 +Buhler, Dalpiaz, Massam+ (CERN, BGNA, STRB)
BARASH 67B PR 156 1399 +Kirsch, Miller, Tan (COLU)
FELDMAN 67C PR 159 1219 +Frati, Gleeson, Halpern, Nussbaum+ (PENN)
DIGIUGNO 66B NC 44A 1272 +Peruzzi, Troise+ (NAPL, FRAS, TRST)
FLATTE 66 PR 145 1050 +Huwe, Murray, Button-Shafer, Solmitz+ (LRL)
JAMES 66 PR 142 896 +Kraybill (YALE, BNL)
BARBARO-... 65 PRL 14 279 Barbaro-Galtieri, Tripp (LRL)
BARMIN 64 JETP 18 1289 +Dolgolenko, Krestnikov+ (ITEP)
Translated from ZETF 45 1879.
KRAEMER 64 PR 136B 496 +Madansky, Fields+ (JHU, NWES, WOOD)
BUSCHBECK 63 Siena Conf. 1 166 +Czapp+ (VIEN, CERN, ANIK)

OTHER RELATED PAPERS

DOLINSKY 86 PL B174 453 +Druzhinin, Dubrovin, Eidelman+ (NOVO)
KURDADZE 83 JETPL 37 733 +Lelchuk, Pakhtusova+ (NOVO)
Translated from ZETFP 37 613.
BARTKE 77 NP B118 360 + (AACH, BERL, BONN, CERN, CRAC, LOIC+)
EMMS 75E NP B98 1 +Kinson, Stacey, Bell, Dale+ (BIRM, DURH, RHEL)
ROOS 75 NP B97 165 (HELS)
ESTABROOKS 74B NP B81 70 +Hyams, Jones, Blum+ (CERN, MPIM)
GREGORIO 74 NC 20A 437 (ICTP)
KRAMER 74 PRL 33 505 +Ayres, Diebold, Greene, Pawlicki+ (ANL)
EISENBERG 72 PR D5 15 +Ballam, Dagan+ (REHO, SLAC, TELA)
ABRAMS 71 PR D4 653 +Barnham, Butler, Coyne, Goldhaber, Hall+ (LBL)
ANGELOV 71 SJNP 12 427 +Gramenitsky, Kanasirsky, Keratschew+ (JINR)
Translated from YAF 12 788.
BARDADIN-... 71 PR D4 2711 Bardadin-Otwinowska, Hofmokl+ (WARS)
BLOODWO... 71 NP B35 133 Bloodworth, Jackson, Prentice, Yoon (TNTO)
CHAPMAN 71 PR D3 38 +Fortney, Fowler (DUKE)
FIELDS 71 PRL 27 1749 +Cooper, Rhines, Allison (ANL, OXF)
MATTHEWS 71B PRL 26 400 +Prentice, Yoon, Carroll, Walker+ (TNTO, WISC)
CASON 70 PR D1 851 +Andrews, Biswas, Groves, Harrington+ (NDAM)
DANBURG 70 PR D2 2564 +Abolins, Dahl, Davies, Hoch, Kirz+ (LRL)
FLATTE 70 PR D1 1 (LRL)
GOLDHABER 70B Phil. Conf. 59 (LRL)
HAGOPIAN 70 PRL 25 1050 +Hagopian, Bogart, Selove (FSU, PENN)
DANBURG 69 UCRL 19275 Thesis (LRL)
ERWIN 69 NP B9 364 +Walker, Goshaw, Weinberg (WISC, PRIN, VAND)
MILLER 69 PR 178 2061 +Lichtman, Willmann (PURD)
STRUGALSKI 69B PL 29B 532 +Chuvilo, Fenyves+ (WARS, JINR, BUDA)
KEY 68 PR 166 1430 +Prentice, Cooper, Manner+ (TNTO, ANL, WISC)
PISUT 68 NP B6 325 +Roos (CERN)
WEHMANN 68 PRL 20 748 +Engels+ (HARV, CASE, SLAC, CORN, MCGI)
HERTZBACH 67 PR 155 1461 +Kraemer, Madanski, Zdanis+ (JHU, BNL)
BINNIE 65 PL 18 348 +Duane, Jane, Jones+ (LOIC, MCHS)
MILLER 65B CU-237/Nevis-131 Thesis (COLU)
ZDANIS 65 PRL 14 721 +Madansky, Kraemer+ (JHU, BNL)
ARMENTEROS 63 Siena Conf. 1 296 +Edwards, Jacobsen+ (CERN, CDEF)
BARMIN 63 Siena Conf. 1 207 +Dolgolenko, Krestnikov+ (ITEP)
GELFAND 63 PRL 11 436 +Miller, Nussbaum, Ratau+ (COLU, RUTG)
MURRAY 63 PL 7 358 +Ferro-Luzzi, Huwe, Shafer, Solmitz+ (LRL)
ALFF-... 62B PRL 9 325 Alff-Steinberger, Berley, Colley+ (COLU, RUTG)
ARMENTEROS 62 CERN Conf. 90 +Budde+ (CERN, CDEF, EPOL)
STEVENSON 62 PR 125 687 +Alvarez, Maglich, Rosenfeld (LRL)
MAGLICH 61 PRL 7 178 +Alvarez, Rosenfeld, Stevenson (LRL)
PEVSNER 61 PRL 7 421 +Kraemer, Nussbaum, Richardson+ (JHU)
XUONG 61 PRL 7 327 +Lynch (LRL)

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Our latest mini-review on this particle can be found in the 1984 edition. See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$\eta'(958)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
957.50±0.24 OUR AVERAGE					
956.3 ±1.0	143 ± 12	GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
957.46±0.33		DUANE	74	MMS	$\pi^- p \to n$ MM
958.2 ±0.5	1414	DANBURG	73	HBC	2.2 $K^- p \to \Lambda X^0$
958 ±1	400	JACOBS	73	HBC	2.9 $K^- p \to \Lambda X^0$
956.1 ±1.1	3415	BASILE	71	CNTR	1.6 $\pi^- p \to n X^0$
957.4 ±1.4	535	BASILE	71	CNTR	1.6 $\pi^- p \to n X^0$
957 ±1		RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\eta'(958)$ WIDTH

We include direct measurements of the $\eta'(958)$ total width and $\gamma\gamma$ partial width together with the measured branching ratios in the fit for the partial decay rates.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.208±0.021 OUR FIT	Error includes scale factor of 1.4.					
0.28 ±0.10	1000	BINNIE	79	MMS	0	$\pi^- p \to n$ MM

$\eta'(958)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\eta$	(44.2 ±1.7) %	S=1.2
Γ_2	$\rho^0\gamma$	(30.0 ±1.5) %	S=1.1
Γ_3	$\pi^0\pi^0\eta$	(20.5 ±1.3) %	S=1.3
Γ_4	$\omega\gamma$	(3.00±0.31) %	
Γ_5	$\gamma\gamma$	(2.16±0.17) %	S=1.5
Γ_6	$3\pi^0$	(1.53±0.26) × 10^{-3}	S=1.1
Γ_7	$\mu^+\mu^-\gamma$	(1.06±0.27) × 10^{-4}	
Γ_8	$\pi^+\pi^-\pi^0$	< 5 %	CL=90%
Γ_9	$\pi^0\rho^0$	< 4 %	CL=90%
Γ_{10}	$\pi^+\pi^-$	< 2 %	CL=90%
Γ_{11}	$\pi^0 e^+ e^-$	< 1.3 %	CL=90%
Γ_{12}	$\eta e^+ e^-$	< 1.1 %	CL=90%
Γ_{13}	$\pi^+\pi^+\pi^-\pi^-$	< 1 %	CL=90%
Γ_{14}	$\pi^+\pi^+\pi^-\pi^-$ neutrals	< 1 %	CL=95%
Γ_{15}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1 %	CL=90%
Γ_{16}	6π	< 1 %	CL=90%
Γ_{17}	$\pi^+\pi^- e^+ e^-$	< 6 × 10^{-3}	CL=90%
Γ_{18}	$\pi^0\pi^0$	< 9 × 10^{-4}	CL=90%
Γ_{19}	$\pi^0\gamma\gamma$	< 8 × 10^{-4}	CL=90%
Γ_{20}	$4\pi^0$	< 5 × 10^{-4}	CL=90%
Γ_{21}	3γ	< 9 × 10^{-5}	CL=90%
Γ_{22}	$\mu^+\mu^-\pi^0$	< 6.0 × 10^{-5}	CL=90%
Γ_{23}	$\mu^+\mu^-\eta$	< 1.5 × 10^{-5}	CL=90%
Γ_{24}	$\pi^+\pi^-\gamma$ (including $\rho^0\gamma$)		
Γ_{25}	e^+e^-	< 2.1 × 10^{-7}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, 2 combinations of partial widths obtained from integrated cross section, and 16 branching ratios uses 40 measurements and one constraint to determine 7 parameters. The overall fit has a $\chi^2 = 28.6$ for 34 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−54					
x_3	−59	−33				
x_4	−25	−26	36			
x_5	−18	−10	20	6		
x_6	−23	−13	38	13	7	
Γ	35	−19	−14	0	−80	−5
	x_1	x_2	x_3	x_4	x_5	x_6

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi^+\pi^-\eta$	0.092 ±0.011	1.3
Γ_2	$\rho^0\gamma$	0.062 ±0.006	1.4
Γ_3	$\pi^0\pi^0\eta$	0.043 ±0.005	1.6
Γ_4	$\omega\gamma$	0.0062 ±0.0009	1.2
Γ_5	$\gamma\gamma$	0.00451±0.00026	1.1
Γ_6	$3\pi^0$	$(3.2 \pm 0.6) \times 10^{-4}$	1.2

$\eta'(958)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_5

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
4.51±0.26 OUR FIT Error includes scale factor of 1.1.				
4.6 ±0.4 OUR AVERAGE				
4.96±0.23±0.72	547	[1] ROE 90B	ASP	$e^+e^- \rightarrow e^+e^-2\gamma$
3.8 ±0.7 ±0.6	34	AIHARA 88C	TPC	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$
4.8 ±0.5 ±0.5	136 ± 14	[1] WILLIAMS 88	CBAL	$e^+e^- \rightarrow e^+e^-2\gamma$
4.7 ±0.6 ±0.9	143 ± 12	GIDAL 87	MRK2	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.0 ±0.9		[2] BARTEL 85E	JADE	$e^+e^- \rightarrow e^+e^-2\gamma$

[1] Using $B(\eta' \rightarrow \gamma\gamma) = (2.16 \pm 0.16)\%$.

[2] Systematic error not evaluated.

$\eta'(958)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

This combination of a partial width with the partial width into $\gamma\gamma$ and with the total width is obtained from the integrated cross section into channel(i) in the $\gamma\gamma$ annihilation.

$\Gamma(\gamma\gamma) \times \Gamma(\rho^0\gamma)/\Gamma_{\text{total}}$ $\Gamma_5\Gamma_2/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
1.35±0.08 OUR FIT Error includes scale factor of 1.2.				
1.32±0.08 OUR AVERAGE Error includes scale factor of 1.2.				
1.35±0.09±0.21		AIHARA 87	TPC	$e^+e^- \rightarrow e^+e^-\rho\gamma$
1.13±0.04±0.13	867 ± 30	ALBRECHT 87B	ARG	$e^+e^- \rightarrow e^+e^-\rho\gamma$
1.53±0.09±0.21		ALTHOFF 84E	TASS	$e^+e^- \rightarrow e^+e^-\rho\gamma$
1.14±0.08±0.11		BERGER 84B	PLUT	$e^+e^- \rightarrow e^+e^-\rho\gamma$
1.85±0.31±0.24	43	BEHREND 83B	CELL	$e^+e^- \rightarrow e^+e^-\rho\gamma$
1.73±0.34±0.35	95	JENNI 83	MRK2	$e^+e^- \rightarrow e^+e^-\rho\gamma$
1.49±0.13±0.027	213	BARTEL 82B	JADE	$e^+e^- \rightarrow e^+e^-\rho\gamma$

$\Gamma(\gamma\gamma) \times \Gamma(\pi^0\pi^0\eta)/\Gamma_{\text{total}}$ $\Gamma_5\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.92±0.08 OUR FIT Error includes scale factor of 1.2.			
1.03±0.08±0.11	ANTREASYAN 87	CBAL	$e^+e^- \rightarrow e^+e^-\eta\pi^0\pi^0$

$\eta'(958)$ α PARAMETER

$|\text{MATRIX ELEMENT}|^2 = (1+\alpha y)^2 + cx^2$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.061±0.012 OUR AVERAGE			
−0.058±0.013	ALDE 86	GAM4	$38\ \pi^-p \rightarrow n\eta\pi^0\pi^0$
−0.08 ±0.03	KALBFLEISCH 74	RVUE	$\eta' \rightarrow \eta\pi^+\pi^-$

$\eta'(958)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))/\Gamma_{\text{total}}$ $.709\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.313±0.012 OUR FIT Error includes scale factor of 1.2.				
0.314±0.026	281	RITTENBERG 69	HBC	1.7–2.7 K^-p

$\Gamma(\pi^+\pi^-\ \text{neutrals})/\Gamma_{\text{total}}$ $(.709\Gamma_1+.291\Gamma_3+.9\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.400±0.010 OUR FIT Error includes scale factor of 1.1.				
0.36 ±0.05 OUR AVERAGE				
0.4 ±0.1	39	LONDON 66	HBC	2.2 K^-p
0.35 ±0.06	33	BADIER 65B	HBC	3 K^-p

$\Gamma(\pi^+\pi^-\eta(\text{charged decay}))/\Gamma_{\text{total}}$ $.291\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.129±0.005 OUR FIT Error includes scale factor of 1.2.				
0.116±0.013 OUR AVERAGE				
0.123±0.014	107	RITTENBERG 69	HBC	1.7–2.7 K^-p
0.1 ±0.04	10	LONDON 66	HBC	2.2 K^-p
0.07 ±0.04	7	BADIER 65B	HBC	3 K^-p

$[\Gamma(\pi^0\pi^0\eta\ (\text{charged decay})) + \Gamma(\omega\ (\text{charged decay})\ \gamma)]/\Gamma_{\text{total}}$ $(.291\Gamma_3+.9\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.087±0.006 OUR FIT Error includes scale factor of 1.2.				
0.045±0.029	42	RITTENBERG 69	HBC	1.7–2.7 K^-p

$\Gamma(\text{neutrals})/\Gamma_{\text{total}}$ $(.709\Gamma_3+.09\Gamma_4+\Gamma_5)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.170±0.010 OUR FIT Error includes scale factor of 1.2.				
0.187±0.017 OUR AVERAGE				
0.185±0.022	535	BASILE 71	CNTR	1.6 $\pi^-p \rightarrow nX^0$
0.189±0.026	123	RITTENBERG 69	HBC	1.7–2.7 K^-p

$\Gamma(\rho^0\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.300±0.015 OUR FIT Error includes scale factor of 1.1.				
0.319±0.030 OUR AVERAGE				
0.329±0.033	298	RITTENBERG 69	HBC	1.7–2.7 K^-p
0.2 ±0.1	20	LONDON 66	HBC	2.2 K^-p
0.34 ±0.09	35	BADIER 65B	HBC	3 K^-p

$\Gamma(\rho^0\gamma)/\Gamma(\pi\pi\eta)$ $\Gamma_2/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.464±0.033 OUR FIT Error includes scale factor of 1.2.			
0.31 ±0.15	DAVIS 68	HBC	5.5 K^-p

$\Gamma(\pi^0e^+e^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.013	90	RITTENBERG 65	HBC	2.7 K^-p

$\Gamma(\eta e^+e^-)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.011	90	RITTENBERG 65	HBC	2.7 K^-p

$\Gamma(\pi^0\rho^0)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.04	90	RITTENBERG 65	HBC	2.7 K^-p

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.006	90	RITTENBERG 65	HBC	2.7 K^-p

$\Gamma(6\pi)/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	LONDON 66	HBC	Compilation

$\Gamma(\omega\gamma)/\Gamma(\pi^+\pi^-\eta)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.068±0.008 OUR FIT Error includes scale factor of 1.1.				
0.068±0.013	68	ZANFINO 77	ASPK	8.4 π^-p

$\Gamma(\rho^0\gamma)/[\Gamma(\pi^+\pi^-\eta) + \Gamma(\pi^0\pi^0\eta) + \Gamma(\omega\gamma)]$ $\Gamma_2/(\Gamma_1+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.443±0.031 OUR FIT Error includes scale factor of 1.1.			
0.25 ±0.14	DAUBER 64	HBC	1.95 K^-p

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0216±0.0017 OUR FIT Error includes scale factor of 1.5.				
0.0196±0.0015 OUR AVERAGE				
0.0200±0.0018		[3] STANTON 80	SPEC	8.45 $\pi^-p \rightarrow n\pi^+\pi^-2\gamma$
0.025 ±0.007		DUANE 74	MMS	$\pi^-p \rightarrow n\,\text{MM}$
0.0171±0.0033	68	DALPIAZ 72	CNTR	1.6 $\pi^-p \rightarrow nX^0$
$0.020\ ^{+0.008}_{-0.006}$	31	HARVEY 71	OSPK	3.65 $\pi^-p \rightarrow nX^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.018 ±0.002	6000	[4] APEL 79	CNTR	15–40 π^-p

[3] Includes APEL 79 result.

[4] Data is included in STANTON 80 evaluation.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID	TECN	COMMENT
<2.1	90	VOROBYEV 88	ND	$e^+e^- \rightarrow \pi^+\pi^-\eta$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	90	RITTENBERG 69	HBC	1.7–2.7 K^-p
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	95	DANBURG 73	HBC	2.2 $K^-p \rightarrow \Lambda X^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	RITTENBERG 69	HBC	$1.7\text{–}2.7\ K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.09	95	DANBURG 73	HBC	$2.2\ K^- p \to \Lambda X^0$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\ \text{neutrals})/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	95	DANBURG 73	HBC	$2.2\ K^- p \to \Lambda X^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.01	90	RITTENBERG 69	HBC	$1.7\text{–}2.7\ K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	RITTENBERG 69	HBC	$1.7\text{–}2.7\ K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\rm total}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	RITTENBERG 69	HBC	$1.7\text{–}2.7\ K^- p$

$\Gamma(\rho^0\gamma)/\Gamma(\pi^+\pi^-\gamma\ (\text{including}\ \rho^0\gamma))$ Γ_2/Γ_{24}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.08±0.08 OUR AVERAGE				
1.15±0.10	473	DANBURG 73	HBC	$2.2\ K^- p \to \Lambda X^0$
1.01±0.15	137	JACOBS 73	HBC	$2.9\ K^- p \to \Lambda X^0$
0.94±0.20		AGUILAR-... 70D	HBC	$3.9\text{–}4.6\ K^- p$

$\Gamma(\pi^0\pi^0\eta\ (3\pi^0\ \text{decay}))/\Gamma_{\rm total}$ $.319\Gamma_3/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.065±0.004 OUR FIT Error includes scale factor of 1.3.				
0.11 ±0.06	4	BENSINGER 70	DBC	$2.2\ \pi^+ d$

$\Gamma(\rho^0\gamma)/\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))$ $\Gamma_2/.709\Gamma_1$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.96±0.08 OUR FIT Error includes scale factor of 1.2.				
0.99±0.11 OUR AVERAGE				
0.92±0.14	473	DANBURG 73	HBC	$2.2\ K^- p \to \Lambda X^0$
1.11±0.18	192	JACOBS 73	HBC	$2.9\ K^- p \to \Lambda X^0$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta(\text{neutral decay}))$ $\Gamma_5/.709\Gamma_3$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.149±0.013 OUR FIT Error includes scale factor of 1.7.				
0.188±0.058	16	APEL 72	OSPK	$3.8\ \pi^- p \to n X^0$

$\Gamma(\mu^+\mu^-\gamma)/\Gamma(\gamma\gamma)$ Γ_7/Γ_5

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
4.9±1.2	33	VIKTOROV 80	CNTR	$25{,}33\ \pi^- p \to 2\mu\gamma$

$\Gamma(\mu^+\mu^-\eta)/\Gamma_{\rm total}$ Γ_{23}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
<1.5	90	DZHELYADIN 81	CNTR	$30\ \pi^- p \to \eta' n$

$\Gamma(\mu^+\mu^-\pi^0)/\Gamma_{\rm total}$ Γ_{22}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
<6.0	90	DZHELYADIN 81	CNTR	$30\ \pi^- p \to \eta' n$

$\Gamma(3\pi^0)/\Gamma(\pi^0\pi^0\eta)$ Γ_6/Γ_3

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
74±12 OUR FIT			
74±12 OUR AVERAGE			
74±15	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s
75±18	BINON 84	GAM2	$30\text{–}40\ \pi^- p \to n + 6\gamma$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_5/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.106±0.009 OUR FIT Error includes scale factor of 1.7.			
0.112±0.002±0.006	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s

$\Gamma(\omega\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.146±0.014 OUR FIT			
0.147±0.016	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s

$\Gamma(3\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_{21}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<4.6	90	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s

$\Gamma(\pi^0\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ Γ_{19}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<37	90	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^0\pi^0\eta)$ Γ_{18}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<45	90	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s

$\Gamma(4\pi^0)/\Gamma(\pi^0\pi^0\eta)$ Γ_{20}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<23	90	ALDE 87B	GAM2	$38\ \pi^- p \to n + 6\gamma$'s

$\eta'(958)$ C-NONCONSERVING DECAY PARAMETER

See the note on η decay parameters in the Stable Particle Full Listings for definition of this parameter.

DECAY ASYMMETRY PARAMETER FOR $\pi^+\pi^-\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.01 ±0.04 OUR AVERAGE				
−0.019±0.056		AIHARA 87	TPC	$2\gamma \to \pi^+\pi^-\gamma$
−0.069±0.078	295	GRIGORIAN 75	STRC	$2.1\ \pi^- p$
0.00 ±0.10	103	KALBFLEISCH 75	HBC	$2.2\ K^- p$
0.07 ±0.08	152	RITTENBERG 65	HBC	$2.1\text{–}2.7\ K^- p$

$\eta'(958)$ REFERENCES

ROE 90B PR D41 17 +Bartha, Burke, Garbincius+ (ASP Collab.)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
VOROBYEV 88 YAF 48 436 +Golubev, Dolinsky, Druzhinin+ (NOVO)
WILLIAMS 88 PR D38 1365 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
AIHARA 87 PR D35 2650 +Alston-Garnjost+ (TPC-2γ Collab.) JP
ALBRECHT 87B PL B199 457 +Andam, Binder+ (ARGUS Collab.)
ALDE 87B ZPHY C36 603 +Binon, Bricman+ (LANL, BELG, SERP, LAPP)
ANTREASYAN 87 PR D36 2633 +Bartels, Besset+ (Crystal Ball Collab.)
GIDAL 87 PRL 59 2012 +Boyer, Butler, Cords, Abrams+ (LBL, SLAC, HARV)
ALDE 86 PL B177 115 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)
BARTEL 85E PL 160B 421 +Becker, Cords, Felst+ (JADE Collab.)
ALTHOFF 84E PL 147B 487 +Braunschweig, Kirschfink, Luebelsmeyer+ (TASSO Collab.)
BERGER 84B PL 142B 125 (AACH, BERG, DESY, GLAS, HAMB, UMD, SIEG+)
BINON 84 PL 140B 264 +Donskov, Duteil+ (SERP, BELG, LAPP, CERN)
BEHREND 83B PL 125B 518 +D'Agostini+ (DESY, KARL, MPIM, LALO, LPNP+)
Also 82C PL 114B 378 Behrend+ (DESY, KARL, MPIM, LALO, LPNP+)
JENNI 83 PR D27 1031 +Burke, Telnov, Abrams, Blocker+ (SLAC, LBL)
BARTEL 82B PL 113B 190 +Cords+ (DESY, HAMB, HEID, LANC, MCHS+)
DZHELYADIN 81 PL 105B 239 +Golovkin, Konstantinov, Kubarovski+ (SERP)
STANTON 80 PL 92 B 353 +Edwards, Legacey+ (OSU, CARL, MCGI, TNTO)
VIKTOROV 80 SJNP 32 520 +Golovkin, Dzhelyadin, Zaitsev, Mukhin+ (NOVO)
Translated from YAF 32 1005.
APEL 79 PL 83B 131 +Augenstein, Bertolucci (KARL, PISA, SERP, WIEN)
BINNIE 79 PL 83B 141 +Carr, Debenham, Jones, Karami, Keyne+ (LOIC)
ZANFINO 77 PRL 38 930 +Brockman+ (CARL, MCGI, OHIO, TNTO)
GRIGORIAN 75 NP B91 232 +Ladage, Mellema, Rudnick+ (UCLA)
KALBFLEISCH 75 PR D11 987 +Strand, Chapman (BNL, MICH)
DUANE 74 PRL 32 425 +Binnie, Camilleri, Carr+ (LOIC, SHMP)
KALBFLEISCH 74 PR D10 916 (BNL)
DANBURG 73 PR D8 3744 +Kalbfleisch, Borenstein, Chapman+ (BNL, MICH) JP
JACOBS 73 PR D8 18 +Chang, Gauthier+ (BRAN, UMD, SYRA, TUFT) JP
APEL 72 PL 40B 680 +Auslander, Muller, Bertolucci+ (KARL, PISA)
DALPIAZ 72 PL 42B 377 +Frabetti, Massam, Navarria, Zichichi (CERN)
BASILE 71 NC 3A 371 +Bollini, Dalpiaz, Frabetti+ (CERN, BGNA, STRB)
HARVEY 71 PRL 27 885 +Marquit, Peterson, Rhoades+ (MINN, MICH)
AGUILAR-... 70D PRL 25 1635 Aguilar-Benitez, Bassano, Samios, Barnes+ (BNL)
BENSINGER 70 PL 33B 505 +Erwin, Thompson, Walker (WISC)
RITTENBERG 69 UCRL 18863 Thesis (LRL) I
DAVIS 68 PL 27B 532 +Ammar, Mott, Dagan, Derrick+ (NWES, ANL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) IJP
BADIER 65B PL 17 337 +Demoulin, Barloutaud+ (EPOL, SACL, AMST)
RITTENBERG 65 PRL 15 556 +Kalbfleisch (LRL, BNL)
DAUBER 64 PRL 13 449 +Slater, Smith, Stork, Ticho (UCLA) JP
Also 64B Dubna Conf. 1 418 Dauber, Slater, Smith, Stork, Ticho (UCLA)

OTHER RELATED PAPERS

BICKERSTAFF 82 ZPHY C16 171 +McKellar (MELB)
ABRAMS 79B PRL 43 477 +Alam, Blocker, Boyarski+ (SLAC, LBL)
DZHELYADIN 79B PL 88B 379 +Golovkin, Gritsuk, Kachanov+ (SERP)
CERRADA 77 NP B126 189 +Wagner, Blockzijl+ (CERN, AMST, NIJM, OXF) JP
DELAGUILA 77 PR D16 2833 +Doncel (BARC) JP
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
LEDNICKY 77 JINR E2-10521,22,23 (JINR) JP
BALTAY 74B PR D9 2999 +Cohen, Csorna, Habibi, Kalelkar+ (COLU, BING) JP
GAULT 74 NC 24A 259 +Jones, Scadron, Thews (DURH, LOIC, ARIZ)
KALBFLEISCH 73 PRL 31 333 +Chapman+ (BNL, MICH, LBL) JP
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
BINNIE 72 PL 39B 275 +Camilleri, Duane, Garbutt, Burton+ (LOIC, SHMP)
BLOODWO... 72B NP B39 525 Bloodworth, Jackson, Prentice, Yoon (TNTO)
RADER 72 PR D6 3059 +Abolins, Dahl, Danburg, Davies, Hoch+ (LBL)
BARDADIN-... 71 PR D4 2711 Bardadin-Otwinowska, Hofmokl+ (WARS)
BASILE 71B NP B33 29 +Bollini, Dalpiaz, Frabetti+ (CERN, BGNA, STRB)
OGIEVETSKY 71 PL 35B 69 +Tybor, Zaslavsky (JINR)
DUFEY 69 PL 29B 605 +Gobbi, Pouchon, Cnops+ (ETH, CERN, SACL) IJP
MOTT 69 PR 177 1966 +Ammar, Davis, Kropac, Slate+ (NWES, ANL)
BARBARO-... 68 PRL 20 349 Barbaro-Galtieri, Matison, Rittenberg+ (LRL) I
BARLOUTAUD 68 PL 26B 674 + (SACL, AMST, BGNA, REHO, EPOL) I
BOLLINI 68D NC 58A 289 +Buhler, Dalpiaz, Massam+ (CERN, BGNA, STRB)
COHN 66 PL 21 347 +McCulloch, Bugg, Condo (ORNL, TENN, UCND)
MARTIN 66 PL 22 352 +Crittenden, Schroeder (IND) I
KIENZLE 65 PL 19 438 +Maglich, Levrat, Lefebvres+ (CERN)
TRILLING 65 PL 19 427 +Brown, Goldhaber, Kadyk, Scanio (LRL)
GOLDBERG 64 PRL 12 546 +Gundzik, Lichtman, Connolly, Hart+ (SYRA, BNL)
GOLDBERG 64B PRL 13 249 +Gundzik, Leitner, Connolly, Hart+ (SYRA, BNL)
KALBFLEISCH 64 PRL 12 527 +Alvarez, Barbaro-Galtieri+ (LRL) JP
KALBFLEISCH 64B PRL 13 349 +Dahl, Rittenberg (LRL) JP

$f_0(975)$ was $S(975)$

$I^G(J^{PC}) = 0^+(0^{++})$

For early work using Breit-Wigner or scattering length parametrization in fits to the $K\overline{K}$ mass spectrum, see reference section and our 1972 edition.

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_0(975)$ MASS OR REAL PART OF POLE POSITION

POLE POSITION DETERMINATIONS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
975.6± 3.1 OUR AVERAGE	Error includes scale factor of 1.2.		
978 ± 9	ABACHI 86B	HRS	$e^+e^- \to \pi^+\pi^-$
974.0± 4.0	GIDAL 81	MRK2	J/ψ decay
986 ±10	AGUILAR-... 78	HBC	$0.7\ \overline{p}p \to K^0_S K^0_S$
969.0± 5.0	LEEPER 77	ASPK	2–$2.4\ \pi^- p$
987 ± 7	BINNIE 73	CNTR	$\pi^- p \to n$ MM
• • • We do not use the following data for averages, fits, limits, etc. • • •			
985.0±39.0	[1] ETKIN 82B	MPS	$23\ \pi^- p \to n2K^0_S$
1012 ± 6	[2] GRAYER 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
1007 ±20	[2] HYAMS 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
997 ± 6	[2] PROTOPOP... 73	HBC	$7\ \pi^+ p \to \pi^+ p\pi^+\pi^-$

[1] ETKIN 82B quotes errors $^{+9}_{-39}$ MeV. We use ±39 MeV in the average.

[2] Included in AGUILAR-BENITEZ 78 fit.

MASS DETERMINATIONS

(Real part of mass matrix eigenvalue)

VALUE (MeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
985	[3] TORNQVIST 82	RVUE
975	[3] ACHASOV 80	RVUE

[3] Coupled channel analysis with finite width corrections.

$f_0(975)$ WIDTH OR IMAGINARY PART OF POLE POSITION

POLE POSITION DETERMINATIONS

(Corresponds to half-width, not full width.)

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
16.8± 2.8 OUR AVERAGE			
29 ± 13	ABACHI 86B	HRS	$e^+e^- \to \pi^+\pi^-$
14.0± 5.0	GIDAL 81	MRK2	J/ψ decay
15.0± 4.0	LEEPER 77	ASPK	2–$2.4\ \pi^- p$
24 ± 7	BINNIE 73	CNTR	$\pi^- p \to n$ MM
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$60.0^{+141.0}_{-10.0}$	ETKIN 82B	MPS	$23\ \pi^- p \to n2K^0_S$
50 ± 40	[4] AGUILAR-... 78	HBC	$0.7\ \overline{p}p \to K^0_S K^0_S$
16 ± 5	[5] GRAYER 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
15 ± 5	[5] HYAMS 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
27 ± 8	[5] PROTOPOP... 73	HBC	$7\ \pi^+ p \to \pi^+ p\pi^+\pi^-$

[4] From coupled channel fit to the HYAMS 73 and PROTOPOPESCU 73 data. With a simultaneous fit to the $\pi\pi$ phase-shifts, inelasticity and to the $K^0_S K^0_S$ invariant mass.

[5] Included in AGUILAR-BENITEZ 78 fit.

FULL WIDTH DETERMINATIONS

(From imaginary part of mass matrix eigenvalue)

VALUE (MeV)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
~ 400	[6] TORNQVIST 82	RVUE
70 to 300	[6] ACHASOV 80	RVUE

[6] Coupled channel analysis with finite width corrections.

$f_0(975)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi\pi$	(78.1±2.4) %	
Γ_2	$K\overline{K}$	(21.9±2.4) %	
Γ_3	$\eta\eta$		
Γ_4	e^+e^-	$< 3 \times 10^{-7}$	90%

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 3 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 2.0 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ll} x_2 & -100 \\ & x_1 \end{array}$$

$f_0(975)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_4

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<8.4	90	VOROBYEV 88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(975)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/[\Gamma(\pi\pi)+\Gamma(K\overline{K})]$ $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.781±0.024 OUR FIT			
$0.781^{+0.027}_{-0.023}$ OUR AVERAGE			
0.67 ±0.09	[7] LOVERRE 80	HBC	$4\ \pi^- p \to K\overline{K}N$
$0.81\ ^{+0.09}_{-0.04}$	[7] CASON 78	STRC	$7\ \pi^- p \to n2K^0_S$
0.78 ±0.03	[7] WETZEL 76	OSPK	$8.9\ \pi^- p \to n2K^0_S$

[7] Measure $\pi\pi$ elasticity assuming two resonances coupled to the $\pi\pi$ and $K\overline{K}$ channels only.

$f_0(975)$ REFERENCES

VOROBYEV	88	YAF 48 436	+Golubev, Dolinsky, Druzhinin+	(NOVO)	
ABACHI	86B	PRL 57 1990	+Derrick, Blockus+	(PURD, ANL, IND, MICH, LBL)	
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)	
TORNQVIST	82	PRL 49 624		(HELS)	
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)	
ACHASOV	80	SJNP 32 566 Translated from YAF 32 1098.	+Devyanin, Shestakov	(NOVO)	
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH)	IJP
AGUILAR-...	78	NP B140 73	Aguilar-Benitez, Cerrada+	(MADR, BOMB, CERN+)	
CASON	78	PRL 41 271	+Baumbaugh, Bishop, Biswas+	(NDAM, ANL)	
LEEPER	77	PR D16 2054	+Buttram, Crawley, Duke, Lamb, Peterson	(ISU)	
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)	
BINNIE	73	PRL 31 1534	+Carr, Debenham, Duane, Garbutt+	(LOIC, SHMP)	
GRAYER	73	Tallahassee	+Hyams, Jones, Blum, Dietl, Koch+	(CERN, MPIM)	
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)	
PROTOPOP...	73	PR D7 1280	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)	

OTHER RELATED PAPERS

AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)	
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)	
MENNESSIER	83	ZPHY C16 241		(MONP)	
BARBER	82	ZPHY C12 1	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)	
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)	
ACHASOV	81	PL 102B 196	+Devyanin, Shestakov	(NOVO)	
AGUILAR-...	81	ZPHY C10 299	Aguilar-Benitez, Done, Martin	(MADR, DURH)	
ROUSSARIE	81	PL 105B 304	+Burke, Abrams, Alam+	(SLAC, LBL)	
WICKLUND	80	PRL 45 1469	+Ayres, Cohen, Diebold, Pawlicki	(ANL)	
ACHASOV	79	PL 88B 367	+Devyanin, Shestakov	(NOVO)	
APEL	79B	NP B160 42	+Auslander, Muller, Rehak+	(KARL, PISA)	
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)	
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC)	JP
ESTABROOKS	79	PR D19 2678		(CARL)	
GREENHUT	79	PR D20 2326	+Intemann	(SETO)	
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)	
BALAND	78	NP B140 220	+Grard+	(MONS, BELG, CERN, LOIC, LALO)	
FROGGATT	77	NP B129 89	+Petersen	(GLAS, NORD)	
MARTIN	77D	NP B121 514	+Ozmutlu, Squires	(DUKE)	
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL)	IJ
BRANDENB...	76C	NP B104 413	Brandenburg, Carnegie, Cashmore+	(SLAC)	
BUTTRAM	76	PR D13 1153	+Crawley, Duke, Lamb, Leeper, Peterson	(ISU)	
CERRADA	76	PL 62B 353	+Gonzalez-Arroyo, Rubio, Yndurain	(CERN, MADR)	
FLATTE	76B	PL 63B 228		(CERN)	
WILKINS	76	PR D13 1831	+Albright, Hagopian, Hagopian, Lannutti	(FSU)	
MORGAN	75	Argonne Conf. 45		(RHEL)	
PAWLICKI	75	PR D12 631	+Ayres, Diebold, Greene, Kramer, Wicklund	(ANL)	
BALLAM	74	NP B76 375	+Chadwick, Bingham, Fretter+	(SLAC, LBL, MPIM)	
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)	
MORGAN	74	PL 51B 71		(RHEL)	
DIAMOND	73	PR D7 1977	+Binkley+	(WISC, DUKE, COLO, TNTO, OHIO)	
FUJII	73	NC 13A 311	+Kato	(TOKY)	
OCHS	73	Thesis		(MPIM)	
BASDEVANT	72	PL 41B 178	+Froggatt, Petersen	(CERN)	
DAMERI	72	NC 9A 1	+Borzatta, Goussu+	(GENO, MILA, SACL)	
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(LPNP, LIVP)	
FLATTE	72	PL 38B 232	+Alston-Garnjost, Barbaro-Galtieri+	(LBL)	
GRAYER	72B	Phil. Conf. 5	+Hyams, Jones, Schlein+	(CERN, MPIM)	
WILLIAMS	72B	PR D6 3178		(FSU)	
ALSTON-...	71B	PL 36B 152	Alston-Garnjost, Barbaro-Galtieri+	(LBL)	
BADIER	70	NP B22 512	+Bonnet, Drevillon, Baubillier+	(EPOL, IPNP)	
BATON	70	PL 33B 528	+Laurens, Reignier	(SACL)	

BEUSCH 70 Phil. Conf. 185 (ETH, CERN)
HYAMS 70B Phil. Conf. 41 +Koch, Beusch+ (CERN, MPIM, ETH, LOIC, HAWA)
Also 70 NP B22 189 Hyams, Koch, Potter, VonLindern+ (CERN, MPIM)
OH 70 PR D1 2494 +Garfinkel, Morse, Walker, Prentice (WISC, TNTO)
AGUILAR-... 69C PL 29B 241 Aguilar-Benitez, Barlow+ (CERN, CDEF)
Also 69 NP B14 195 Aguilar-Benitez, Barlow+ (CERN, CDEF)
HOANG 69 NC 61A 325 (ANL)
HOANG 69B PR 184 1363 +Eartly, Phelan, Roberts+ (ANL, ILLC)
ALITTI 68B PRL 21 1705 +Barnes, Crennell, Flaminio, Goldberg+ (BNL)
LAI 68 Phil. Conf. 303 (BNL)
PHELAN 68 Thesis (ANL, STLO)
Also 68 PRL 21 316 Hoang, Eartly, Phelan+ (ANL, CHIC, NDAM)
BARLOW 67 NC 50A 701 +Lillestol, Montanet+ (CERN, CDEF, IRAD, LIVP)
BEUSCH 67 PL 25B 357 +Fischer, Gobbi, Astbury+ (ETH, CERN)
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL)
CRENNELL 66 PRL 16 1025 +Kalbfleisch, Lai, Scarr, Schumann+ (BNL)
HESS 66 PRL 17 1109 +Dahl, Hardy, Kirz, Miller (LRL)
BALTAY 64 Dubna Conf. 1 409 +Lach, Crennell, Oren, Stump+ (YALE, BNL)
BARMIN 64B Dubna Conf. 1 433 +Dolgolenko, Yerofeev, Krestni– (ITEP)
BIGI 62 CERN Conf. 247 +Brandt, Carrara+ (CERN)
BINGHAM 62 CERN Conf. 240 +Bloch+ (EPOL, CERN)
ERWIN 62 PRL 9 34 +Hoyer, March, Walker, Wangler (WISC, BNL)
WANG 61 JETP 13 323 +Veksler, Vrana+ (JINR)
Translated from ZETF 40 464.

$a_0(980)$
was $\delta(980)$

$I^G(J^{PC}) = 1^-(0^{++})$

NOTE ON $a_0(980)$

A conventional $q\overline{q}$ assignment of this scalar meson still remains an intriguing question.

Its observed mass and width are inconsistent, *a priori*, with the properties expected for a member of a $L = 1$ $q\overline{q}$ nonet. However, since the mass and width are distorted by the proximity of the $K\overline{K}$ threshold, its nature can be better investigated using different experimental observations.

TORNQVIST 82 has shown that it is possible to understand the unusual experimental features of this particle within a unitarized quark model. As for the $f_0(975)$, the $a_0(980)$ can be interpreted as a normal $q\overline{q}$ resonance with a large admixture of $K\overline{K}$, $\eta'\pi$, and $\eta'\pi$ continuum state.

Assuming the dominance of the decay chain $\eta'(958) \to a_0(980)\pi \to \eta\pi\pi$, BRAMON 80 concludes that the experimental value $\Gamma(\eta'(958) \to \eta\pi\pi) \approx 200$ keV is fully consistent with a $q\overline{q}$ interpretation. The same analysis finds additional evidence in favor of a $q\overline{q}$ interpretation of the $a_0(980)$: in fact, if the $a_0(980)$ is a $q\overline{q}$ state, one expects that the decay chain $f_1 \to a_0(980)\pi \to \eta\pi\pi$ will be more important for the $f_1(1285)$ than for the $f_1(1420)$, the reverse being true if the $a_0(980)$ were a $q\overline{q}q\overline{q}$ state with a strange quark component. In practice, the $f_1(1285) \to a_0(980)\pi \to \eta\pi\pi$ is observed, while the $f_1(1420) \to a_0(980)\pi \to \eta\pi\pi$ is (practically) absent.

The main point in favor of the interpretation of this particle as a $q\overline{q}q\overline{q}$ state is its almost complete degeneracy in mass with the isoscalar $f_0(975)$, together with the fact that the $f_0(975)$ couples much more to the $K\overline{K}$ than to the $\pi\pi$ system. A Crystal Ball measurement of the $a_0(980) \to \gamma\gamma$ suppression in the reaction $\gamma\gamma \to a_0(980) \to \eta\pi$ (ANTREASYAN 86) has reinforced this four-quark interpretation point of view. ACHASOV 88B points out that none of the calculations performed in the framework of a $q\overline{q}$ scheme has been able to predict such a narrow $a_0(980) \to \gamma\gamma$ width as the one found by the Crystal Ball. He then argues in favor of an unusual nature of the $a_0(980)$ resonance and shows that a four-quark model is instead able to give the correct order of magnitude for the suppression of the 2γ production for both the scalar $a_0(980)$ and $f_0(975)$ mesons.

Another interesting non-$q\overline{q}$ interpretation is given by the model of WEINSTEIN 83B, 89. In this work the $q\overline{q}q\overline{q}$ system is investigated using the nonrelativistic quark model; assuming a large hyperfine interaction, the $a_0(980)$ and $f_0(975)$ are both interpreted as $K\overline{K}$ bound states and then the P-wave $q\overline{q}$ states would be all in the 1300 MeV mass region. With this S-wave $K\overline{K}$ molecule assignment, many of the peculiar properties of the $a_0(980)$ and $f_0(975)$ (masses, widths, branching fractions and two photon widths) appear clarified.

$a_0(980)$ MASS

$\eta\pi$ FINAL STATE ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
983.3± 2.6 OUR AVERAGE	Error includes scale factor of 1.2.				
976 ± 6		ATKINSON 84E	OMEG	±	25–55 $\gamma p \to \eta\pi n$
986 ± 3	500	[1] EVANGELISTA 81	OMEG		12 $\pi^- p \to \eta\pi p$
990.0± 7.0	145	[1] GURTU 79	HBC	±	4.2 $K^- p \to \Lambda\eta 2\pi$
977.0± 7.0		GRASSLER 77	HBC	−	16 $\pi^\mp p \to p\eta 3\pi$
972 ±10	150	DEFOIX 72	HBC	±	0.7 $\overline{p}p \to 7\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
980 ±11	47	CONFORTO 78	OSPK	−	4.5 $\pi^- p \to pX^-$
978.0±16.0	50	CORDEN 78	OMEG	±	12–15 $\pi^- p \to n\eta 2\pi$
989.0± 4.0	70	WELLS 75	HBC	−	3.1–6 $K^- p \to \Lambda\eta 2\pi$
970.0±15.0	20	BARNES 69C	HBC	−	4–5 $K^- p \to \Lambda\eta 2\pi$
980 ±10		CAMPBELL 69	DBC	±	2.7 $\pi^+ d$
980.0±10.0	15	MILLER 69B	HBC	−	4.5 $K^- N \to \eta\pi\Lambda$
980.0±10.0	30	AMMAR 68	HBC	±	5.5 $K^- p \to \Lambda\eta 2\pi$

[1] From $f_1(1285)$ decay.

$K\overline{K}$ ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
976 ± 6	316	DEBILLY 80	HBC	±	1.2–2 $\overline{p}p \to f_1(1285)\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1016 ±10	100	[2] ASTIER 67	HBC	±	0.0 $\overline{p}p$
1003.3± 7.0	143	[3] ROSENFELD 65	RVUE	±	

[2] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.
[3] Plus systematic errors.

$a_0(980)$ WIDTH

$\eta\pi$ FINAL STATE ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
57 ±11 OUR AVERAGE					
62 ±15	500	[4] EVANGELISTA 81	OMEG		12 $\pi^- p \to \eta\pi p$
60.0±20.0	145	[4] GURTU 79	HBC	±	4.2 $K^- p \to \Lambda\eta 2\pi$
44.0±22.0		GRASSLER 77	HBC	−	16 $\pi^\mp p \to p\eta 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$60\ ^{+50}_{-30}$	47	CONFORTO 78	OSPK	−	4.5 $\pi^- p \to pX^-$
$86.0^{+60.0}_{-50.0}$	50	CORDEN 78	OMEG	±	12–15 $\pi^- p \to n\eta 2\pi$
80 to 300		[5] FLATTE 76	RVUE	−	4.2 $K^- p \to \Lambda\eta 2\pi$
$16.0^{+25.0}_{-16.0}$	70	WELLS 75	HBC	−	3.1–6 $K^- p \to \Lambda\eta 2\pi$
30 ± 5	150	DEFOIX 72	HBC	±	0.7 $\overline{p}p \to 7\pi$
40 ±15		CAMPBELL 69	DBC	±	2.7 $\pi^+ d$
60.0±30.0	15	MILLER 69B	HBC	−	4.5 $K^- N \to \eta\pi\Lambda$
80.0±30.0	30	AMMAR 68	HBC	±	5.5 $K^- p \to \Lambda\eta 2\pi$

[4] From $f_1(1285)$ decay.
[5] Using a two-channel resonance parametrization of GAY 76B data.

$K\overline{K}$ ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 25	100	[6] ASTIER 67	HBC	±
57.0±13.0	143	[7] ROSENFELD 65	RVUE	±

[6] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.
[7] Plus systematic errors.

$a_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi$	seen
Γ_2	$K\overline{K}$	seen
Γ_3	$\rho\pi$	
Γ_4	$\pi\eta'(958)$	
Γ_5	$\gamma\gamma$	seen
Γ_6	e^+e^-	

$a_0(980)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
$0.19\pm0.07^{+0.10}_{-0.07}$	ANTREASYAN 86	CBAL	$e^+e^- \to e^+e^-\pi^0\eta$

$\Gamma(\eta\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_6/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<1.5	90	VOROBYEV 88	ND	$e^+e^- \to \pi^0\eta$

$a_0(980)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\eta\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.7 ±0.3	[8] CORDEN 78	OMEG		12–15 $\pi^- p \to n\eta 2\pi$
0.25±0.08	[8] DEFOIX 72	HBC	±	0.7 $\overline{p} \to 7\pi$

[8] From the decay of $f_1(1285)$.

$\Gamma(\rho\pi)/\Gamma(\eta\pi)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	70	AMMAR 70	HBC	±	4.1,5.5 $K^- p \to \Lambda\eta 2\pi$

$a_0(980)$ REFERENCES

VOROBYEV	88	YAF 48 436	+Golubev, Dolinsky, Druzhinin+	(NOVO)
ANTREASYAN	86	PR D33 1847	+Aschman, Besset, Bienlein+	(Crystal Ball Collab.)
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
DEBILLY	80	NP B176 1	+Briand, Duboc, Levy+	(CURI, LAUS, NEUC, GLAS)
GURTU	79	NP B151 181	+Gavillet, Blokzijl+	(CERN, ZEEM, NIJM, OXF)
CONFORTO	78	LNC 23 419	+Conforto, Key+	(RHEL, TNTO, CHIC, FNAL+)
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
GRASSLER	77	NP B121 189	+	(AACH, BERL, BONN, CERN, CRAC, HEID+)
FLATTE	76	PL 63B 224		(CERN)
GAY	76B	PL 63B 220	+Chaloupka, Blokzijl, Heinen+	(CERN, AMST, NIJM) JP
WELLS	75	NP B101 333	+Radojicic, Roscoe, Lyons	(OXF)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
AMMAR	70	PR D2 430	+Kropac, Davis+	(KANS, NWES, ANL, WISC)
BARNES	69C	PRL 23 610	+Chung, Eisner, Bassano, Goldberg+	(BNL, SYRA)
CAMPBELL	69	PRL 22 1204	+Lichtman, Loeffler+	(PURD)
MILLER	69B	PL 29B 255	+Kramer, Carmony+	(PURD)
Also	69	PR 188 2011	Yen, Ammann, Carmony, Eisner+	(PURD)
AMMAR	68	PRL 21 1832	+Davis, Kropac, Derrick, Fields+	(NWES, ANL)
ASTIER	67	PL 25B 294	+Montanet, Baubillier, Duboc+	(CDEF, CERN, IRAD)
Includes data of BARLOW 67, CONFORTO 67, and ARMENTEROS 65.				
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
CONFORTO	67	NP B3 469	+Marechal+	(CERN, CDEF, IPNP, LIVP)
ARMENTEROS	65	PL 17 344	+Edwards, Jacobsen+	(CERN, CDEF)
ROSENFELD	65	Oxford Conf. 58		(LRL)

OTHER RELATED PAPERS

WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ACHASOV	88B	ZPHY C41 309	+Shestakov	(NOVO)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
TORNQVIST	82	PRL 49 624		(HELS)
BRAMON	80	PL 93B 65	+Masso	(BARC)
KIENZLE	65	PL 19 438	+Maglich, Levrat, Lefebvres+	(CERN)
TURKOT	63	Siena Conf. 1 661	+Collins, Fujii, Kemp+	(BNL, PITT)

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\phi(1020)$ MASS

We average mass and width values only when the systematic errors have been evaluated.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1019.412±0.008 OUR AVERAGE				
1019.7 ±0.3	2012	DAVENPORT 86	MPSF	400 $pA \to 4K X$
1019.411±0.008	642k	[1] DIJKSTRA 86	SPEC	100–200 $\pi^\pm$, $\overline{p}$, p, $K^\pm$, on Be
1019.7 ±0.1 ±0.1	5079	ALBRECHT 85D	ARG	$e^+e^- \to$ hadrons
1019.3 ±0.1	1500	ARENTON 82	AEMS	11.8 polar. $pp \to KK$
1019.67 ±0.17	25080	[2] PELLINEN 82	RVUE	
1019.52 ±0.13		BUKIN 78C	OLYA	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1019.8 ±0.7		ARMSTRONG 86	OMEG	85 $\pi^+/pp \to \pi^+/p4Kp$
1020.1 ±0.11	5526	[3] ATKINSON 86	OMEG	20–70 γp
1019.7 ±1.0		BEBEK 86	CLEO	$e^+e^- \to \Upsilon(4S)$
1020.9 ±0.2		[3] FRAME 86	OMEG	13 $K^+p \to \phi K^+p$
1021.0 ±0.2		[3] ARMSTRONG 83B	OMEG	18.5 $K^-p \to K^-K^+\Lambda$
1020.0 ±0.5		[3] ARMSTRONG 83B	OMEG	18.5 $K^-p \to K^-K^+\Lambda$
1019.7 ±0.3		[3] BARATE 83	GOLI	190 π^- Be $\to 2\mu X$
1019.8 ±0.2 ±0.5	766	IVANOV 81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
1019.4 ±0.5	337	COOPER 78B	HBC	0.7–0.8 $\overline{p}p \to K^0_S K^0_L$
1020.0 ±1.0	383	[3] BALDI 77	CNTR	10 $\pi^-p \to \pi^-\phi p$
1018.9 ±0.6	800	COHEN 77	ASPK	6 $\pi^\pm N \to K^+K^-N$
1019.7 ±0.5	454	KALBFLEISCH 76	HBC	2.18 $K^-p \to K\overline{K}n$
1019.4 ±0.8	984	BESCH 74	CNTR	2 $\gamma p \to pK^+K^-$
1020.3 ±0.4	100	BALLAM 73	HBC	2.8–9.3 γp
1019.4 ±0.7		BINNIE 73B	CNTR	$\pi^-p \to \phi n$
1019.6 ±0.5	120	[4] AGUILAR-... 72B	HBC	3.9,4.6 $K^-p \to \Lambda K^+K^-$
1019.9 ±0.5	100	[4] AGUILAR-... 72B	HBC	3.9,4.6 $K^-p \to K^-pK^+K^-$
1020.4 ±0.5	131	COLLEY 72	HBC	10 $K^+p \to K^+p\phi$
1019.9 ±0.3	410	STOTTLEMYER 71	HBC	2.9 $K^-p \to \Sigma/\Lambda K\overline{K}$

[1] Weighted and scaled average of 12 measurements of DIJKSTRA 86.

[2] PELLINEN 82 review includes AKERLOF 77, DAUM 81, BALDI 77, AYRES 74, DEGROOT 74.

[3] Systematic errors not evaluated.

[4] Mass errors enlarged by us to $\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

$\phi(1020)$ WIDTH

We average mass and width values only when the systematic errors have been evalutated.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
4.41±0.07 OUR FIT Error includes scale factor of 1.2.				
4.41±0.06 OUR AVERAGE				
4.45±0.06	271k	DIJKSTRA 86	SPEC	100 π^- Be
4.5 ±0.7	1500	ARENTON 82	AEMS	11.8 polar. $pp \to KK$
4.2 ±0.6	766	[5] IVANOV 81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
4.3 ±0.6		[5] CORDIER 80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
4.36±0.29	3681	[5,6] BUKIN 78C	OLYA	e^+e^-
4.5 ±0.50	1300	[5,7] AKERLOF 77	SPEC	400 $pA \to K^+K^-X$
4.4 ±0.6	984	[5] BESCH 74	CNTR	2 $\gamma p \to pK^+K^-$
3.81±0.37		COSME 74B	OSPK	e^+e^-
3.8 ±0.7	454	[5] BORENSTEIN 72	HBC	2.18 $K^-p \to K\overline{K}n$
4.67±0.72	681	[5] BALAKIN 71	OSPK	e^+e^-
4.09±0.29		BIZOT 70	OSPK	e^+e^-

• • • We do not use the following data for averages, fits, limits, etc. • • •

8.9 ±0.3		[7] FRAME	86	OMEG	13 $K^+ p \to \phi K^+ p$
3.6 ±0.8	337	[5] COOPER	78B	HBC	0.7–0.8 $\bar{p}p \to K^0_S K^0_L$
4.5 ±0.8	500	[5,7] AYRES	74	ASPK	3–6 $\pi^- p \to K^+ K^- n$, $K^- p \to K^+ K^- \Lambda/\Sigma^0$
4.2 ±1.3	170	[5,7] DEGROOT	74	HBC	4.2 $K^- p \to \Lambda K^+ K^-$
3.8 ±1.5	100	[5] BALLAM	73	HBC	2.8–9.3 γp
4.5 ±1.1		BINNIE	73B	CNTR	$\pi^- p \to \phi n$
4.6 ±1.7	120	[5] AGUILAR-...	72B	HBC	3.9,4.6 $K^- p \to \Lambda K^+ K^-$
4.7 ±1.9	100	[5] AGUILAR-...	72B	HBC	3.9,4.6 $K^- p \to K^- p K^+ K^-$
5.0 ±1.8	131	[5] COLLEY	72	HBC	10 $K^+ p \to K^+ p \phi$
4.2 ±1.4	150	[5] AUGUSTIN	69	OSPK	$e^+ e^-$

[5] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[6] Number of events includes a small background contribution.

[7] Systematic errors not evaluated.

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.5 ± 1.1) %	S=1.4
Γ_2	$K^0_L K^0_S$	(34.4 ± 0.9) %	S=1.4
Γ_3	$\rho\pi$	(12.9 ± 0.7) %	
Γ_4	$\pi^+\pi^-\pi^0$	$(1.9 ^{+1.2}_{-1.0})$ %	S=1.3
Γ_5	$\eta\gamma$	(1.28 ± 0.06) %	S=1.2
Γ_6	$\pi^0\gamma$	$(1.31 \pm 0.13) \times 10^{-3}$	
Γ_7	e^+e^-	$(3.11 \pm 0.10) \times 10^{-4}$	
Γ_8	$\mu^+\mu^-$	$(2.48 \pm 0.34) \times 10^{-4}$	
Γ_9	$\eta e^+ e^-$	$(1.3 ^{+0.8}_{-0.6}) \times 10^{-4}$	
Γ_{10}	$\pi^+\pi^-$	$(8 ^{+5}_{-4}) \times 10^{-5}$	S=1.5
Γ_{11}	$\omega\gamma$	< 5 %	CL=84%
Γ_{12}	$\rho\gamma$	< 2 %	CL=84%
Γ_{13}	$\pi^+\pi^-\gamma$	$< 7 \times 10^{-3}$	CL=90%
Γ_{14}	$f_0(975)\gamma$	$< 2 \times 10^{-3}$	CL=90%
Γ_{15}	$\pi^0\pi^0\gamma$	$< 1 \times 10^{-3}$	CL=90%
Γ_{16}	$\pi^+\pi^-\pi^+\pi^-$	$< 8.7 \times 10^{-4}$	CL=90%
Γ_{17}	$\eta'(958)\gamma$	$< 4.1 \times 10^{-4}$	CL=90%
Γ_{18}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	$< 1.5 \times 10^{-4}$	CL=95%
Γ_{19}	$\pi^0 e^+ e^-$	$< 1.2 \times 10^{-4}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 9 branching ratios uses 40 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 = 42.1$ for 35 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−50				
x_3	0	0			
x_4	−48	−34	−57		
x_5	−3	−3	0	−1	
Γ	0	0	−27	15	0
	x_1	x_2	x_3	x_4	x_5

	Mode	Rate (MeV)	Scale factor
Γ_1	K^+K^-	2.19 ±0.06	1.3
Γ_2	$K^0_L K^0_S$	1.52 ±0.05	1.3
Γ_3	$\rho\pi$	0.570 ±0.030	
Γ_4	$\pi^+\pi^-\pi^0$	0.08 ±0.05	1.3
Γ_5	$\eta\gamma$	0.0567±0.0029	1.2

$\phi(1020)$ PARTIAL WIDTHS

$\Gamma(\rho\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.570±0.030 OUR FIT				
0.57 ±0.03	JULLIAN	76	OSPK	$e^+ e^-$

$\Gamma(e^+ e^-)$ Γ_7

VALUE (keV)	DOCUMENT ID
1.37±0.05 OUR EVALUATION	

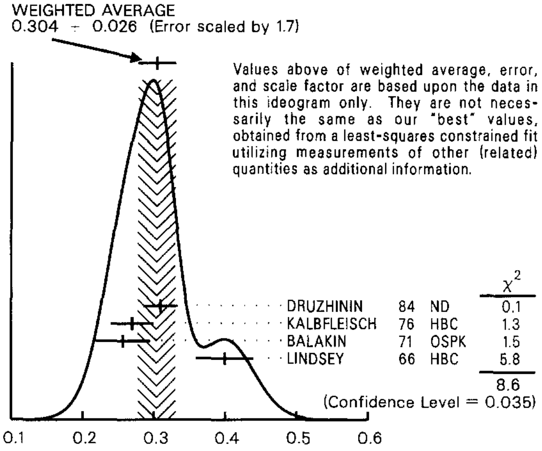
$\phi(1020)$ BRANCHING RATIOS

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.495±0.011 OUR FIT Error includes scale factor of 1.4.					
0.497±0.019 OUR AVERAGE					
0.45 ±0.05	321	KALBFLEISCH	76	HBC	2.18 $K^- p$
0.49 ±0.06	270	DEGROOT	74	HBC	4.2 $K^- p \to \Lambda\phi$
0.540±0.034		BALAKIN	71	OSPK	$e^+ e^-$
0.486±0.044		CHATELUS	71	OSPK	$e^+ e^-$
0.48 ±0.04	252	LINDSEY	66	HBC	2.7 $K^- p$

$\Gamma(K^0_L K^0_S)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.344±0.009 OUR FIT Error includes scale factor of 1.4.					
0.304±0.026 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.					
0.310±0.024		DRUZHININ	84	ND	$e^+ e^- \to K^0_L K^0_S$
0.27 ±0.03	133	KALBFLEISCH	76	HBC	2.18 $K^- p$
0.257±0.038		BALAKIN	71	OSPK	$e^+ e^-$
0.40 ±0.04	167	LINDSEY	66	HBC	2.7 $K^- p$



$\Gamma(K^0_L K^0_S)/\Gamma_{\text{total}}$

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma_{\text{total}}$ $(\Gamma_3+\Gamma_4)/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.148±0.010 OUR FIT Error includes scale factor of 1.7.				
0.139±0.007	[8] PARROUR	76B	OSPK	$e^+ e^-$

[8] Using total width 4.1 MeV. The 3π mode is more than 80%. $\rho\pi$ at the 90% confidence level.

$\Gamma(K^0_L K^0_S)/\Gamma(K\bar{K})$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.410±0.010 OUR FIT Error includes scale factor of 1.3.					
0.45 ±0.04 OUR AVERAGE					
0.44 ±0.07		LONDON	66	HBC	2.2 $K^- p$
0.48 ±0.07	52	BADIER	65B	HBC	3 $K^- p$
0.40 ±0.10	10	SCHLEIN	63	HBC	2.0 $K^- p$

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K\bar{K})$ $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.177±0.014 OUR FIT Error includes scale factor of 1.7.				
0.24 ±0.04 OUR AVERAGE				
0.237±0.039	CERRADA	77B	HBC	4.2 $K^- p \to \Lambda 3\pi$
0.30 ±0.15	LONDON	66	HBC	2.2 $K^- p$

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^0_L K^0_S)$ $(\Gamma_3+\Gamma_4)/\Gamma_2$

VALUE	DOCUMENT ID		TECN	COMMENT
0.431±0.035 OUR FIT Error includes scale factor of 1.6.				
0.49 ±0.05 OUR AVERAGE				
0.56 ±0.13	BUKIN	78C	OLYA	$e^+ e^-$
0.47 ±0.06	COSME	74	OSPK	$e^+ e^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
2.48±0.34 OUR AVERAGE				
2.69±0.46	HAYES	71	CNTR	Photoproduction
2.17±0.60	EARLES	70	CNTR	6.0 Bremsstr.
2.34±1.01	MOY	69	CNTR	Photoproduction

$\Gamma(\eta\gamma)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0128±0.0006 OUR FIT Error includes scale factor of 1.2.				
0.0128±0.0007 OUR AVERAGE Error includes scale factor of 1.2.				
0.0130±0.0006		[9] DRUZHININ 84	ND	$e^+ e^- \to 3\gamma$
0.014 ±0.002		[10] DRUZHININ 84	ND	$e^+ e^- \to 6\gamma$
0.0088±0.0020	290	KURDADZE 83C	OLYA	$e^+ e^- \to 3\gamma$
0.0135±0.0029		ANDREWS 77	CNTR	6.7–10 γCu
0.015 ±0.004	54	[9] COSME 76	OSPK	$e^+ e^-$

[9] From 2γ decay mode of η.

[10] From $3\pi^0$ decay mode of η.

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	COSME 74	OSPK	$e^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	90	KALBFLEISCH 75	HBC	2.2 $K^- p$
<0.04		LINDSEY 65	HBC	2.7 $K^- p$

$\Gamma(\omega\gamma)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	84	LINDSEY 66	HBC	2.7 $K^- p$

$\Gamma(\rho\gamma)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	84	LINDSEY 66	HBC	2.7 $K^- p$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
3.11±0.10 OUR AVERAGE			
3.00±0.21	BUKIN 78C	OLYA	$e^+ e^-$
3.10±0.14	[11] PARROUR 76	OSPK	$e^+ e^-$
3.3 ±0.3	COSME 74	OSPK	$e^+ e^-$
2.81±0.25	BALAKIN 71	OSPK	$e^+ e^-$
3.50±0.27	CHATELUS 71	OSPK	$e^+ e^-$

[11] Using total width 4.2 MeV. They detect 3π mode and observe significant interference with ω tail. This is accounted for in the result quoted above.

$\Gamma(\pi^0\gamma)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.31±0.13 OUR AVERAGE				
1.30±0.13		DRUZHININ 84	ND	$e^+ e^- \to 3\gamma$
1.4 ±0.5	32	COSME 76	OSPK	$e^+ e^-$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
$0.8^{+0.5}_{-0.4}$ OUR AVERAGE Error includes scale factor of 1.5.				
$0.63^{+0.37}_{-0.28}$		[12] GOLUBEV 86	ND	$e^+ e^- \to \pi^+\pi^-$
$1.94^{+1.03}_{-0.81}$		[12] VASSERMAN 81	OLYA	$e^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.6	95	BUKIN 78B	OLYA	$e^+ e^-$
<4.0	95	JULLIAN 76	OSPK	$e^+ e^-$
<2.7	95	ALVENSLEBEN 72	OSPK	γC

[12] Using $\Gamma(e^+e^-)/\Gamma_{\text{total}} = 3.1 \times 10^{-4}$.

$\Gamma(K^0_L K^0_S)/\Gamma(K^+K^-)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.694±0.030 OUR FIT Error includes scale factor of 1.3.				
0.736±0.030 OUR AVERAGE				
0.70 ±0.05		BUKIN 78C	OLYA	$e^+ e^-$
0.82 ±0.08		LOSTY 78	HBC	4.2 $K^- p \to \phi$ hyperon
0.71 ±0.05		LAVEN 77	HBC	10 $K^- p \to K^+ K^- \Lambda$
0.71 ±0.08		LYONS 77	HBC	3–4 $K^- p \to \Lambda\phi$
0.89 ±0.10	144	AGUILAR-... 72B	HBC	3.9,4.6 $K^- p$

$[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^+K^-)$ — $(\Gamma_3+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.299±0.025 OUR FIT Error includes scale factor of 1.7.				
0.28 ±0.09	34	AGUILAR-... 72B	HBC	3.9,4.6 $K^- p$

$\Gamma(\eta e^+e^-)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
$1.3^{+0.8}_{-0.6}$	7	GOLUBEV 85	ND	$e^+ e^- \to \gamma\gamma e^+ e^-$

$\Gamma(\eta'(958)\gamma)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<4.1	90	DRUZHININ 87	ND	$e^+ e^- \to \gamma\eta\pi^+\pi^-$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<1	90	DRUZHININ 87	ND	$e^+ e^- \to 5\gamma$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma(K^+K^-)$ — Γ_{18}/Γ_1

0.04 CL for 1σ with $\phi \to K^+K^- = 0.47$; 0.09 CL for 1σ for num/total

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	95	AGUILAR-... 72B	HBC	3.9,4.6 $K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<1.5	95	BARKOV 88	CMD	$e^+ e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<8.7	90	CORDIER 79	WIRE	$e^+ e^- \to 4\pi$

$\Gamma(\rho\pi)/[\Gamma(\rho\pi) + \Gamma(\pi^+\pi^-\pi^0) + \Gamma(\eta\gamma)]$ — $\Gamma_3/(\Gamma_3+\Gamma_4+\Gamma_5)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.8	90	JULLIAN 76	OSPK	$e^+ e^-$

$\Gamma(f_0(975)\gamma)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<2	90	DRUZHININ 87	ND	$e^+ e^- \to \pi^0\pi^0\gamma$

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ — Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2 \times 10^{-4}$	90	DOLINSKY 88	ND	$e^+ e^- \to \pi^0 e^+ e^-$

$\phi(1020)$ REFERENCES

BARKOV	88	SJNP 47 248	+Vasserman, Vorobyev, Ivanov+	(NOVO)
DOLINSKY	88	YAF 48 442	+Druzhinin, Dubrovin, Golubev+	(NOVO)
DRUZHININ	87	ZPHY C37 1	+Dubrovin, Eidelman, Golubev+	(NOVO)
ARMSTRONG	86	PL 166B 245	+Bloodworth, Carney+	(ATHU, BARI, BIRM, CERN)
ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
BEBEK	86	PRL 56 1893	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
DAVENPORT	86	PR 33 2519		(TUFT, ARIZ, FNAL, FSU, NDAM, VAND)
DIJKSTRA	86	ZPHY C31 375	+Bailey+	(ANIK, BRIS, CERN, CRAC, MPIM, RAL)
FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
GOLUBEV	86	SJNP 44 409	+Druzhinin, Ivanchenko, Perevedentsev+	(NOVO)
		Translated from YAF 44 633.		
ALBRECHT	85D	PL 153B 343	+Drescher, Binder, Drews+	(ARGUS Collab.)
GOLUBEV	85	SJNP 41 756	+Druzhinin, Ivanchenko, Peryshkin+	(NOVO)
		Translated from YAF 41 1183.		
DRUZHININ	84	PL 144B 136	+Golubev, Ivanchenko, Peryshkin+	(NOVO)
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
KURDADZE	83C	JETPL 38 366	+Lelchuk, Root+	(NOVO)
		Translated from ZETFP 38 306.		
ARENTON	82	PR D25 2241	+Ayres, Diebold, May, Swallow+	(ANL, ILL)
PELLINEN	82	PS 25 599	+Roos	(HELS)
DAUM	81	PL 100B 439	+Bardsley+	(AMST, BRIS, CERN, CRAC, MPIM+)
IVANOV	81	PL 107B 297	+Kurdadze, Lelchuk, Sidorov, Skrinsky+	(NOVO)
Also	82	Private Comm.	Eidelman	(NOVO)
VASSERMAN	81	PL 99B 62	+Kurdadze, Sidorov, Skrinsky+	(NOVO)
CORDIER	80	NP B172 13	+Delcourt, Eschstruth, Fulda+	(LALO)
CORDIER	79	PL 81B 389	+Delcourt, Eschstruth, Fulda+	(LALO)
BUKIN	78B	SJNP 27 521	+Kurdadze, Sidorov, Skrinsky+	(NOVO)
		Translated from YAF 27 985.		
BUKIN	78C	SJNP 27 516	+Kurdadze, Serednyakov, Sidorov+	(NOVO)
		Translated from YAF 27 976.		
COOPER	78B	NP B146 1	+Gurtu+	(TATA, CERN, CDEF, MADR)
LOSTY	78	NP B133 38	+Holmgren, Blokzijl+	(CERN, AMST, NIJM, OXF)
AKERLOF	77	PRL 39 861	+Alley, Bintinger, Ditzler+	(FNAL, MICH, PURD)
ANDREWS	77	PRL 38 198	+Fukushima, Harvey, Lobkowicz, May+	(ROCH)
BALDI	77	PL 68B 381	+Bohringer, Dorsaz, Hungerbuhler+	(GEVA)
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF)
COHEN	77	PRL 38 269	+Ayres, Diebold, Kramer, Pawlicki, Wicklund	(ANL)
LAVEN	77	NP B127 43	+Otter, Klein+	(AACH, BERL, CERN, LOIC, WIEN)
LYONS	77	NP B125 207	+Cooper, Clark	(OXF)
COSME	76	PL 63B 352	+Courau, Dudelzak, Grelaud, Jean-Marie+	(ORSA)
JULLIAN	76	Tbilisi 2 B19		(ORSA)
KALBFLEISCH	76	PR D13 22	+Strand, Chapman	(BNL, MICH)
PARROUR	76	PL 63B 357	+Grelaud, Cosme, Courau, Dudelzak+	(ORSA)
PARROUR	76B	PL 63B 362	+Grelaud, Cosme, Courau, Dudelzak+	(ORSA)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
AYRES	74	PRL 32 1463	+Diebold, Greene, Kramer, Levine+	(ANL)
BESCH	74	NP B70 257	+Hartmann, Kose, Krautschneider, Paul+	(BONN)
COSME	74	PL 48B 155	+Jean-Marie, Jullian, Laplanche+	(ORSA)
COSME	74B	PL 48B 159	+Jean-Marie, Jullian, Laplanche+	(ORSA)
DEGROOT	74	NP B74 77	+Hoogland, Jongejans, Metzger+	(AMST, NIJM)
BALLAM	73	PR D7 3150	+Chadwick, Eisenberg, Bingham+	(SLAC, LBL)
BINNIE	73B	PR D8 2789	+Carr, Debenham, Duane+	(LOIC, SHMP)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
ALVENSLEBEN	72	PRL 28 66	+Becker, Biggs, Binkley+	(MIT, DESY)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH)
COLLEY	72	NP B50 1	+Jobes, Riddiford, Griffiths+	(BIRM, GLAS)
BALAKIN	71	PL 34B 328	+Budker, Pakhtusova, Sidorov, Skrinsky+	(NOVO)
CHATELUS	71	LAL 1247 Thesis		(STRB)
Also	70	PL 32 416	Bizot, Buon, Chatelus, Jeanjean+	(ORSA)
HAYES	71	PR D4 899	+Imlay, Joseph, Keizer, Stein	(CORN)
STOTTLEMYER	71	ORO 2504 170 Thesis		(UMD)
BIZOT	70	PL 32 416	+Buon, Chatelus, Jeanjean+	(ORSA)
Also	69	Liverpool Sym. 69	Perez-y-Jorba	
EARLES	70	PRL 25 1312	+Faissler, Gettner, Lutz, Moy, Tang+	(NEAS)
AUGUSTIN	69	PL 28B 517	+Bizot, Buon, Delcourt, Haissinski+	(ORSA)
MOY	69	Thesis		(NEAS)
LINDSEY	66	PR 147 913	+Smith	(LRL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
BADIER	65B	PL 17 337	+Demoulin, Barloutaud+	(EPOL, SACL, AMST)
LINDSEY	65	PRL 15 221	+Smith	(LRL)
LINDSEY 65 data included in LINDSEY 66.				
SCHLEIN	63	PRL 10 368	+Slater, Smith, Stork, Ticho	(UCLA)

OTHER RELATED PAPERS

GEORGIO...	85	PL 152B 428	Georgiopoulos+	(TUFT, ARIZ, FNAL, FSU, NDAM+)
ROOS	80	LNC 27 321	+Pellinen	(HELS)
BARTALUCCI	78	NC 44A 587	+Basini, Bertolucci+	(DESY, FRAS)
COURANT	77	PR D16 1	+Makdisi, Marshak, Peterson, Ruddick+	(MINN)
EVANGELISTA	77	NP B127 384	+	(BARI, BONN, CERN, DARE, GLAS+)
BIZZARRI	74	NC 20A 393	+Ciapetti, Dionisi, Dore, Gaspero+	(ROMA)
BALAKIN	72	PL 40B 431	+Bokin, Pakhtusova, Sidorov+	(NOVO)
BASILE	72	NP B44 605	+Dalpiaz, Frabetti, Zichichi+	(CERN, BGNA, STRB)
BENAKSAS	72C	PL 42B 511	+Cosme, Jean-Marie, Jullian, Laplanche+	(ORSA)
ALVENSLEBEN	71B	PRL 27 441	+Becker, Busza, Chen+	(MIT, DESY)
DIBIANCA	71	NP B35 13	+Einschlag, Endorf, Engler, Fisk+	(CORN)
BIZOT	70B	LNC 4 1273	+Delcourt, Jeanjean, Lalanne+	(ORSA)
HYAMS	70	NP B22 189	+Koch, Potter, VonLindern+	(CERN, MPIM)
SCOTTER	69	NC 62A 1057	+Erskine, Paler+	(BIRM, GLAS, LOIC, MPIM, OXF)
ABRAMS	68	PR 175 1697	+Glasser, Kehoe, Sechi-Zorn, Wolsky	(UMD)
ASTVACAT...	68	PL 27B 45	Astvacaturov, Azimov, Baldin+	(JINR, MOSU)
Also	67	PRL 19 869	Asbury, Becker, Bertram, Ting+	(DESY, COLU)
BINNIE	68	PL 27B 106	+Duane, Faruqi, Horsey+	(LOIC, RHEL)
BOLLINI	68B	NC 56A 1171	+Buhler, Dalpiaz, Massam+	(CERN, BGNA, STRB)
MOSTEK	68	PRL 20 1057	+Eisenhandler, McClellan, Mistry+	(CORN)
WEHMANN	68	PRL 20 748	+Engels+	(HARV, CASE, SLAC, CORN, MCGI)
ABRAMS	67	MD Tech Rep 720 Thesis		(UMD)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
CHASE	67	PRL 18 710	+Rothwell, Weinstein	(CEA, NEAS)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)
HERTZBACH	67	PR 155 1461	+Kraemer, Madanski, Zdanis+	(JHU, BNL)
KHACHAT...	67	PL 24B 349	Khachaturyan, Azimov, Baldin, Belousov+	(JINR)
GRAY	66	PRL 17 501	+Hagerty, Bizzarri, Ciapetti+	(SYRA, ROMA) GJP
LINDSEY	66B	PL 20 93	+Smith	(LRL)
BARBARO-...	65	PRL 14 279	Barbaro-Galtieri, Tripp	(LRL)
BERLEY	65B	PR 139B 1097	+Gelfand	(BNL, COLU)
MILLER	65B	CU-237/Nevis-131 Thesis		(COLU)
ARMENTEROS	63B	Siena Conf. 2 70	+Edwards, Astier+	(CERN, CDEF)
GELFAND	63B	PRL 11 438	+Miller, Nussbaum, Kirsch+	(COLU, RUTG)
BERTANZA	62	PRL 9 180	+Brisson, Connolly, Hart+	(BNL, SYRA)

$h_1(1170)$
was $H(1190)$

$I^G(J^{PC}) = 0^-(1^{+-})$

$h_1(1170)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1170±21 OUR AVERAGE					
1167±22	[2] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to 3\pi n$
1190±60	[1] DANKOWY...	81	SPEC	0	$8\ \pi p \to 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1160±50	ANDO	87	SPEC	0	$8\ \pi p \to 3\pi n$

[1] Uses the model of BOWLER 75.

[2] This result supersedes ANDO 87.

$h_1(1170)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
311±33 OUR AVERAGE					
304±45	[4] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to 3\pi n$
320±50	[3] DANKOWY...	81	SPEC	0	$8\ \pi p \to 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
340±30	ANDO	87	SPEC	0	$8\ \pi p \to 3\pi n$

[3] Uses the model of BOWLER 75.

[4] This result supersedes ANDO 87.

$h_1(1170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen

$h_1(1170)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ANDO	87	SPEC	0	$8\ \pi p \to 3\pi n$
seen	ATKINSON	84	OMEG		20–70 $\gamma p \to \pi^+\pi^-\pi^0 p$
seen	DANKOWY...	81	SPEC		$8\ \pi p \to 3\pi n$

$h_1(1170)$ REFERENCES

TAKAMATSU	90	Hadron 89 Conf.	+Ando+	(KEK)
ANDO	87	Hadron 87 Conf.	+Imai, Inaba	(KEK)
ATKINSON	84	NP B231 15	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
DANKOWY...	81	PRL 46 580	Dankowych+	(TNTO, BNL, CARL, MCGI, OHIO)
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXF, DARE)

$b_1(1235)$
was $B(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

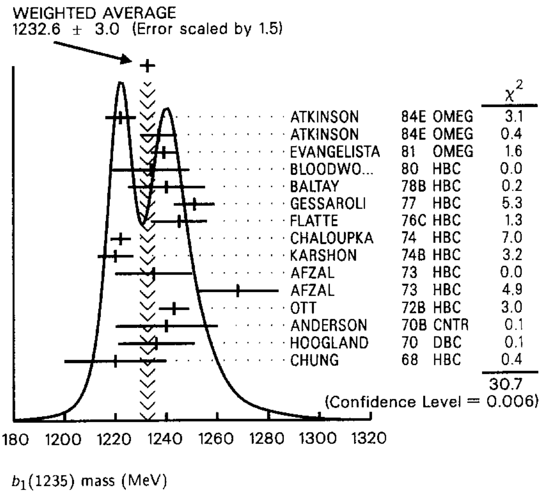
$b_1(1235)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1233 ±10 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.				
1232.6± 3.0 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.				
1222 ± 6		ATKINSON	84E	OMEG	±	25–55 $\gamma p \to \omega\pi X$
1237 ± 7		ATKINSON	84E	OMEG	0	25–55 $\gamma p \to \omega\pi X$
1239 ± 5		EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
1234.0±15.0	105	BLOODWO...	80	HBC	−	$8.2\ K^- p$
1240.0±15.0	225	BALTAY	78B	HBC	+	$15\ \pi^+ p \to p 4\pi$
1251.0± 8.0	450	GESSAROLI	77	HBC	−	$11\ \pi^- p \to \pi^-\omega p$
1245.0±11.0	890	FLATTE	76C	HBC	−	$4.2\ K^- p \to \pi^-\omega\Sigma^+$
1222 ± 4	1400	CHALOUPKA	74	HBC	−	$3.9\ \pi^- p$
1220 ± 7	600	KARSHON	74B	HBC	+	$4.9\ \pi^+ p$
1235 ±15		AFZAL	73	HBC	+	$11.7\ \pi^+ p$
1268 ±16		AFZAL	73	HBC	−	$11.2\ \pi^- p$
1243 ± 6	1163	[1] OTT	72B	HBC	+	$7.1\ \pi^+ p$
1240.0±20.0		ANDERSON	70B	CNTR	0	5–18 γp
1236.0±15.0		HOOGLAND	70	DBC	−	$3.0\ K^- d$
1220 ±20		CHUNG	68	HBC	−	3.2,4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1311 ±10		[2] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to \eta\rho n$
1275 ± 4		TAKAMATSU	90	SPEC	0	$9\ \pi^- p \to \omega\pi^0 n$
1190 ±10		AUGUSTIN	89	DM2	±	$e^+e^- \to 5\pi$
1213 ± 5		ATKINSON	84C	OMEG	0	20–70 γp
1271 ±11		COLLICK	84	SPEC	+	$200\ \pi^+ Z \to Z\pi\omega$
1208.0±18.0	360	GAVILLET	78B	HBC	−	$4.2\ K^- p$ backward
1228 ± 5		[3] FRENKIEL	72	HBC	±	$0.0\ \overline{p}p$, 5π

[1] From fit of the mass spectrum.

[2] Breit–Wigner fitting of PWA of $\eta\pi\pi$ system.

[3] Fit requires an additional $J^P = 1^-$ resonance at 1256 MeV, width 129 MeV.



$b_1(1235)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
150 ±10 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.				
150 ± 7 OUR AVERAGE						
170 ±15		EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
150.0±50.0	105	BLOODWO...	80	HBC	−	$8.2\ K^- p$
170.0±50.0	225	BALTAY	78B	HBC	+	$15\ \pi^+ p \to p 4\pi$
155.0±32.0	450	GESSAROLI	77	HBC	−	$11\ \pi^- p \to \pi^-\omega p$
182.0±45.0	890	FLATTE	76C	HBC	−	$4.2\ K^- p \to \pi^-\omega\Sigma^+$
135 ±20	1400	CHALOUPKA	74	HBC	−	$3.9\ \pi^- p$
156 ±22	600	KARSHON	74B	HBC	+	$4.9\ \pi^+ p$
120 ±50		AFZAL	73	HBC	+	$11.7\ \pi^+ p$
130 ±50		AFZAL	73	HBC	−	$11.2\ \pi^- p$
$134\ ^{+23}_{-26}$	1163	[4] OTT	72B	HBC	+	$7.1\ \pi^+ p$
132.0±20.0		HOOGLAND	70	DBC	−	$3.0\ K^- d$
150 ±20		CHUNG	68	HBC	−	3.2,4.2 $\pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

126 ±10		[5] TAKAMATSU 90	SPEC	0	$8\ \pi^- p \rightarrow \eta \rho n$
181 ± 7		TAKAMATSU 90	SPEC	0	$9\ \pi^- p \rightarrow \omega \pi^0 n$
210 ±19		AUGUSTIN 89	DM2	±	$e^+ e^- \rightarrow 5\pi$
231 ±14		ATKINSON 84C	OMEG	0	$20\text{–}70\ \gamma p$
232 ±29		COLLICK 84	SPEC	+	$200\ \pi^+ Z \rightarrow Z \pi \omega$
163.0±50.8	360	GAVILLET 78B	HBC	+	$4.2\ K^- p$ backward
126 ±10		[6] FRENKIEL 72	HBC	±	$0.0\ \overline{p} p$, 5π

[4] From fit of the mass spectrum.
[5] Breit–Wigner fitting of PWA of $\eta \pi \pi$ system.
[6] See note under the FRENKIEL 72 mass above.

$b_1(1235)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\omega \pi$ [D/S amplitude ratio = 0.26 ± 0.04]	dominant	
Γ_2	$\pi^\pm \gamma$	$(1.5 \pm 0.4) \times 10^{-3}$	
Γ_3	$\eta \rho$	seen	
Γ_4	$\pi^+ \pi^+ \pi^- \pi^0$	< 50 %	84%
Γ_5	$\eta \pi$	< 25 %	90%
Γ_6	$\pi \pi$	< 15 %	90%
Γ_7	$(K \overline{K})^\pm \pi^0$	< 8 %	90%
Γ_8	$K^0_S K^0_L \pi^\pm$	< 6 %	90%
Γ_9	$K \overline{K}$	< 2 %	84%
Γ_{10}	$K^0_S K^0_S \pi^\pm$	< 2 %	90%
Γ_{11}	$\pi \phi$	< 1.5 %	84%

$b_1(1235)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm \gamma)$ Γ_2

VALUE (keV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
230.0±60.0	COLLICK 84	SPEC	+	$200\ \pi^+ Z \rightarrow Z \pi \omega$

$b_1(1235)$ D-wave/S-wave RATIO IN DECAY OF $b_1(1235) \rightarrow \omega \pi$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.260±0.035 OUR AVERAGE					
0.235±0.047		ATKINSON 84C	OMEG		$20\text{–}70\ \gamma p$
$0.4\ ^{+0.1}_{-0.1}$		GESSAROLI 77	HBC	−	$11\ \pi^- p \rightarrow \pi^- \omega p$
0.21 ±0.08		CHUNG 75B	HBC	+	$7.1\ \pi^+ p$
0.3 ±0.1		CHALOUPKA 74	HBC	−	$3.9\text{–}7.5\ \pi^- p$
0.35 ±0.25	600	KARSHON 74B	HBC	+	$4.9\ \pi^+ p$

$b_1(1235)$ BRANCHING RATIOS

$\Gamma(\eta \rho)/\Gamma(\omega \pi)$ Γ_3/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
seen	TAKAMATSU 90	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.10	ATKINSON 84D	OMEG	$20\text{–}70\ \gamma p$

$\Gamma(\pi^+ \pi^+ \pi^- \pi^0)/\Gamma(\omega \pi)$ Γ_4/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.5	ABOLINS 63	HBC	+	$3.5\ \pi^+ p$

$\Gamma(\eta \pi)/\Gamma(\omega \pi)$ Γ_5/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.25	90	BALTAY 67	HBC	±	$0.0\ \overline{p} p$

$\Gamma(\pi \pi)/\Gamma(\omega \pi)$ Γ_6/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.15	90	OTT 72B	HBC	+	$7.1\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3		ADERHOLZ 64B	HBC		$4.0\ \pi^+ p$

$\Gamma((K \overline{K})^\pm \pi^0)/\Gamma(\omega \pi)$ Γ_7/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.08	90	BALTAY 67	HBC	±	$0.0\ \overline{p} p$

$\Gamma(K^0_S K^0_L \pi^\pm)/\Gamma(\omega \pi)$ Γ_8/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.06	90	BALTAY 67	HBC	±	$0.0\ \overline{p} p$

$\Gamma(K \overline{K})/\Gamma(\omega \pi)$ Γ_9/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.02		DAHL 67	HBC	−	$1.6\text{–}4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.08	95	BIZZARRI 69	HBC	±	$0.0\ \overline{p} p$
<0.10	90	BALTAY 67	HBC	±	$0.0\ \overline{p} p$

$\Gamma(K^0_S K^0_S \pi^\pm)/\Gamma(\omega \pi)$ Γ_{10}/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.02	90	BALTAY 67	HBC	±	$0.0\ \overline{p} p$

$\Gamma(\pi \phi)/\Gamma(\omega \pi)$ Γ_{11}/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.015		DAHL 67	HBC		$1.6\text{–}4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	95	BIZZARRI 69	HBC	±	$0.0\ \overline{p} p$

$b_1(1235)$ REFERENCES

TAKAMATSU 90 Hadron 89 Conf. +Ando+ (KEK)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+) JP
ATKINSON 84D NP B242 269 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 84E PL 138B 459 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
COLLICK 84 PRL 53 2374 +Heppelmann, Berg+ (MINN, ROCH, FNAL)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
BLOODWO... 80 LNC 27 555 Bloodworth+ (BIRM, CERN, GLAS, MSU, LPNP)
BALTAY 78B PR D17 62 +Cautis, Cohen, Csorna+ (COLU, BING)
GAVILLET 78B PL 78B 158 +Dionisi, Gurtu+ (CERN, AMST, NIJM, OXF) JP
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI) JP
FLATTE 76C PL 64B 225 +Gay, Blokzijl, Metzger+ (CERN, AMST, NIJM, OXF) JP
CHUNG 75B PR D11 2426 +Protopopescu, Lynch, Flatte+ (BNL, LBL, UCSC) JP
CHALOUPKA 74 PL 51B 407 +Ferrando, Losty, Montanet (CERN) JP
KARSHON 74B PR D10 3608 +Mikenberg, Eisenberg, Pitluck, Ronat+ (REHO) JP
AFZAL 73 LNC 15A 61 +Bassler+ (DURH, GENO, DESY, MILA, SACL) JP
FRENKIEL 72 NP B47 61 +Ghesquiere, Lillestol, Chung+ (CDEF, CERN) JP
OTT 72B LBL-1547 Thesis (LBL) JP
ANDERSON 70B PR D1 27 +Gustavson, Johnson+ (SLAC, CIT, UCSB, NEAS)
HOOGLAND 70 PL 33B 631 +Kluyver, DeVries+ (SABRE Collab.)
BIZZARRI 69 NP B14 169 +Foster, Gavillet, Montanet+ (CERN, CDEF)
CHUNG 68 PR 165 1491 +Dahl, Kirz, Miller (LRL)
BALTAY 67 PRL 18 93 +Franzini, Severiens, Yeh, Zanello (COLU)
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL)
ADERHOLZ 64B PL 10 240 + (AACH, BERL, BIRM, BONN, HAMB, LOIC+)
ABOLINS 63 PRL 11 381 +Lander, Mehlhop, Nguyen, Yager (UCSD)

OTHER RELATED PAPERS

BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.) JP
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+) JP
WONG 81 PRL 46 974 +Key, Frisken, Cline+ (TNTO, YORK, PURD)
DUBOVIKOV 75 SJNP 20 229 +Erofeev (ITEP) JP
Translated from YAF 20 428.
BALLAM 74 NP B76 375 +Chadwick, Bingham, Fretter+ (SLAC, LBL, MPIM)
ARMENISE 73 NC 17A 707 +Forino, Cartacci+ (BARI, BGNA, FIRZ)
ARMENISE 73B LNC 8 425 +Forino, Cartacci+ (BARI, BGNA, FIRZ)
ARNOLD 73 LNC 6 707 +Engel, Escoubes, Kurtz, Lloret, Paty+ (STRB)
CASON 73 PR D7 1971 +Biswas, Kenney, Madden+ (NDAM)
CASON 73B NP B64 14 +Madden, Bishop, Biswas, Kenney+ (NDAM)
CHUNG 73 PL 47B 526 +Protopopescu, Lynch, Flatte+ (BNL, LBL, UCSC) JP
COHEN 73C PR D8 23 +Ferbel, Slattery (ROCH)
SISTERSON 72 NP B48 493 +Harrison, Heyda, Johnson+ (HARV)
DEVONS 71 PRL 27 1614 +Kozlowski, Horwitz+ (COLU, SYRA)
CASO 70 LNC 3 707 +Conte, Tomasini+ (GENO, HAMB, MILA, SACL)
CASON 70 PR D1 851 +Andrews, Biswas, Groves, Harrington+ (NDAM)
EROFEEV 70 SJNP 11 450 +Vetlitsky, Wladimirsky, Grigorev+ (ITEP)
Translated from YAF 11 805.
HONES 70 PR D2 827 +Cason, Biswas, Helland, Kenney+ (NDAM)
MIYASHITA 70 PR D1 771 +VonKrogh, Kopelman, Libby (COLO)
POLS 70 NP B25 109 +Boeckmann, Cirba+ (BONN, DURH, EPOL, TORI)
WERBROUCK 70 LNC 4 1267 +Rinaudo+ (TORI, NIJM, BONN, LBL) JP
ASCOLI 68B PRL 20 1411 +Crawley, Mortara, Shapiro (ILL) JP
BOESEBECK 68 NP B4 501 +Deutschmann+ (AACH, BERL, CERN)
CASO 68 NC 54A 983 +Conte, Cords, Diaz+ (GENO, HAMB, MILA, SACL)
LEE 67 PR 159 1156 +Moebs, Roe, Sinclair, VanderVelde (MICH)
SLATTERY 67 NC 50A 377 +Kraybill, Forman, Ferbel (YALE, ROCH)
GOLDHABER 65 PRL 15 118 +Goldhaber, Kadyk, Shen (LRL)
CARMONY 64 PRL 12 254 +Lander, Rindfleisch, Xuong, Yager (UCB) JP
BONDAR 63B PL 5 209 +Dodd+ (AACH, BIRM, HAMB, LOIC, MPIM)

$f_0(1240)$

was $g_S(1240)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Seen in phase shift analysis of $K^0_S K^0_S$ system. Named g_S by ETKIN 82C. Needs confirmation.

$f_0(1240)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1240.0±10±20	ETKIN 82C	MPS	0	$23\ \pi^- p \rightarrow n 2K^0_S$

$f_0(1240)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
140.0±10±20	ETKIN 82C	MPS	0	$23\ \pi^- p \rightarrow n 2K^0_S$

$f_0(1240)$ DECAY MODES

	Mode
Γ_1	$K \overline{K}$

$f_0(1240)$ REFERENCES

ETKIN 82C PR D25 2446 +Foley, Lai+ (BNL, CUNY, TUFT, VAND) JP

$a_1(1260)$ was $A_1(1270)$

$I^G(J^{PC}) = 1^-(1^{++})$

NOTE ON $a_1(1260)$

For quite some time even the existence as a genuine resonance of this broad bump in the 3π mass spectrum was called into question. Today the $a_1(1260)$ situation appears to be satisfactorily clarified and its resonance parameters are well determined, at least if one restricts the fits to include one resonance only. For an attempt to fit the leptonic data with two resonances see IIZUKA 89.

The experimental data can be grouped into two classes:

1) Hadronically-produced $a_1(1260)$. There are two high-statistics experiments, diffractive production from incident π^- (DAUM 80, 81B) and charge-exchange production with low-energy π^- (DANKOWYCH 81), both on hydrogen. The extraction of the $a_1(1260)$ resonance parameters from these hadronic experiments is troubled by the presence of a coherent background, attributed to the Deck effect. Both experiments perform a partial-wave analysis. The phenomenological amplitude used to explain the 1^+S0^+ data consists of a rescattered Deck amplitude (calculated from one-pion exchange and not allowed to vary) plus a direct resonance production term. Both experiments agree with an $a_1(1260)$ mass of $\simeq$ 1270 MeV, but DAUM 81B finds a width somewhat smaller than the one from charge-exchange data ($\simeq$300 MeV against $\simeq$380 MeV). Rather lower values for the $a_1(1260)$ mass and width [(1122±17) MeV and (254±11) MeV] have been recently obtained with a partial-wave analysis of the $\pi^+\pi^-\pi^0$ system in a high statistics π^-p charge-exchange reaction by TAKAMATSU 90. However in this PWA only Breit Wigner terms are considered.

2) Four experiments have reported good data on the heavy lepton decay $\tau \rightarrow a_1(1260)\nu_\tau$ [$a_1(1260) \rightarrow \rho\pi$] (RUCKSTUHL 86, SCHMIDKE 86, ALBRECHT 86B, and BAND 87). The significance of this channel is that the $a_1(1260)$ from τ decay is expected to be (almost) free from any background. The four sets of τ decays show some inconsistencies in the values quoted for the $a_1(1260)$ mass; however, according to BOWLER 86, these discrepancies can be attributed to the different assumptions and approximations made in fitting the data. Furthermore, all these τ decays seem to indicate a consistent $a_1(1260)$ width $\geq$ 400 MeV, considerably larger than the one found by DAUM 81B.

This discrepancy between the hadronic and the τ decay results has stimulated several reanalyses of the experimental data. BOWLER 86, TORNQVIST 87, and ISGUR 89 have studied the process $\tau \rightarrow 3\pi\nu_\tau$ (BOWLER 86 has made fits to the data of ALBRECHT 86B and SCHMIDKE 86, while TORNQVIST 87 and ISGUR 89 have also taken into account RUCKSTUHL 86). BOWLER 86 assumes that the 3π state is wholly $a_1(1260)$, with no background, coherent or incoherent. Fits are made to the data, always using the same theoretical form with a "normal" Breit-Wigner shape and various behaviors of the $a_1(1260)$ axial coupling as a function of the 3π mass. TORNQVIST 87 fits a modified Breit-Wigner form to the data that includes, besides $\rho\pi$ and $K^*(892)\overline{K} + \overline{K}^*(892)K$ threshold effects, an energy-dependent real part of the $a_1(1260)$ mass parameter ("running mass shift function"). ISGUR 89 deduces a full mass-dependent covariant amplitude for $\tau \rightarrow 3\pi\nu_\tau$ from theory; all the ambiguities due to the non-pointlikeness of the hadrons (like unknown off-shell behaviors of propagators and vertices) are associated with a parameterized nonresonant background amplitude. Since this background is small anyway, the $a_1(1260)$ parameters do not depend critically on its form. Despite these quite different approaches, all three analyses find a good overall description of all the τ decay data with an $a_1(1260)$ mass in the range of 1230 MeV, consistent with hadronic data; however their widths (400 MeV for BOWLER 86, 420 MeV for ISGUR 89 and 600 MeV for TORNQVIST 87) continue to stay significantly higher than that extracted from diffractive-hadronic data.

BOWLER 88 has finally returned to the diffractive data and investigated their consistency with an $a_1(1260)$ width $\geq$400 MeV, as required by the heavy-lepton decay. He has verified that a width of $\sim$300 MeV is a direct consequence of the fixed particular shape for the Deck amplitude as used in DAUM 81B; freeing this shape, good fits are achieved for an $a_1(1260)$ width of $\simeq$400 MeV. There is then no longer any contradiction between the hadronic data and the τ decay data and the $a_1(1260)$ parameters are now well constrained. The best estimates found in BOWLER 88 are (1260±25) MeV for the $a_1(1260)$ mass and (396±43) MeV for its width.

$a_1(1260)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1260 ±30 OUR ESTIMATE					
1260 ±25	[1] BOWLER	88	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1122 ±17	[2] TAKAMATSU	90	SPEC	0	8 $\pi^- p \rightarrow 3\pi n$
1220 ±15	[3] ISGUR	89	RVUE		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
1166 ±18 ±11	BAND	87	MAC		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
1164 ±41 ±23	BAND	87	MAC		$\tau^+ \rightarrow \pi^+\pi^0\pi^0\nu$
1250 ±40	[3] TORNQVIST	87	RVUE		
1046 ±11	[4] ALBRECHT	86B	ARG		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
1235 ±40	[3] BOWLER	86	RVUE		
1056 ±20 ±15	[4] RUCKSTUHL	86	DLCO		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
1194 ±14 ±10	[4] SCHMIDKE	86	MRK2		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
1240.0±80.0	[5] DANKOWY...	81	SPEC	0	8.45 $\pi^- p \rightarrow n3\pi$
1280.0±30.0	[5] DAUM	81B	CNTR		63,94 $\pi^- p \rightarrow p3\pi$
1041.0±13.0	[6] GAVILLET	77	HBC	+	4.2 $K^- p \rightarrow \Sigma 3\pi$

[1] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.

[2] Results of Breit–Wigner fitting to intensity distribution of $1 1 - \rho S_1$ + wave.

[3] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.

[4] Included in BOWLER 86, TORNQVIST 87, and ISGUR 89 reviews.

[5] Uses the model of BOWLER 75.

[6] Produced in K^- backward scattering.

$a_1(1260)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
350 to 500 OUR ESTIMATE					
396 ± 43	[7] BOWLER	88	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
254 ± 11	[12] TAKAMATSU	90	SPEC	0	$8\ \pi^- p \rightarrow 3\pi n$
420 ± 40	[8] ISGUR	89	RVUE		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
405 ± 75 ±25	BAND	87	MAC		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
419 ±108 ±57	BAND	87	MAC		$\tau^+ \rightarrow \pi^+\pi^0\pi^0\nu$
600 ±100	[8] TORNQVIST	87	RVUE		
521 ± 27	[9] ALBRECHT	86B	ARG		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
400 ±100	[8] BOWLER	86	RVUE		
$476\ ^{+132}_{-120}$ ±54	[9] RUCKSTUHL	86	DLCO		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
462 ± 56 ±30	[9] SCHMIDKE	86	MRK2		$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu$
380.0±100.0	[10] DANKOWY...	81	SPEC	0	$8.45\ \pi^- p \rightarrow n 3\pi$
300.0± 50.0	[10] DAUM	81B	CNTR		$63,94\ \pi^- p \rightarrow p 3\pi$
230.0± 50.0	[11] GAVILLET	77	HBC	+	$4.2\ K^- p \rightarrow \Sigma 3\pi$

[7] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.

[8] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.

[9] Included in BOWLER 86, TORNQVIST 87, and ISGUR 89 reviews.

[10] Uses the model of BOWLER 75.

[11] Produced in K^- backward scattering.

[12] Results of Breit—Wigner fitting to intensity distribution of $1 1 + \rho S_1 +$ wave.

$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\rho\pi$	dominant	
Γ_2	$\pi\gamma$	seen	
Γ_3	$\pi(\pi\pi)_{S\text{-wave}}$	[a] <0.7 %	90%

[a] This is only an educated guess; the error given is larger than the error on the average of the published values.

$a_1(1260)$ PARTIAL WIDTHS

$\Gamma(\pi\gamma)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
640.0±246.0	ZIELINSKI	84C	SPEC	$200\ \pi^+ Z \rightarrow Z 3\pi$

$a_1(1260)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN
0.003±0.003	[13] LONGACRE	82	RVUE

[13] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from GAVILLET 77, DAUM 80, and DANKOWYCH 81.

$a_1(1260)$ REFERENCES

TAKAMATSU	90	Hadron 89 Conf.	+Ando+	(KEK)
ISGUR	89	PR D39 1357	+Morningstar, Reader	(TNTO)
BOWLER	88	PL B209 99		(OXF)
BAND	87	PL B198 297	+Camporesi, Chadwick, Delfino+	(MAC Collab.)
TORNQVIST	87	ZPHY C36 695		(HELS)
ALBRECHT	86B	ZPHY C33 7	+Donker, Gabriel, Edwards+	(ARGUS Collab.)
BOWLER	86	PL B182 400		(OXF)
RUCKSTUHL	86	PRL 56 2132	+Stroynowski, Atwood, Barish+	(DELCO Collab.)
SCHMIDKE	86	PRL 57 527	+Abrams, Matteuzzi, Amidei+	(Mark II Collab.)
ZIELINSKI	84C	PRL 52 1195	+Berg, Chandlee, Cihangir+	(ROCH, MINN, FNAL)
LONGACRE	82	PR D26 83		(BNL)
DANKOWY...	81	PRL 46 580	Dankowych+	(TNTO, BNL, CARL, MCGI, OHIO)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
DAUM	80	PL 89B 281	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
GAVILLET	77	PL 69B 119	+Blockzijl, Engelen+	(AMST, CERN, NIJM, OXF) JP
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXF, DARE)

OTHER RELATED PAPERS

IIZUKA	89	PR D39 3357	+Koibuchi, Masuda	(NAGO, IBAR, TSUK)
TORNQVIST	87	ZPHY C36 695		(HELS)
BASDEVANT	77	PR D16 657	+Berger	(FNAL, ANL) JP
ADERHOLZ	64	PL 10 226	+	(AACH, BERL, BIRM, BONN, DESY, HAMB+)
GOLDHABER	64	PRL 12 336	+Brown, Kadyk, Shen+	(LRL, UCB)
LANDER	64	PRL 13 346A	+Abolins, Carmony, Hendricks, Xuong+	(UCSD) JP
BELLINI	63	NC 29 896	+Fiorini, Herz, Negri, Ratti	(MILA)

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also minireview under non-$q\bar{q}$ candidates.

$f_2(1270)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1274 ± 5 OUR ESTIMATE					
1275.0± 1.3 OUR AVERAGE	Error includes scale factor of 1.1.				
1269.7± 5.2		AUGUSTIN	89	DM2	$e^+e^- \rightarrow 5\pi$
1283 ± 6	400 ± 50	ALDE	87	GAM4	$100\ \pi^- p \rightarrow 4\pi^0 n$
1274 ± 4		AUGUSTIN	87	DM2	$J/\psi \rightarrow \gamma\pi^+\pi^-$
1283.0± 6.0		[1] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow n 2K^0_S$
1276.0± 7.0		COURAU	84	DLCO	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
1273.3± 2.3		CHABAUD	83	ASPK	$17\ \pi^- p$ polarized
1280.0± 4.0		CASON	82	STRC	$8\ \pi^+ p \rightarrow p\pi^+ 2\pi^0$
1281.0± 7.0		GIDAL	81	MRK2	J/ψ decay
1282.0± 5.0		CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \rightarrow n 2\pi$
1269 ± 4	10k	APEL	75	CNTR	$40\ \pi^- p \rightarrow n 2\pi^0$
1272 ± 4	4600	ENGLER	74	DBC	$6\ \pi^+ n \rightarrow \pi^+\pi^- p$
1277.0± 4.0	5300	FLATTE	71	HBC	$7.0\ \pi^+ p$
1265 ± 8		BOESEBECK	68	HBC	$8\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1288.0±12.0		ABACHI	86B	HRS	$e^+e^- \rightarrow \pi^+\pi^-$
1270.0±10.0	1665	BREAKSTONE	86	SFM	$pp \rightarrow pp\pi^+\pi^-$
1284.0±30.0	3k	BINON	83	GAM2	$38\ \pi^- p \rightarrow n 2\eta$
1280.0±20.0	3k	APEL	82	CNTR	$25\ \pi^- p \rightarrow n 2\pi^0$
1284.0±10.0	16000	DEUTSCH...	76	HBC	$16\ \pi^+ p$
1258.0±10.0	600	TAKAHASHI	72	HBC	$8\ \pi^- p \rightarrow n 2\pi$
1275.0±13.0		ARMENISE	70	HBC	$9\ \pi^+ n \rightarrow p\pi^+\pi^-$
1261 ± 5	1960	[2] ARMENISE	68	DBC	$5.1\ \pi^+ n \rightarrow p\pi^+ MM^-$
1270 ±10	360	[2] ARMENISE	68	DBC	$5.1\ \pi^+ n \rightarrow p\pi^0$ MM
1268.0± 6.0		[3] JOHNSON	68	HBC	$3.7\text{–}4.2\ \pi^- p$
1276 ±11		RABIN	67	HBC	$8.5\ \pi^+ p$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[2] Mass errors enlarged by us to $\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[3] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.

$f_2(1270)$ WIDTH

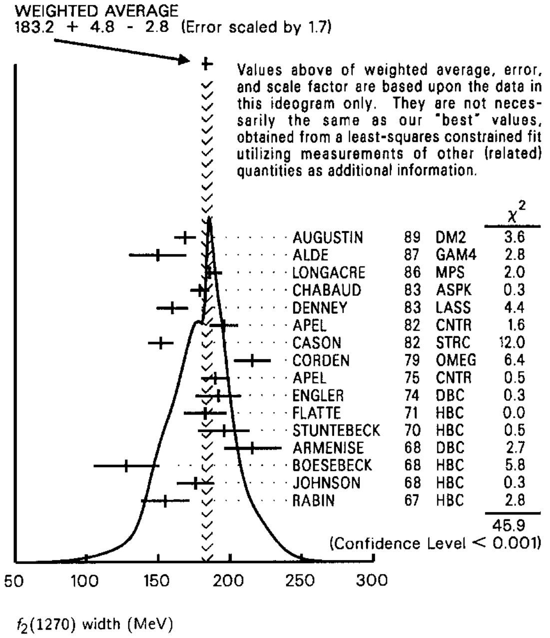
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
185 ±20 OUR ESTIMATE					
184.1± 2.8 OUR FIT	Error includes scale factor of 1.7.				
$183.2^{+4.8}_{-2.8}$ OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.				
169.0± 7.5		AUGUSTIN	89	DM2	$e^+e^- \rightarrow 5\pi$
150 ±20	400 ± 50	ALDE	87	GAM4	$100\ \pi^- p \rightarrow 4\pi^0 n$
$186.0^{+9.0}_{-2.0}$		[4] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow n 2K^0_S$
$179.2^{+6.9}_{-6.6}$		[5] CHABAUD	83	ASPK	$17\ \pi^- p$ polarized
160.0±11.0		DENNEY	83	LASS	$10\ \pi^+ N$
196.0±10.0	3k	APEL	82	CNTR	$25\ \pi^- p \rightarrow n 2\pi^0$
152.0± 9.0		CASON	82	STRC	$8\ \pi^+ p \rightarrow p\pi^+ 2\pi^0$
216.0±13.0		CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \rightarrow n 2\pi$
190 ±10	10k	APEL	75	CNTR	$40\ \pi^- p \rightarrow n 2\pi^0$
192 ±16	4600	ENGLER	74	DBC	$6\ \pi^+ n \rightarrow \pi^+\pi^- p$
183.0±15.0	5300	FLATTE	71	HBC	$7\ \pi^+ p \rightarrow \Delta^{++} f_2$
196.0±18.0		STUNTEBECK	70	HBC	$8\ \pi^- p$, $5.4\ \pi^+ d$
216 ±20	1960	[6] ARMENISE	68	DBC	$5.1\ \pi^+ n \rightarrow p\pi^+ MM^-$
128 ±23		BOESEBECK	68	HBC	$8\ \pi^+ p$
176.0±13.0		[7] JOHNSON	68	HBC	$3.7\text{–}4.2\ \pi^- p$
155 ±17		RABIN	67	HBC	$8.5\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
196.0±34.0	1665	BREAKSTONE	86	SFM	$pp \rightarrow pp\pi^+\pi^-$
240.0±40.0	3k	BINON	83	GAM2	$38\ \pi^- p \rightarrow n 2\eta$
186.0±27.0		GIDAL	81	MRK2	J/ψ decay
187.0±30.0	650	[6] ANTIPOV	77	CIBS	$25\ \pi^- p \rightarrow p 3\pi$
225.0±38.0	16000	DEUTSCH...	76	HBC	$16\ \pi^+ p$
166.0±28.0	600	[6] TAKAHASHI	72	HBC	$8\ \pi^- p \rightarrow n 2\pi$
173.0±25.0		ARMENISE	70	HBC	$9\ \pi^+ n \rightarrow p\pi^+\pi^-$

[4] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[5] CHABAUD 83 analysis includes HYAMS 75.

[6] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[7] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.



$f_2(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	$(85.1\ ^{+2.3}_{-1.3})$ %	S=1.3
Γ_2	$\pi^+\pi^-2\pi^0$	$(6.6\ ^{+1.5}_{-2.6})$ %	S=1.4
Γ_3	$K\overline{K}$	$(4.7\ \pm0.5)$ %	S=3.0
Γ_4	$2\pi^+2\pi^-$	$(2.8\ \pm0.4)$ %	S=1.2
Γ_5	$\eta\eta$	$(4.5\ \pm1.0) \times 10^{-3}$	S=2.4
Γ_6	$4\pi^0$	$(3.0\ \pm1.0) \times 10^{-3}$	
Γ_7	$\gamma\gamma$	$(1.50\pm0.08) \times 10^{-5}$	
Γ_8	$\eta\pi\pi$	$< 9 \times 10^{-3}$	CL=95%
Γ_9	$K^0K^-\pi^+$ + c.c.	$< 3.4 \times 10^{-3}$	CL=95%
Γ_{10}	e^+e^-	$< 9 \times 10^{-9}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 4 partial widths, and 6 branching ratios uses 44 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 80.8$ for 37 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta p_i \delta p_j\right>/(\delta p_i{\cdot}\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−91						
x_3	12	−41					
x_4	11	−36	1				
x_5	2	−9	0	0			
x_6	0	−7	0	0	0		
x_7	23	−22	4	3	1	0	
Γ	−82	76	−13	−9	−3	0	−29
	x_1	x_2	x_3	x_4	x_5	x_6	x_7

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi\pi$	$156.7\ ^{+3.0}_{-1.3}$	
Γ_2	$\pi^+\pi^-2\pi^0$	$12.2\ ^{+2.9}_{-4.9}$	1.4
Γ_3	$K\overline{K}$	$8.6\ \pm0.9$	3.0
Γ_4	$2\pi^+2\pi^-$	$5.2\ \pm0.7$	1.2
Γ_5	$\eta\eta$	$0.83\ \pm0.19$	2.4
Γ_6	$4\pi^0$	$0.55\ \pm0.18$	
Γ_7	$\gamma\gamma$	0.00276 ± 0.00014	

$f_2(1270)$ PARTIAL WIDTHS

$\Gamma(\pi\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$156.7^{+3.0}_{-1.3}$ OUR FIT			
$157.0^{+6.0}_{-1.0}$	[8] LONGACRE 86	MPS	$22\ \pi^- p \rightarrow n2K^0_S$

$\Gamma(K\overline{K})$ Γ_3

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
8.6±0.9 OUR FIT Error includes scale factor of 3.0.			
$9.0^{+0.7}_{-0.3}$	[8] LONGACRE 86	MPS	$22\ \pi^- p \rightarrow n2K^0_S$

$\Gamma(\eta\eta)$ Γ_5

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.83±0.19 OUR FIT Error includes scale factor of 2.4.			
1.0 ±0.1	[8] LONGACRE 86	MPS	$22\ \pi^- p \rightarrow n2K^0_S$

$\Gamma(\gamma\gamma)$ Γ_7

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
2.76±0.14 OUR FIT			
2.76±0.14 OUR AVERAGE			
3.2 ±0.1 ±0.4	[9] AIHARA 86B	TPC	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
2.5 ±0.1 ±0.5	BEHREND 84B	CELL	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
2.85±0.25±0.5	BERGER 84	PLUT	$e^+e^- \rightarrow e^+e^-2\pi$
2.70±0.21	COURAU 84	DLCO	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
2.52±0.13±0.38	SMITH 84C	MRK2	$e^+e^- \rightarrow e^+e^-K^+K^-$
2.3 ±0.2 ±0.5	FRAZER 83	JADE	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
2.7 ±0.2 ±0.6	EDWARDS 82F	CBAL	$e^+e^- \rightarrow e^+e^-2\pi^0$
3.2 ±0.2 ±0.6	BRANDELIK 81B	TASS	$e^+e^- \rightarrow e^+e^-2\pi^0$
3.6 ±0.3 ±0.5	ROUSSARIE 81	MRK2	$e^+e^- \rightarrow e^+e^-2\pi^0$
2.3 ±0.8	[10] BERGER 80B	PLUT	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$2.9\ ^{+0.6}_{-0.4}\ \pm0.6$	[11] EDWARDS 82F	CBAL	$e^+e^- \rightarrow e^+e^-2\pi^0$

$\Gamma(e^+e^-)$ Γ_{10}

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<1.7	90	VOROBYEV 88	ND	$e^+e^- \rightarrow \pi^0\pi^0$

[8] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[9] Radiative corrections modify the partial widths; for instance the COURAU 84 value becomes 2.66 ± 0.21 in the calculation of LANDRO 86.

[10] Using mass, width and B($f_2(1270) \rightarrow 2\pi$) from PDG 78.

[11] If helicity = 2 assumption is not made.

$f_2(1270)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.851^{+0.023}_{-0.013}$ OUR FIT Error includes scale factor of 1.3.				
0.837±0.020 OUR AVERAGE				
0.849±0.025		CHABAUD 83	ASPK	$17\ \pi^- p$ polarized
0.85 ±0.05	250	BEAUPRE 71	HBC	$8\ \pi^+ p \rightarrow \Delta^{++} f_2$
0.8 ±0.04	600	OH 70	HBC	$1.26\ \pi^- p \rightarrow \pi^+\pi^- n$

$\Gamma(\pi^+\pi^-2\pi^0)/\Gamma(\pi\pi)$ Γ_2/Γ_1

Should be twice $\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ if decay is $\rho\rho$. (See ASCOLI 68D.)

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.078^{+0.019}_{-0.032}$ OUR FIT Error includes scale factor of 1.4.				
0.15 ±0.06	600	EISENBERG 74	HBC	$4.9\ \pi^+ p \rightarrow \Delta^{++} f_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07		EMMS 75D	DBC	$4\ \pi^+ n \rightarrow p f_2$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ Γ_3/Γ_1

We average only experiments which either take into account $f_2(1270)$-$a_2(1320)$ interference explicitly or demonstrate that $a_2(1320)$ production is negligible.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.055±0.006 OUR FIT Error includes scale factor of 2.9.				
$0.040^{+0.005}_{-0.006}$ OUR AVERAGE				
$0.037^{+0.008}_{-0.021}$		ETKIN 82B	MPS	$23\ \pi^- p \rightarrow n2K^0_S$
0.045±0.009		CHABAUD 81	ASPK	$17\ \pi^- p$ polarized
0.039±0.008		LOVERRE 80	HBC	$4\ \pi^- p \rightarrow K\overline{K}N$

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.036 ± 0.005		[12] COSTA...	80	OMEG	$1\text{–}2.2\ \pi^- p \to K^+K^- n$
0.030 ± 0.005		[13] MARTIN	79	RVUE	
0.027 ± 0.009		[14] POLYCHRO...	79	STRC	$7\ \pi^- p \to n2K^0_S$
0.025 ± 0.015		EMMS	75D	DBC	$4\ \pi^+ n \to p f_2$
0.031 ± 0.012	20	ADERHOLZ	69	HBC	$8\ \pi^+ p \to K^+K^-\pi^+ p$

[12] Re-evaluated by CHABAUD 83.
[13] Includes PAWLICKI 77 data.
[14] Takes into account the $f_2(1270)$ − $f'_2(1525)$ interference.

$\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.033 ± 0.005 OUR FIT Error includes scale factor of 1.2.					
0.033 ± 0.004 OUR AVERAGE Error includes scale factor of 1.1.					
0.024 ± 0.006	160	EMMS	75D	DBC	$4\ \pi^+ n \to p f_2$
0.051 ± 0.025	70	EISENBERG	74	HBC	$4.9\ \pi^+ p \to \Delta^{++} f_2$
$0.043^{+0.007}_{-0.011}$	285	LOUIE	74	HBC	$3.9\ \pi^- p \to n f_2$
0.037 ± 0.007	154	ANDERSON	73	DBC	$6\ \pi^+ n \to p f_2$
0.047 ± 0.013		OH	70	HBC	$1.26\ \pi^- p \to \pi^+\pi^- n$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
4.5 ± 1.0 OUR FIT Error includes scale factor of 2.4.				
3.1 ± 0.8 OUR AVERAGE Error includes scale factor of 1.3.				
2.8 ± 0.7	ALDE	86D	GAM4	$100\ \pi^- p \to 4\gamma$
5.2 ± 1.7	BINON	83	GAM2	$38\ \pi^- p \to 4\gamma$

$\Gamma(\eta\eta)/\Gamma(\pi\pi)$ Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	95	EDWARDS	82F	CBAL	$e^+e^- \to e^+e^- 2\eta$
<0.016	95	EMMS	75D	DBC	$4\ \pi^+ n \to p f_2$
<0.09	95	EISENBERG	74	HBC	$4.9\ \pi^+ p \to \Delta^{++} f_2$

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0030 ± 0.0010 OUR FIT					
$0.003\ \pm0.001$	400 ± 50	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(\eta\pi\pi)/\Gamma(\pi\pi)$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.010	95	EMMS	75D	DBC	$4\ \pi^+ n \to p f_2$

$\Gamma(K^0K^-\pi^+ + \text{c.c.})/\Gamma(\pi\pi)$ Γ_9/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	95	EMMS	75D	DBC	$4\ \pi^+ n \to p f_2$

$f_2(1270)$ REFERENCES

AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
VOROBYEV	88	YAF 48 436	+Golubev, Dolinsky, Druzhinin+	(NOVO)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
ABACHI	86B	PRL 57 1990	+Derrick, Blockus+	(PURD, ANL, IND, MICH, LBL)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
BREAKSTONE	86	ZPHY C31 185	+	(ISU, BGNA, CERN, DORT, HEID, WARS)
LANDRO	86	PL B172 445	+Mork, Olsen	(UTRO)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
BEHREND	84B	ZPHY C23 223	+Fenner, Schachter, Schroeder+	(CELLO Collab.)
BERGER	84	ZPHY C26 199	+Klovning, Burger+	(PLUTO Collab.)
COURAU	84	PL 147B 227	+Johnson, Sherman, Atwood, Baillon+	(CIT, SLAC)
SMITH	84C	PR D30 851	+Burke, Abrams, Blocker, Levi+	(SLAC, LBL, HARV)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
Also	83B	SJNP 38 561 Translated from YAF 38 934.	Binon, Gouanere+	(BELG, LAPP, SERP, CERN)
CHABAUD	83	NP B223 1	+Gorlich, Cerrada+	(CERN, CRAC, MPIM)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
FRAZER	83	Aachen Conf.		(UCSD)
APEL	82	NP B201 197	+Augenstein+	(KARL, PISA, SERP, WIEN, CERN)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
EDWARDS	82F	PL 110B 82	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
BRANDELIK	81B	ZPHY C10 117	+Boerner+	(TASSO Collab.)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
ROUSSARIE	81	PL 105B 304	+Burke, Abrams, Alam+	(SLAC, LBL)
BERGER	80B	PL 94B 254	+Genzer+	(AACH, BERG, DESY, HAMB, UMD+)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC)
MARTIN	79	NP B158 520	+Ozmutlu	(DURH)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)
PDG	78	PL 75B	Bricman+	
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL)
DEUTSCH...	76	NP B103 426	Deutschmann+	(AACH, BERL, BONN, CERN+)
APEL	75	PL 57B 398	+Augenstein+	(KARL, PISA, SERP, WIEN, CERN)
EMMS	75D	NP B96 155	+Kinson, Stacey, Votruba+	(BIRM, DURH, RHEL)
HYAMS	75	NP B100 205	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
EISENBERG	74	PL 52B 239	+Engler, Haber, Karshon+	(REHO)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)
LOUIE	74	PL 48B 385	+Alitti, Gandois, Chaloupka+	(SACL, CERN)
ANDERSON	73	PRL 31 562	+Engler, Kraemer, Toaff, Diaz+	(CMU, CASE)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHO, PENN, NDAM, ANL)
BEAUPRE	71	NP B28 77	+Deutschmann, Graessler+	(AACH, BERL, CERN)
FLATTE	71	PL 34B 551	+Alston-Garnjost, Barbaro-Galtieri+	(LBL)
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)
OH	70	PR D1 2494	+Garfinkel, Morse, Walker, Prentice	(WISC, TNTO) JP
STUNTEBECK	70	PL 32B 391	+Kenney, Deery, Biswas, Cason+	(NDAM)
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH, BERL, CERN, JAGL, WARS)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSA)
ASCOLI	68D	PRL 21 1712	+Crawley, Mortara+	(ILL)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
JOHNSON	68	PR 176 1651	+Poirier, Biswas, Gutay+	(NDAM, PURD, SLAC)
EISNER	67	PR 164 1699	+Johnson, Klein, Peters, Sahni, Yen+	(PURD)
RABIN	67	Thesis		(RUTG)
DERADO	65	PRL 14 872	+Kenney, Poirier, Shephard	(NDAM)
LEE	64	PRL 12 342	+Roe, Sinclair, VanderVelde	(MICH)
BONDAR	63	PL 5 153	+	(AACH, BIRM, BONN, DESY, LOIC, MPIM)

$f_1(1285)$
was $D(1285)$

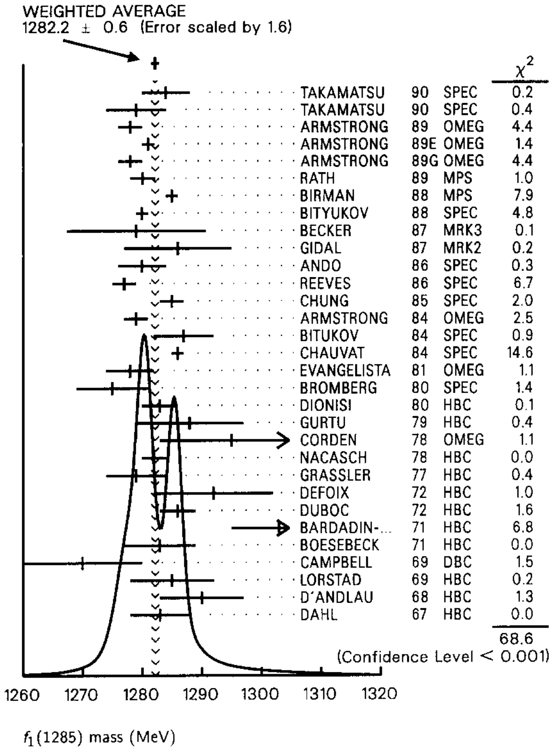
$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

$f_1(1285)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$1282\ \pm\ 5$ OUR ESTIMATE						
$1282.2\pm\ 0.6$ OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.						
$1284\ \pm\ 4$		TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to K\overline{K}\pi n$
$1279\ \pm\ 5$		TAKAMATSU	90	SPEC	0	$8\ \pi^- p \to \eta\pi^+\pi^- n$
$1278\ \pm\ 2$	140 ± 12	ARMSTRONG	89	OMEG		$300\ pp \to K\overline{K}\pi pp$
$1281\ \pm\ 1$		ARMSTRONG	89E	OMEG		$300\ pp \to pp2(\pi^+\pi^-)$
$1278\ \pm\ 2$		ARMSTRONG	89G	OMEG		$85\ \pi^+ p \to 4\pi\pi p,\ pp \to 4\pi pp$
$1280.1\pm\ 2.1$	60 ± 20	RATH	89	MPS		$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
$1285\ \pm\ 1$	4750 ± 100	[1] BIRMAN	88	MPS		$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
$1280\ \pm\ 1$	504 ± 84	BITYUKOV	88	SPEC		$32.5\ \pi^- p \to K^+K^-\pi^0 n$
$1279\ \pm\ 6\ \pm10$	16 ± 6	BECKER	87	MRK3		$e^+e^- \to \phi K\overline{K}\pi$
$1286\ \pm\ 9$		GIDAL	87	MRK2		$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
$1280\ \pm\ 4$		ANDO	86	SPEC		$8\ \pi^- p \to n\eta\pi^+\pi^-$
$1277.0\pm\ 2.0$	420	REEVES	86	SPEC		$6.6\ p\overline{p} \to KK\pi X$
$1285.0\pm\ 2.0$		CHUNG	85	SPEC		$8\ \pi^- p \to NK\overline{K}\pi$
$1279.0\pm\ 2.0$	604	ARMSTRONG	84	OMEG		$85\ \pi^+ p \to K\overline{K}\pi\pi p,\ pp \to K\overline{K}\pi pp$
$1287.0\pm\ 5.0$	353	BITUKOV	84	SPEC		$32\ \pi^- p \to K^+K^-\pi^0 n$
$1286.0\pm\ 1.0$		CHAUVAT	84	SPEC		ISR 31.5 pp
$1278\ \pm\ 4$		EVANGELISTA	81	OMEG		$12\ \pi^- p \to \eta\pi p$
$1275.0\pm\ 6.0$	31	BROMBERG	80	SPEC		$100\ \pi^- p \to K\overline{K}\pi X$
$1283.0\pm\ 3.0$	103	DIONISI	80	HBC		$4\ \pi^- p \to K\overline{K}\pi n$
$1288.0\pm\ 9.0$	200	GURTU	79	HBC		$4.2\ K^- p \to n\eta 2\pi$
1295.0 ± 12.0	85	CORDEN	78	OMEG		$12\text{–}15\ \pi^- p \to n5\pi$
$1282.0\pm\ 2.0$	320	NACASCH	78	HBC		$0.7, 0.76\ \overline{p}p \to K\overline{K}3\pi$
$1279.0\pm\ 5.0$	210	GRASSLER	77	HBC		$16\ \pi^\mp p$
$1292\ \pm10$	150	DEFOIX	72	HBC		$0.7\ \overline{p}p \to 7\pi$
$1286\ \pm\ 3$	180	DUBOC	72	HBC		$1.2\ \overline{p}p \to 2K4\pi$
$1303.0\pm\ 8.0$		BARDADIN-...	71	HBC		$8\ \pi^+ p \to p6\pi$
$1283.0\pm\ 6.0$		BOESEBECK	71	HBC		$16.0\ \pi p \to p5\pi$
1270.0 ± 10.0		CAMPBELL	69	DBC		$2.7\ \pi^+ d$
$1285\ \pm\ 7$		LORSTAD	69	HBC		$0.7\ \overline{p}p$, 4,5-body
$1290\ \pm\ 7$		D'ANDLAU	68	HBC		$1.2\ \overline{p}p$, 5–6 body
$1283.0\pm\ 5.0$		DAHL	67	HBC		$1.6\text{–}4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 1279		[2] TORNQVIST	82B	RVUE		
~ 1275.0	46	[3] STANTON	79	CNTR		$8.5\ \pi^- p \to n2\gamma 2\pi$
1271.0 ± 10.0	34	CORDEN	78	OMEG		$12\text{–}15\ \pi^- p \to K^+K^-\pi n$
$1280\ \pm\ 3$	500	[4] THUN	72	MMS		$13.4\ \pi^- p$

[1] From partial wave analysis of $K^+\overline{K}^0\pi^-$ system.
[2] From a unitarized quark-model calculation.
[3] From phase shift analysis of $\eta\pi^+\pi^-$ system.
[4] Seen in the missing mass spectrum.



$f_1(1285)$ WIDTH

Only experiments giving width error less than 20 MeV are kept for averaging.

VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
24 ± 3 OUR ESTIMATE						
24.2± 1.1 OUR AVERAGE			Error includes scale factor of 1.1.			
22 ± 5			TAKAMATSU 90	SPEC	0	8 $\pi^- p \rightarrow K\overline{K}\pi n$
25 ± 4		140 ± 12	ARMSTRONG 89	OMEG		300 $pp \rightarrow K\overline{K}\pi pp$
31 ± 5			ARMSTRONG 89E	OMEG		300 $pp \rightarrow pp2(\pi^+\pi^-)$
41 ±12			ARMSTRONG 89G	OMEG		85 $\pi^+ p \rightarrow 4\pi\pi p$, $pp \rightarrow 4\pi pp$
17.9±10.9		60 ± 20	RATH 89	MPS		21.4 $\pi^- p \rightarrow K^0_S K^0_S \pi^0 n$
22 ± 2		4750 ± 100	[5] BIRMAN 88	MPS		8 $\pi^- p \rightarrow K^+\overline{K}^0\pi^- n$
25 ± 4		504 ± 84	BITYUKOV 88	SPEC		32.5 $\pi^- p \rightarrow K^+K^-\pi^0 n$
14 $^{+20}_{-14}$ ±10		16 ± 6	BECKER 87	MRK3		$e^+e^- \rightarrow \phi K\overline{K}\pi$
19 ± 5			ANDO 86	SPEC		8 $\pi^- p \rightarrow n\eta\pi^+\pi^-$
32.0± 8.0		420	REEVES 86	SPEC		6.6 $p\overline{p} \rightarrow KK\pi X$
22.0± 2.0			CHUNG 85	SPEC		8 $\pi^- p \rightarrow NK\overline{K}\pi$
32.0± 3.0		604	ARMSTRONG 84	OMEG		85 $\pi^+ p \rightarrow K\overline{K}\pi\pi p$, $pp \rightarrow K\overline{K}\pi pp$
24.0± 3.0			CHAUVAT 84	SPEC		ISR 31.5 pp
26 ±12			EVANGELISTA 81	OMEG		12 $\pi^- p \rightarrow \eta\pi p$
29.0±10.0		103	DIONISI 80	HBC		4 $\pi^- p \rightarrow K\overline{K}\pi n$
25.0±15.0		200	GURTU 79	HBC		4.2 $K^- p \rightarrow n\eta 2\pi$
28.3± 6.7		320	NACASCH 78	HBC		0.7,0.76 $\overline{p}p \rightarrow K\overline{K}3\pi$
24.0±18.0		210	GRASSLER 77	HBC		16 $\pi^\mp p$
10.0±10.0			BOESEBECK 71	HBC		16.0 $\pi p \rightarrow p5\pi$
30.0±15.0			CAMPBELL 69	DBC		2.7 $\pi^+ d$

• • • We do not use the following data for averages, fits, limits, etc. • • •

<20	90		TAKAMATSU 90	SPEC	0	8 $\pi^- p \rightarrow \eta\pi^+\pi^- n$
~ 10.0			[6] STANTON 79	CNTR		8.5 $\pi^- p \rightarrow n2\gamma 2\pi$
28 ± 5		150	[7] DEFOIX 72	HBC		0.7 $\overline{p}p \rightarrow 7\pi$
46 ± 9		180	[7] DUBOC 72	HBC		1.2 $\overline{p}p \rightarrow 2K4\pi$
37 ± 5		500	[8] THUN 72	MMS		13.4 $\pi^- p$
60 ±15			[7] LORSTAD 69	HBC		0.7 $\overline{p}p$, 4,5-body
35.0±10.0			[7] DAHL 67	HBC		1.6–4.2 $\pi^- p$

[5] From partial wave analysis of $K^+\overline{K}^0\pi^-$ system.
[6] From phase shift analysis of $\eta\pi^+\pi^-$ system.
[7] Resolution is not unfolded.
[8] Seen in the missing mass spectrum.

$f_1(1285)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	4π	(38 ±4) %	S=1.1
Γ_2	$\rho\pi\pi$	dominates 4π	
Γ_3	$\rho^0\pi^+\pi^-$		
Γ_4	$\eta\pi\pi$	(50 ±5) %	S=1.1
Γ_5	$a_0(980)\pi$	(37 ±7) %	
Γ_6	$2\pi^+2\pi^-$		
Γ_7	$K\overline{K}\pi$	(11.9±1.4) %	S=1.1
Γ_8	$\phi\gamma$	(10 ±4) × 10^{-4}	
Γ_9	$\gamma\gamma^*$	(11 ±3) × 10^{-5}	
Γ_{10}	$4\pi^0$	< 7 × 10^{-4}	CL=90%
Γ_{11}	$2\pi^+2\pi^-$ (including $\rho^0\pi^+\pi^-$)		
Γ_{12}	$\gamma\gamma$		
Γ_{13}	$K\overline{K}^*(892)$	not seen	

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 8 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 6.2 for 6 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i\delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ccc}
x_4 & -96 & \\
x_7 & 39 & -62 \\
 & x_1 & x_4
\end{array}$$

$f_1(1285)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_4\Gamma_{12}/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.62	95	GIDAL 87	MRK2	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{\text{total}}$ $\Gamma_4\Gamma_9/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
1.4 ±0.4 OUR AVERAGE		Error includes scale factor of 1.4.		
1.18±0.25±0.20	26	[9,10] AIHARA 88B	TPC	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$
2.30±0.61±0.42		[9,11] GIDAL 87	MRK2	$e^+e^- \rightarrow e^+e^-\eta\pi^+\pi^-$

[9] Assuming a ρ-pole form factor.
[10] Published value multiplied by $\eta\pi\pi$ branching ratio 0.49.
[11] Published value divided by 2 and multiplied by the $\eta\pi\pi$ branching ratio 0.49.

$f_1(1285)$ BRANCHING RATIOS

The $f_1(1285)$ branching ratios fit is made with the assumptions that the $f_1(1285) \rightarrow 4\pi$ decay is all $\rho\pi\pi$ and that the $\pi\pi$ pair has $I = 1$.

$\Gamma(K\overline{K}\pi)/\Gamma(4\pi)$ Γ_7/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.31±0.04 OUR FIT Error includes scale factor of 1.1.			
0.32±0.04 OUR AVERAGE Error includes scale factor of 1.2.			
0.28±0.05	[12] ARMSTRONG 89E	OMEG	300 $pp \rightarrow pp f_1(1285)$
0.37±0.03±0.05	[13] ARMSTRONG 89G	OMEG	85 $\pi p \rightarrow 4\pi X$

[12] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.
[13] 4π consistent with being entirely $\rho\pi\pi$.

$\Gamma(K\overline{K}\pi)/\Gamma(\eta\pi\pi)$ Γ_7/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.24±0.05 OUR FIT Error includes scale factor of 1.1.			
0.23±0.06 OUR AVERAGE Error includes scale factor of 1.2.			
0.42±0.15	GURTU 79	HBC	4.2 $K^- p$
0.5 ±0.2	CORDEN 78	OMEG	12–15 $\pi^- p$
0.20±0.08	[14] DEFOIX 72	HBC	0.7 $\overline{p}p \to 7\pi$
0.16±0.08	CAMPBELL 69	DBC	2.7 $\pi^+ d$

[14] $K\overline{K}$ system characterized by the $I = 1$ threshold enhancement. (See under $a_0(980)$).

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ Γ_5/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.74±0.12 OUR AVERAGE			
0.72±0.15	GURTU 79	HBC	4.2 $K^- p$
0.6 $^{+0.3}_{-0.2}$	CORDEN 78	OMEG	12–15 $\pi^- p$
1.0 ±0.3	GRASSLER 77	HBC	16 $\pi^\mp p$

$\Gamma(4\pi)/\Gamma(\eta\pi\pi)$ Γ_1/Γ_4

VALUE	DOCUMENT ID	TECN	COMMENT
0.76±0.16 OUR FIT Error includes scale factor of 1.1.			
0.83±0.24 OUR AVERAGE			
0.64±0.40	GURTU 79	HBC	4.2 $K^- p$
0.93±0.30	[15] GRASSLER 77	HBC	16 $\pi^\mp p$

[15] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.

$\Gamma(K\overline{K}^*(892))/\Gamma_{total}$ Γ_{13}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
not seen	NACASCH 78	HBC	0.7,0.76 $\overline{p}p \to K\overline{K}3\pi$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2\pi^+2\pi^-$ (including $\rho^0\pi^+\pi^-$)) $\frac{1}{3}\Gamma_3/\Gamma_{11}$

VALUE	DOCUMENT ID	TECN	COMMENT
1.0±0.4	GRASSLER 77	HBC	16 GeV $\pi^\pm p$

$\Gamma(\rho\pi)/\Gamma(\eta\pi\pi)$ Γ_2/Γ_4

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.4	95	[16] CORDEN 78	OMEG	12–15 $\pi^- p$

[16] Note that CORDEN 78 and GRASSLER 77 are in disagreement.

$\Gamma(4\pi^0)/\Gamma_{total}$ Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<7	90	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$\Gamma(\phi\gamma)/\Gamma(K\overline{K}\pi)$ Γ_8/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
0.82±0.21±0.20	19 ± 5	BITYUKOV 88	SPEC	32.5 $\pi^- p \to K^+ K^- \pi^0 n$

$f_1(1285)$ REFERENCES

TAKAMATSU	90	Hadron 89 Conf.	+Ando+	(KEK)
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP) JPC
ARMSTRONG	89E	PL B228 536	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF, LPNP)
ARMSTRONG	89G	ZPHY C43 55	+Bloodworth	(CERN, BIRM, BARI, ATHU, LPNP)
RATH	89	PR D40 693	+Cason+	(NDAM, BRAN, BNL, CUNY, DUKE)
AIHARA	88B	PL B209 107	+Alston-Garnjost+	(TPC-2γ Collab.)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, SMAS) JP
BITYUKOV	88	PL B203 327	+Borisov, Dorofeev+	(SERP)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+) IJP
REEVES	86	PR 34 1960	+Chung, Crittenden+	(FLOR, BNL, IND, SMAS) JP
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, SMAS) JP
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN) JP
BITUKOV	84	PL 144B 133	+Dorofeev, Dzhelyadin, Golovkin, Kulik+	(SERP)
CHAUVAT	84	PL 148B 382	+Meritet, Bonino+	(CERN, UDCF, UCLA, SACL)
TORNQVIST	82B	NP B203 268		(HELS)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
BROMBERG	80	PR D22 1513	+Haggerty, Abrams, Dzierba	(CIT, FNAL, ILLC, IND)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)
GURTU	79	NP B151 181	+Gavillet, Blokzijl+	(CERN, ZEEM, NIJM, OXF)
STANTON	79	PRL 42 346	+Brockman+	(OSU, CARL, MCGI, TNTO) JP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC) JP
NACASCH	78	NP B135 203	+Defoix, Dobrzynski+	(PARI, MADR, CERN)
GRASSLER	77	NP B121 189	+	(AACH, BERL, BONN, CERN, CRAC, HEID+)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(LPNP, LIVP)
THUN	72	PRL 28 1733	+Blieden, Finocchiaro, Bowen+	(STON, NEAS)
BARDADIN-...	71	PR D4 2711	Bardadin-Otwinowska, Hofmokl+	(WARS)
BOESEBECK	71	PL 34B 659		(AACH, BERL, BONN, CERN, CRAC, HEID, WARS)
CAMPBELL	69	PRL 22 1204	+Lichtman, Loeffler+	(PURD)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN) JP
D'ANDLAU	68	NP B5 693	+Astier, Barlow+	(CDEF, CERN, IRAD, LIVP) IJP
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL) IJP

OTHER RELATED PAPERS

AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.) JPC
ASTON	85	PR D32 2255	+Carnegie, Dunwoodie+	(SLAC, CARL, CNRC)
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
GAVILLET	82	ZPHY C16 119	+Armenteros+	(CERN, CDEF, PADO, ROMA)
DEBILLY	80	NP B176 1	+Briand, Duboc, Levy+	(CURI, LAUS, NEUC, GLAS) JP
IRVING	78	NP B139 327	+Sepangi	(LIVP)
HANDLER	76	NP B110 173	+Plano, Brucker, Koller+	(RUTG, STEV, SETO)
VUILLEMIN	76	NC 33A 133	+	(LAUS, NEUC, LPNP, LIVP, GLAS)
VUILLEMIN	75	LNC 14 165	+	(LAUS, NEUC, LPNP, LIVP, GLAS) JP
WELLS	75	NP B101 333	+Radojicic, Roscoe, Lyons	(OXF)
BERENYI	72	NP B37 621	+Prentice, Steenberg, Yoon, Walker	(TNTO, WISC)
CHAPMAN	72	NP B42 1	+Church, Lys, Murphy, Ring, VanderVelde	(MICH)
GOLDBERG	71	LNC 1 627	+Makowski, Touchard, Donald+	(IPN, LIVP) JP
AMMAR	70	PR D2 430	+Kropac, Davis+	(KANS, NWES, ANL, WISC)
OTWINOWSKI	69	PL 29B 529		(WARS)
DEFOIX	68B	PL 28B 353	+Rivet, Siaud, Conforto+	(CDEF, IPNP, CERN)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
D'ANDLAU	65	PL 17 347	+Barlow, Adamson+	(CDEF, CERN, IRAD, LIVP)
MILLER	65	PRL 14 1074	+Chung, Dahl, Hess, Hardy, Kirz+	(LRL, UCB)

$\eta(1295)$

was $\eta(1275)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\eta(1295)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1295±4	[1] TAKAMATSU 90	SPEC	0	9 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1279±5	ANDO 86	SPEC		8 $\pi^- p \to n\eta\pi^+\pi^-$
~ 1275	STANTON 79	CNTR		8.4 $\pi^- p \to n\eta 2\pi$

[1] This result supersedes ANDO 86.

$\eta(1295)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
35± 6	[2] TAKAMATSU 90	SPEC	0	9 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
32±10	ANDO 86	SPEC		8 $\pi^- p \to n\eta\pi^+\pi^-$
~ 70	STANTON 79	CNTR		8.4 $\pi^- p \to n\eta 2\pi$

[2] This result supersedes ANDO 86.

$\eta(1295)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^+\pi^-$	seen
Γ_2	$a_0(980)\pi$	seen
Γ_3	$\gamma\gamma$	

$\eta(1295)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi^+\pi^-) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.6	90	AIHARA 88C	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
<0.3		ANTREASYAN 87	CBAL	$e^+e^- \to e^+e^-\eta\pi\pi$

$\eta(1295)$ BRANCHING RATIOS

$\Gamma(a_0(980)\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	BIRMAN 88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
large	ANDO 86	SPEC	8 $\pi^- p \to n\eta\pi^+\pi^-$
large	STANTON 79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ REFERENCES

TAKAMATSU	90	Hadron 89 Conf.	+Ando+	(KEK)
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, SMAS) JP
ANTREASYAN	87	PR D36 2633	+Bartels, Besset+	(Crystal Ball Collab.)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+) IJP
STANTON	79	PRL 42 346	+Brockman+	(OSU, CARL, MCGI, TNTO) JP

Meson Full Listings

$\pi(1300)$, $a_0(1320)$, $a_2(1320)$

$\pi(1300)$

$I^G(J^{PC}) = 1^-(0^{-+})$

$\pi(1300)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1300 ±100 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1190 ± 30	ZIELINSKI 84	SPEC	$200\ \pi^+ Z \rightarrow Z 3\pi$
1240 ± 30	BELLINI 82	SPEC	$40\ \pi^- A \rightarrow A 3\pi$
1273.0± 50.0	[1] AARON 81	RVUE	
1342 ± 20	BONESINI 81	OMEG	$12\ \pi^- p \rightarrow p 3\pi$
~ 1400	DAUM 81B	SPEC	$63{,}94\ \pi^- p$

[1] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
200 to 600 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
440 ± 80	ZIELINSKI 84	SPEC	$200\ \pi^+ Z \rightarrow Z 3\pi$
360 ±120	BELLINI 82	SPEC	$40\ \pi^- A \rightarrow A 3\pi$
580.0±100.0	[2] AARON 81	RVUE	
220 ± 70	BONESINI 81	OMEG	$12\ \pi^- p \rightarrow p 3\pi$
~ 600	DAUM 81B	SPEC	$63{,}94\ \pi^- p$

[2] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\pi(\pi\pi)_{S\text{-wave}}$	seen
Γ_3	$f_0(1400)\pi$	

$\pi(1300)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
2.12	[3] AARON 81	RVUE

[3] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ REFERENCES

ZIELINSKI 84 PR D30 1855 +Berg, Chandlee, Cihangir+ (ROCH, MINN, FNAL)
BELLINI 82 PRL 48 1697 +Frabetti, Ivanshin, Litkin+ (MILA, BGNA, JINR)
AARON 81 PR D24 1207 +Longacre (NEAS, BNL)
BONESINI 81 PL 103B 75 +Donald+ (MILA, LIVP, DARE, CERN, BARI, BONN)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
DAUM 81B NP B182 269 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
DAUM 80 PL 89B 281 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXF, DARE)

$a_0(1320)$

$I^G(J^{PC}) = 1^-(0^{++})$

OMITTED FROM SUMMARY TABLE

Intensity peaking at the mass of the $a_2(1320)$ and with a comparable width. Needs confirmation.

$a_0(1320)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1322±30	POULET 90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$a_0(1320)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
130±30	POULET 90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$a_0(1320)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\eta'\pi^0$	

$a_0(1320)$ BRANCHING RATIOS

$\Gamma(\eta\pi^0)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	POULET 90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$\Gamma(\eta'\pi^0)/\Gamma(\eta\pi^0)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.40	95	POULET 90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$a_0(1320)$ REFERENCES

POULET 90 Hadron 89 Conf. +Boutemeur (SERP, BELG, LANL, LAPP, PISA, KEK)

$a_2(1320)$

was $A_2(1320)$

$I^G(J^{PC}) = 1^-(2^{++})$

$a_2(1320)$ MASS

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1318.4± 0.7 OUR AVERAGE		Includes data from the datablock that follows this one. Error includes scale factor of 1.1.			
1323.8± 2.3		AUGUSTIN 89	DM2	±	$e^+ e^- \rightarrow 5\pi$
1320.6± 3.1		AUGUSTIN 89	DM2	0	$e^+ e^- \rightarrow 5\pi$
1317.0± 2.0	25000	[1] DAUM 80C	SPEC	−	$63{,}94\ \pi^- p \rightarrow 3\pi p$
1320.0±10.0	1097	[1] BALTAY 78B	HBC	+0	$15\ \pi^+ p \rightarrow p 4\pi$
1306.0± 8.0		FERRERSORIA 78	OMEG	−	$9\ \pi^- p \rightarrow p 3\pi$
1318 ± 7	1600	[1] EMMS 75	DBC	0	$4\ \pi^+ n \rightarrow p(3\pi)^0$
1315 ± 5		[1] ANTIPOV 73C	CNTR	−	$25{,}40\ \pi^- p \rightarrow p\eta\pi^-$
1306 ± 9	1580	CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1310 ± 2		[1] EVANGELISTA 81	OMEG	−	$12\ \pi^- p \rightarrow 3\pi p$
1343.0±11.0	490	BALTAY 78B	HBC	0	$15\ \pi^+ p \rightarrow \Delta 3\pi$
1285.0± 9.0		CORDEN 78B	OMEG	−	$12{,}15\ \pi^- p \rightarrow 3\pi n$
1298 ± 8	1200	[1] WAGNER 75	HBC	0	$7\ \pi^+ p \rightarrow \Delta^{++}(3\pi)^0$
1307 ± 7	160	BLOODWO... 72	HBC	+	$5.45\ \pi^+ p \rightarrow p 3\pi$
1304.0± 4.5	360	BARNHAM 71	HBC	+	$3.7\ \pi^+ p \rightarrow (3\pi)^+ p$
1307 ± 5	10000	BINNIE 71	MMS	−	$\pi^- p$ near a_2 threshold
1309 ± 5	5000	BINNIE 71	MMS	−	$\pi^- p$ near a_2 threshold
1299.0± 6.0	28000	BOWEN 71	MMS	−	$5\ \pi^- p$
1300 ± 6.0	24000	BOWEN 71	MMS	+	$5\ \pi^+ p$
1309.0± 4.0	17000	BOWEN 71	MMS	−	$7\ \pi^- p$
1306.0± 4.0	941	ALSTON-... 70	HBC	+	$7.0\ \pi^+ p \rightarrow 3\pi p$
1313.0± 7.0	280	BOECKMANN 70	HBC	0	$5\ \pi^+ p$
1310.0±14.0		EISENBERG 69	HBC	+	$4.3{,}5.3\ \gamma p$
1311.0± 6.0	260	ARMENISE 68B	DBC	0	$5.1\ \pi^+ d$
1320 ±10	120	BOESEBECK 68	HBC	0	$8\ \pi^+ p$

[1] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.

$K^\pm K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1330.0±11.0	1000	[2,3] CLELAND	82B	SPEC	+	$30\ \pi^+ p \rightarrow K^0_S K^+ p$
1319.0± 5.0	4700	[2,3] CLELAND	82B	SPEC	+	$50\ \pi^+ p \rightarrow K^0_S K^+ p$
1324.0± 6.0	5200	[2,3] CLELAND	82B	SPEC	−	$50\ \pi^- p \rightarrow K^0_S K^- p$
1320.0± 2.0	4000	CHABAUD	80	SPEC	−	$17\ \pi^- A \rightarrow K^0_S K^- A$
1312.0± 4.0	11000	CHABAUD	78	SPEC	−	$9.8\ \pi^- p \rightarrow K^- K^0_S p$
1316.0± 2.0	4730	CHABAUD	78	SPEC	−	$18.8\ \pi^- p \rightarrow K^- K^0_S p$
1324.0± 5.0	350	HYAMS	78	ASPK	+	$12.7\ \pi^+ p \rightarrow K^+ K^0_S p$
1318 ± 1		[2,4] MARTIN	78D	SPEC	−	$10\ \pi^- p \rightarrow K^0_S K^- p$
1320.0± 2.0	2724	MARGULIE	76	SPEC	−	$23\ \pi^- p \rightarrow K^- K^0_S p$
1313.0± 4.0	730	FOLEY	72	CNTR	−	$20.3\ \pi^- p \rightarrow K^- K^0_S p$
1319.0± 3.0	1500	[4] GRAYER	71	ASPK	−	$17.2\ \pi^- p \rightarrow K^- K^0_S p$

[2] From a fit to $J^P = 2^+$ partial wave.

[3] Number of events evaluated by us.

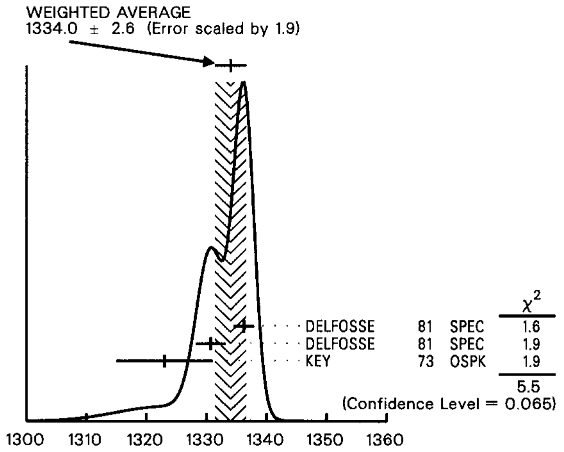
[4] Systematic error in mass scale subtracted.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1334.0±2.6 OUR AVERAGE	Error includes scale factor of 1.9. See the ideogram below.					
1336.2±1.7	2561	DELFOSSE	81	SPEC	+	$\pi^\pm p \rightarrow p \pi^\pm \eta$
1330.7±2.4	1653	DELFOSSE	81	SPEC	−	$\pi^\pm p \rightarrow p \pi^\pm \eta$
1323 ±8	1000	[5] KEY	73	OSPK	−	$6\ \pi^- p \rightarrow p \pi^- \eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1324 ±8	6200	[5,6] CONFORTO	73	OSPK	−	$6\ \pi^- p \rightarrow p\ MM^-$

[5] Error includes 5 MeV systematic mass-scale error.

[6] Missing mass with enriched MMS $= \eta\pi^-$, $\eta = 2\gamma$.



$a_2(1320)$ mass, $\eta\pi$ mode (MeV)

$a_2(1320)$ WIDTH

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
102.7± 2.2 OUR AVERAGE						
107.0± 9.7		AUGUSTIN	89	DM2	±	$e^+ e^- \rightarrow 5\pi$
118.5±12.5		AUGUSTIN	89	DM2	0	$e^+ e^- \rightarrow 5\pi$
97 ± 5		[7] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \rightarrow 3\pi p$
96.0± 9.0	25000	[7] DAUM	80C	SPEC	−	$63,94\ \pi^- p \rightarrow 3\pi p$
110.0±15.0	1097	[7] BALTAY	78B	HBC	+0	$15\ \pi^+ p \rightarrow p 4\pi$
112 ±18	1600	[7] EMMS	75	DBC	0	$4\ \pi^+ n \rightarrow p(3\pi)^0$
122 ±14	1200	[7,8] WAGNER	75	HBC	0	$7\ \pi^+ p \rightarrow \Delta^{++}(3\pi)^0$
115 ±15		[7] ANTIPOV	73C	CNTR	−	$25,40\ \pi^- p \rightarrow p\eta\pi^-$
99 ±15	1580	CHALOUPKA	73	HBC	−	$3.9\ \pi^- p$
105.0± 5.0	28000	BOWEN	71	MMS	−	$5\ \pi^- p$
99.0± 5.0	24000	BOWEN	71	MMS	+	$5\ \pi^+ p$
103.0± 5.0	17000	BOWEN	71	MMS	−	$7\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
115.0±14.0	490	BALTAY	78B	HBC	0	$15\ \pi^+ p \rightarrow \Delta 3\pi$
150.0±20.0		CORDEN	78B	OMEG	−	$12,15\ \pi^- p \rightarrow 3\pi n$
111.4±18.0	360	BARNHAM	71	HBC	+	$3.7\ \pi^+ p \rightarrow (3\pi)^+ p$
100	10000	BINNIE	71	MMS	−	$\pi^- p$ near a_2 threshold
72 ±16	5000	BINNIE	71	MMS	−	$\pi^- p$ near a_2 threshold
79.0±12.0	941	ALSTON-...	70	HBC	+	$7.0\ \pi^+ p \rightarrow 3\pi p$
96.0±16.0	260	ARMENISE	68B	DBC	0	$5.1\ \pi^+ d$

[7] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.

[8] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

$K^\pm K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
110 ± 5 OUR ESTIMATE						
109.8± 2.4 OUR AVERAGE						
121.0±51.0	1000	[9,10] CLELAND	82B	SPEC	+	$30\ \pi^+ p \rightarrow K^0_S K^+ p$
112.0±20.0	4700	[9,10] CLELAND	82B	SPEC	+	$50\ \pi^+ p \rightarrow K^0_S K^+ p$
120.0±25.0	5200	[9,10] CLELAND	82B	SPEC	−	$50\ \pi^- p \rightarrow K^0_S K^- p$
106.0± 4.0	4000	CHABAUD	80	SPEC	−	$17\ \pi^- A \rightarrow K^0_S K^- A$
126.0±11.0	11000	CHABAUD	78	SPEC	−	$9.8\ \pi^- p \rightarrow K^- K^0_S p$
101.0± 8.0	4730	CHABAUD	78	SPEC	−	$18.8\ \pi^- p \rightarrow K^- K^0_S p$
110.0±18.0	350	HYAMS	78	ASPK	+	$12.7\ \pi^+ p \rightarrow K^+ K^0_S p$
113 ± 4		[9,11] MARTIN	78D	SPEC	−	$10\ \pi^- p \rightarrow K^0_S K^- p$
105.0± 8.0	2724	[11] MARGULIE	76	SPEC	−	$23\ \pi^- p \rightarrow K^- K^0_S p$
113.0±19.0	730	FOLEY	72	CNTR	−	$20.3\ \pi^- p \rightarrow K^- K^0_S p$
123.0±13.0	1500	[11] GRAYER	71	ASPK	−	$17.2\ \pi^- p \rightarrow K^- K^0_S p$

[9] From a fit to $J^P = 2^+$ partial wave.

[10] Number of events evaluated by us.

[11] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
113 ±4 OUR AVERAGE						
112.2±5.7	2561	DELFOSSE	81	SPEC	+	$\pi^\pm p \rightarrow p \pi^\pm \eta$
116.6±7.7	1653	DELFOSSE	81	SPEC	−	$\pi^\pm p \rightarrow p \pi^\pm \eta$
108 ±9	1000	KEY	73	OSPK	−	$6\ \pi^- p \rightarrow p \pi^- \eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
104 ±9	6200	[12] CONFORTO	73	OSPK	−	$6\ \pi^- p \rightarrow p\ MM^-$

[12] Model dependent.

$a_2(1320)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\rho\pi$	(70.1±2.7) %	S=1.2
Γ_2	$\eta\pi$	(14.5±1.2) %	
Γ_3	$\omega\pi\pi$	(10.6±3.2) %	S=1.3
Γ_4	$K\overline{K}$	(4.9±0.8) %	
Γ_5	$\pi^\pm\gamma$	(2.7±0.6) × 10^{-3}	
Γ_6	$\gamma\gamma$	(8.2±1.0) × 10^{-6}	
Γ_7	$\pi^+\pi^-\pi^-$	< 8 %	CL=90%
Γ_8	$\eta'(958)\pi$	< 1.0 %	CL=95%
Γ_9	e^+e^-	< 2.3 × 10^{-7}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 18 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 9.3 for 15 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$
\begin{array}{cccc}
x_2 & 10 & & \\
x_3 & -89 & -46 & \\
x_4 & -1 & -2 & -24 \\
 & x_1 & x_2 & x_3
\end{array}
$$

$a_2(1320)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ Γ_5

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
295± 60	CIHANGIR 82	SPEC	+	$200\ \pi^+ A$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
461±110	[12] MAY 77	SPEC	±	$9.7\ \gamma A$

$\Gamma(\gamma\gamma)$ Γ_6

VALUE (keV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.90±0.10 OUR AVERAGE					
0.90±0.27±0.15	56	[13] ALTHOFF 86	TASS	0	$e^+e^- \rightarrow e^+e^-3\pi$
1.14±0.20±0.26		[14] ANTREASYAN 86	CBAL	0	$e^+e^- \rightarrow e^+e^-\pi^0\eta$
1.06±0.18±0.19		BERGER 84C	PLUT	0	$e^+e^- \rightarrow e^+e^-3\pi$
$0.81\pm0.19^{+0.42}_{-0.11}$	35	[13] BEHREND 83B	CELL	0	$e^+e^- \rightarrow e^+e^-3\pi$
0.84±0.07±0.15		[13] FRAZER 83	JADE	0	$e^+e^- \rightarrow e^+e^-3\pi$
0.77±0.18±0.27	22	[14] EDWARDS 82F	CBAL	0	$e^+e^- \rightarrow e^+e^-\pi^0\eta$

[13] From $\rho\pi$ decay mode.
[14] From $\eta\pi^0$ decay mode.

$\Gamma(e^+e^-)$ Γ_9

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<25	90	VOROBYEV 88	ND	$e^+e^- \rightarrow \pi^0\eta$

$a_2(1320)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\rho\pi)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.070±0.012 OUR FIT					
0.078±0.017		CHABAUD 78	RVUE		

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.056±0.014	50	[15] CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$
0.097±0.018	113	[15] ALSTON-... 71	HBC	+	$7.0\ \pi^+ p$
0.06 ±0.03		[15] ABRAMOVI... 70B	HBC	−	$3.93\ \pi^- p$
0.054±0.022		[15] CHUNG 68	HBC	−	$3.2\ \pi^- p$

[15] Included in CHABAUD 78 review.

$\Gamma(\eta\pi)/[\Gamma(\rho\pi) + \Gamma(\eta\pi) + \Gamma(K\overline{K})]$ $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.162±0.012 OUR FIT					
0.140±0.028 OUR AVERAGE					
0.13 ±0.04		ESPIGAT 72	HBC	±	$0.0\ \overline{p}p$
0.15 ±0.04	34	BARNHAM 71	HBC	+	$3.7\ \pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\rho\pi)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.207±0.018 OUR FIT					
0.213±0.020 OUR AVERAGE					
0.18 ±0.05		FORINO 76	HBC		$11\ \pi^- p$
0.22 ±0.05	52	ANTIPOV 73	CNTR	−	$40\ \pi^- p$
0.211±0.044	149	CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$
0.246±0.042	167	ALSTON-... 71	HBC	+	$7.0\ \pi^+ p$
0.25 ±0.09	15	BOECKMANN 70	HBC	+	$5.0\ \pi^+ p$
0.23 ±0.08	22	ASCOLI 68	HBC	−	$5\ \pi^- p$
0.12 ±0.08		CHUNG 68	HBC	−	$3.2\ \pi^- p$
0.22 ±0.09		CONTE 67	HBC	−	$11.0\ \pi^- p$

$\Gamma(\eta'(958)\pi)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.02	97	BARNHAM 71	HBC	+	$3.7\ \pi^+ p$
0.004±0.004		BOESEBECK 68	HBC	+	$8\ \pi^+ p$

$\Gamma(\eta'(958)\pi)/\Gamma(\rho\pi)$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.011	90	EISENSTEIN 73	HBC	−	$5\ \pi^- p$
<0.04		ALSTON-... 71	HBC	+	$7.0\ \pi^+ p$
$0.04\ ^{+0.03}_{-0.04}$		BOECKMANN 70	HBC	0	$5.0\ \pi^+ p$

$\Gamma(K\overline{K})/[\Gamma(\rho\pi) + \Gamma(\eta\pi) + \Gamma(K\overline{K})]$ $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.054±0.009 OUR FIT					
0.048±0.012 OUR AVERAGE					
0.05 ±0.02		TOET 73	HBC	+	$5\ \pi^+ p$
0.09 ±0.04		TOET 73	HBC	0	$5\ \pi^+ p$
0.03 ±0.02	8	DAMERI 72	HBC	−	$11\ \pi^- p$
0.06 ±0.03	17	BARNHAM 71	HBC	+	$3.7\ \pi^+ p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.020±0.004		[16] ESPIGAT 72	HBC	±	$0.0\ \overline{p}p$

[16] Not averaged because of discrepancy between masses from $K\overline{K}$ and $\rho\pi$ modes.

$\Gamma(\pi^+\pi^-\pi^-)/\Gamma(\rho\pi)$ Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.12	90	ABRAMOVI... 70B	HBC	−	$3.93\ \pi^- p$

$\Gamma(\pi^\pm\gamma)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	DOCUMENT ID	TECN	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN	COMMENT
$0.005^{+0.005}_{-0.003}$	[17] EISENBERG 72	HBC	$4.3,5.25,7.5\ \gamma p$

[17] Pion-exchange model used in this estimation.

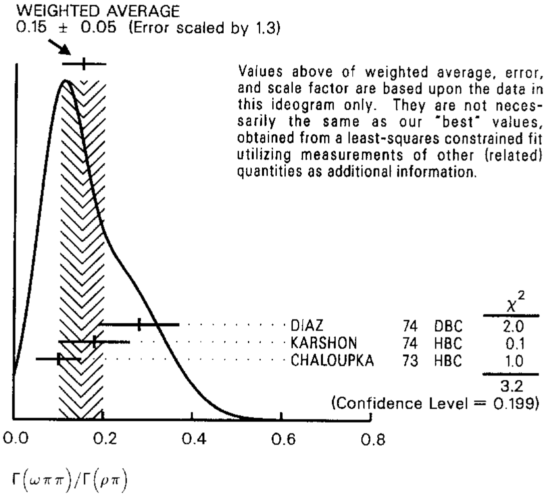
$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.15±0.05 OUR FIT Error includes scale factor of 1.3.					
0.15±0.05 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
0.28±0.09	60	DIAZ 74	DBC	0	$6\ \pi^+ n$
0.18±0.08		[18] KARSHON 74	HBC		Avg. of above two
0.10±0.05	279	CHALOUPKA 73	HBC	−	$3.9\ \pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.29±0.08	140	[18] KARSHON 74	HBC	0	$4.9\ \pi^+ p$
0.10±0.04	60	[18] KARSHON 74	HBC	+	$4.9\ \pi^+ p$
0.19±0.08		DEFOIX 73	HBC	0	$0.7\ \overline{p}p$

[18] KARSHON 74 suggest an additional $I = 0$ state strongly coupled to $\omega\pi\pi$ which could explain discrepancies in branching ratios and masses. We use a central value and a systematic spread.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\eta'(958)\pi)/\Gamma(\eta\pi)$ Γ_8/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.07	95	POULET 90	GAM4	$100\ \pi^- p \rightarrow 4\gamma n$

$a_2(1320)$ REFERENCES

POULET	90	Hadron 89 Conf.	+Boutemeur	(SERP, BELG, LANL, LAPP, PISA, KEK)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
VOROBYEV	88	YAF 48 436	+Golubev, Dolinsky, Druzhinin+	(NOVO)
ALTHOFF	86	ZPHY C31 537	+Boch, Foster, Bernardi+	(TASSO Collab.)
ANTREASYAN	86	PR D33 1847	+Aschman, Besset, Bienlein+	(Crystal Ball Collab.)
BERGER	84C	PL 149B 427	+Klovning, Burger+	(PLUTO Collab.)
BEHREND	83B	PL 125B 518	+D'Agostini+	(DESY, KARL, MPIM, LALO, LPNP+)
FRAZER	83	Aachen Conf.		(UCSD)
CIHANGIR	82	PL 117B 123	+Berg, Biel, Chandlee+	(FNAL, MINN, ROCH)
CLELAND	82B	NP B208 228	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
EDWARDS	82F	PL 110B 82	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
CHABAUD	80	NP B175 189	+Hyams, Papadopoulou+	(CERN, MPIM, AMST)
DAUM	80C	PL 89B 276	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)
CHABAUD	78	NP B145 349	+Hyams, Jones, Weilhammer, Blum+	(CERN, MPIM)
CORDEN	78B	NP B138 235	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
FERRERSORIA	78	PL 74B 287	+Treille+	(ORSA, CERN, CDEF, LPNP)
HYAMS	78	NP B146 303	+Jones, Weilhammer, Blum+	(CERN, MPIM, ATEN)
MARTIN	78D	PL 74B 417	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA) JP
MAY	77	PR D16 1983	+Abramson, Andrews, Busnello+	(ROCH, CORN)
FORINO	76	NC 35A 465	+Gessaroli+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)
MARGULIE	76	PR D14 667	+Kramer, Foley, Love, Lindenbaum+	(BNL, CUNY)
EMMS	75	PL 58B 117	+Jones, Kinson, Stacey, Bell+	(BIRM, DURH, RHEL) JP
WAGNER	75	PL 58B 201	+Tabak, Chew	(LBL) JP
DIAZ	74	PRL 32 260	+Dibianca, Fickinger, Anderson+	(CASE, CMU)
KARSHON	74	PRL 32 852	+Mikenberg, Pitluck, Eisenberg, Ronat+	(REHO)
ANTIPOV	73	NP B63 175	+Ascoli, Busnello, Focacci+	(CERN, SERP) JP
ANTIPOV	73C	NP B63 153	+Ascoli, Busnello, Focacci+	(CERN, SERP) JP
CHALOUPKA	73	PL 44B 211	+Dobrzynski, Ferrando, Losty+	(CERN)

CONFORTO	73	PL 45B 154	+Mobley, Key+	(EFI, FNAL, TNTO, WISC)	
DEFOIX	73	PL 43B 141	+Dobrzynski, Espigat, Nascimento+	(CDEF)	
EISENSTEIN	73	PR D7 278	+Schultz, Ascoli, Ioffredo+	(ILL)	
KEY	73	PRL 30 503	+Conforto, Mobley+	(TNTO, EFI, FNAL, WISC)	
TOET	73	NP B63 248	+Thuan, Major+	(NIJM, BONN, DURH, TORI)	
BLOODWO...	72	NP B37 203	Bloodworth, Jackson, Prentice, Yoon	(TNTO)	
DAMERI	72	NC 9A 1	+Borzatta, Goussu+	(GENO, MILA, SACL)	
EISENBERG	72	PR D5 15	+Ballam, Dagan+	(REHO, SLAC, TELA)	
ESPIGAT	72	NP B36 93	+Ghesquiere, Lillestol, Montanet	(CERN, CDEF)	
FOLEY	72	PR D6 747	+Love, Ozaki, Platner, Lindenbaum+	(BNL, CUNY)	
ALSTON-...	71	PL 34B 156	Alston-Garnjost, Barbaro, Buhl, Derenzo+	(LRL)	
BARNHAM	71	PRL 26 1494	+Abrams, Butler, Coyne, Goldhaber, Hall+	(LBL)	
BINNIE	71	PL 36B 257	+Camilleri, Duane, Faruqi, Burton+	(LOIC, SHMP)	
BOWEN	71	PRL 26 1663	+Earles, Faissler, Blieden+	(NEAS, STON)	
GRAYER	71	PL 34B 333	+Hyams, Jones, Schlein, Blum+	(CERN, MPIM)	
ABRAMOVI...	70B	NP B23 466	Abramovich, Blumenfeld, Bruyant+	(CERN)	JP
ALSTON-...	70	PL 33B 607	Alston-Garnjost, Barbaro, Buhl, Derenzo+	(LRL)	
BOECKMANN	70	NP B16 221	+Major+	(BONN, DURH, NIJM, EPOL, TORI)	
EISENBERG	69	PRL 23 1322	+Haber, Ballam, Chadwick+	(REHO, SLAC)	
ARMENISE	68B	PL 26B 336	+Forino, Cartacci+	(BARI, BGNA, FIRZ, ORSA)	
ASCOLI	68	PRL 20 1321	+Crawley, Mortara, Shapiro, Bridges+	(ILL)	JP
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)	
CHUNG	68	PR 165 1491	+Dahl, Kirz, Miller	(LRL)	
CONTE	67	NC 51A 175	+Tomasini, Cords+	(GENO, HAMB, MILA, SACL)	

OTHER RELATED PAPERS

JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)	
BEHREND	82C	PL 114B 378	+	(DESY, KARL, MPIM, LALO, LPNP+)	
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)	
BALTAY	78E	PRL 40 87	+Cautis, Kalelkar	(COLU)	JP
CORDEN	78C	NP B136 77	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC)	JP
MARTIN	78B	NP B140 158	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)	
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF)	
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL)	IJ
HANDLER	76	NP B110 173	+Plano, Brucker, Koller+	(RUTG, STEV, SETO)	
ABASHIAN	75	PRL 34 691	+Beamer, Bross, Eisenstein+	(ILL, ANL, ISU)	
LOSTY	75	PL 56B 96	+Chaloupka, Montanet, Gandois+	(CERN, SACL)	JP
UNDERWOOD	75	PR D11 2345	+Conforto, Key+	(EFI, FNAL, TNTO, WISC)	
Also	73	PL 45B 154	Conforto, Mobley, Key+	(EFI, FNAL, TNTO, WISC)	
Also	73	PRL 30 503	Key, Conforto, Mobley+	(TNTO, EFI, FNAL, WISC)	
OTTER	74	NP B80 1	+Rudolph+	(AACH, BERL, BONN, CERN, HEID)	JP
THOMPSON	74B	NP B69 381	+Badewitz, Gaidos, McIlwain+	(PURD)	JP
THOMPSON	74D	PR D9 560	+Gaidos, McIlwain, Willmann	(PURD)	JP
AMMANN	73	PR D7 1345	+Carmony, Garfinkel+	(PURD, IUPU)	
ANKENBRA...	73	PR D8 2785	Ankenbrandt, Brabson, Crittenden, Heinz+	(IND)	
ANTIPOV	73B	NP B63 141	+Ascoli, Busnello, Focacci+	(CERN, SERP)	JP
CASON	73B	NP B64 14	+Madden, Bishop, Biswas, Kenney+	(NDAM)	
ANKENBRA...	72B	PRL 29 1688	Ankenbrandt, Brabson, Crittenden, Heinz+	(IND)	
BERENYI	72	NP B37 621	+Prentice, Steenberg, Yoon, Walker	(TNTO, WISC)	
DIEBOLD	72	Batavia Conf. 3 1		(ANL)	
LASSILA	72	PRL 28 1491	+Young	(IOWA)	
MORSE	72	NP B43 77	+Oh, Walker, Johnston, Yoon	(WISC, TNTO)	
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)	
BEKETOV	71	SJNP 4 765	+Sombkowsky, Konovalov, Krutschinin+	(ITEP)	JP
		Translated from unknown journal.			
BINNIE	71B	PL 36B 537	+Camilleri, Duane, Faruqi, Burton+	(LOIC, SHMP)	
CRENNELL	71	PL 35B 185	+Gordon, Lai, Scarr	(BNL)	
FARBER	71	NP B29 237	+DePinto, Biswas, Cason, Deery, Kenney+	(NDAM)	
FOLEY	71	PRL 26 413	+Love, Ozaki, Platner, Lindenbaum+	(BNL, CUNY)	
LYNCH	71	UCRL 20022		(LBL)	
Also 1971 Amsterdam Conference.					
RINAUDO	71	NC 5A 239	+	(TORI, BONN, DURH, NIJM, EPOL)	JP
ASCOLI	70	PRL 25 962	+Brockway, Crawley, Eisenstein, Hanft+	(ILL)	JP
BASILE	70B	LNC 4 838	+Dalpiaz, Frabetti, Massam+	(CERN, BGNA, STRB)	
BAUD	70B	Phil. Conf. 311		(CERN Boson Spectrometer Collab.)	
BAUD	70C	PL 31B 401	+Benz+	(CERN Boson Spectrometer Collab.)	
BAUD	70D	PL 31B 397	+Benz+	(CERN Boson Spectrometer Collab.)	
BUTLER	70	UCRL 19845 Thesis		(LRL)	
CAROLL	70	PRL 25 1393	+Firebaugh, Garfinkel, Morse, Oh+	(WISC, TNTO)	
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)	
DIAZ	70	NP B16 239	+Gavillet, Labrosse, Montanet+	(CERN, CDEF)	JP
DZIERBA	70	PR D2 2544	+Shephard, Biswas, Cason, Johnson+	(NDAM)	
GARFINKEL	70	PL 33B 536	+Ammann, Carmony, Yen	(PURD)	JPC
JOHNSTON	70	NP B24 253	+Key, Prentice, Yoon, Garfinkel+	(TNTO, WISC)	
KRUSE	70	Phil. Conf. 359		(ILL)	JP
SUTHERLAND	70	Phil. Conf. 369		(GLAS)	
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH, BERL, CERN, JAGL, WARS)	
AGUILAR-...	69B	PL 29B 62	Aguilar-Benitez, Barlow+	(CERN, CDEF, LIVP)	
AGUILAR-...	69C	PL 29B 241	Aguilar-Benitez, Barlow+	(CERN, CDEF)	
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)	
ARMENISE	69	LNC 2 501	+Ghidini, Forino, Cartacci+	(BARI, BGNA, FIRZ)	
CHIKOVANI	69	PL 28B 526	+Focacci+	(CERN Missing Mass Spect. Collab.)	JP
CRENNELL	69	PRL 22 1327	+Karshon, Lai+	(BNL)	IJP
DONALD	69B	NP B12 325	+Edwards, Foster, Moore	(LIVP)	
VETLITSKY	69B	SJNP 9 596	+Grigorev, Grishin+	(ITEP)	
		Translated from YAF 9 1018.			
BALLAM	68	PRL 21 934	+Brody, Chadwick, Fries, Guiragossian+	(SLAC)	
BENZ	68	PL 28B 233	+Chikovani+	(CERN Missing Mass Spect. Collab.)	
CASO	68	NC 54A 983	+Conte, Cords, Diaz+	(GENO, HAMB, MILA, SACL)	
CRENNELL	68C	PRL 20 1318	+Karshon, Lai, Scarr, Skillicorn	(BNL)	
DONALD	68	PL 26B 327	+Frodesen, Bettini+	(LIVP, OSLO, PADO)	
FRIDMAN	68	PR 167 1268	+Maurer, Michalon, Oudet+	(HEID, STRB)	
JUNKMANN	68	NP B8 471	+Cocconi+	(AACH, BERL, BONN, CERN, WARS)	
KEY	68	PR 166 1430	+Prentice, Cooper, Manner+	(TNTO, ANL, WISC)	
LAMSA	68	PR 166 1395	+Cason, Biswas, Derado, Groves+	(NDAM)	
VONKROGH	68	PL 27B 253	+Miyashita, Kopelman, Libby	(COLO)	
ARMENISE	67	PL 25B 53	+Forino+	(BARI, BGNA, FIRZ, ORSA)	
BALTAY	67C	PL 25B 160	+Kirsch, Kung, Yeh, Rabin	(COLU, BNL, RUTG)	
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)	
BARTSCH	67	PL 25B 48	+Deutschmann, Grote+	(AACH, BERL, CERN)	
BEUSCH	67	PL 25B 357	+Fischer, Gobbi, Astbury+	(ETH, CERN)	
CASON	67	PRL 18 880	+Lamsa, Biswas, Derado, Groves+	(NDAM)	
CHIKOVANI	67	PL 25B 44	+Focacci+	(CERN Missing Mass Spect. Collab.)	
CHUNG	67	PRL 18 100	+Dahl, Hardy, Hess, Kirz, Miller	(LRL)	
Also	66B	UCRL 16832 Thesis	Hess	(LRL)	
COHN	67	NP B1 57	+McCulloch, Bugg, Condo	(ORNL, TENN)	
CONFORTO	67	NP B3 469	+Marechal+	(CERN, CDEF, IPNP, LIVP)	
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)	
DANYSZ	67B	NC 51A 801	+French, Simak	(CERN)	
SLATTERY	67	NC 50A 377	+Kraybill, Forman, Ferbel	(YALE, ROCH)	JP
BARNES	66	PRL 16 41	+Fowler, Lai, Orenstein+	(BNL, CUNY)	
EHRLICH	66	PR 152 1194	+Selove, Yuta	(PENN)	
FERBEL	66	PL 21 111		(ROCH)	
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)	
ABOLINS	65	Athens Conf.	+Carmony, Lander, Xuong, Yager	(UCSD)	I
ADERHOLZ	65	PR 138B 897		(AACH, BERL, BIRM, BONN, HAMB, LOIC, MPIM)	
ALITTI	65	PL 15 69	+Baton, Deler, Crussard+	(SACL, BGNA)	JP
CHUNG	65	PRL 15 325	+Dahl, Hardy, Hess, Jacobs, Kirz	(LRL)	
FORINO	65B	PL 19 68	+Gessaroli+	(BGNA, BARI, FIRZ, ORSA, SACL)	
LEFEBVRES	65	PL 19 434	+Levrat+	(CERN Missing Mass Spect. Collab.)	
SEIDLITZ	65	PRL 15 217	+Dahl, Miller	(LRL)	
ADERHOLZ	64	PL 10 226	+	(AACH, BERL, BIRM, BONN, DESY, HAMB+)	
CHUNG	64	PRL 12 621	+Dahl, Hardy, Hess, Kalbfleisch, Kirz	(LRL)	
GOLDHABER	64B	Dubna Conf. 1 480	+Goldhaber, O'Halloran, Shen	(LRL)	
Also	64	PRL 12 336	Goldhaber, Brown, Kadyk, Shen+	(LRL, UCB)	
LANDER	64	PRL 13 346A	+Abolins, Carmony, Hendricks, Xuong+	(UCSD)	

$h_1(1380)$

$I^G(J^{PC}) = ?^-(1^{+?})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^0_S K^\pm \pi^\mp$ system. Evidence for $K^* \overline{K} + \overline{K}^* K$ decays (ASTON 88C). Needs confirmation.

$h_1(1380)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1380±20	ASTON	88C	LASS	11 $K^- p \rightarrow K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1380)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
80±30	ASTON	88C	LASS	11 $K^- p \rightarrow K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1380)$ DECAY MODES

	Mode
Γ_1	$K \overline{K}^*(892)$ + *c.c.*

$h_1(1380)$ REFERENCES

ASTON	88C	PL B201 573	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)

$\omega(1390)$

$I^G(J^{PC}) = 0^-(1^{--})$

See also $\omega(1600)$.

$\omega(1390)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1391±18	DONNACHIE	89	RVUE	$e^+ e^- \rightarrow \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1425±25	GOVORKOV	88	RVUE	

$\omega(1390)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
224±49	DONNACHIE	89	RVUE	$e^+ e^- \rightarrow \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300±25	GOVORKOV	88	RVUE	

$\omega(1390)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	$e^+ e^-$	

$\omega(1390)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\mathrm{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{\mathrm{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
137±40	DONNACHIE	89	RVUE	$e^+ e^- \rightarrow \rho\pi$

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\mathrm{total}}$ $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<41	68	DONNACHIE	89	RVUE	$e^+ e^- \rightarrow \omega 2\pi$

$\omega(1390)$ REFERENCES

DONNACHIE 89 ZPHY C42 663 +Clegg (CERN, MCHS)
GOVORKOV 88 SJNP 48 150 (JINR)
Translated from YAF 48 237.

OTHER RELATED PAPERS

ATKINSON 87 ZPHY C34 157 + (BONN, CERN, GLAS, LANC, MCHS, LPNP)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSA)

$f_0(1400)$
was $\epsilon(1300)$

$I^G(J^{PC}) = 0^+(0^{++})$

NOTE ON S-WAVE $\pi\pi$, $K\overline{K}$, AND $\eta\eta$ INTERACTIONS

In this note we discuss results on the nonstrange $I^G J^{PC} = 0^+0^{++}$ partial wave (S wave) coupled to the $\pi\pi$, $K\overline{K}$, and $\eta\eta$ systems.

Up to the ρ meson mass region, the $I = 0$ S-wave phase shift δ_0^0 is (qualitatively) uniquely determined: it rises monotonically and reaches 60° to 70° near 700 MeV. In the early phase shift analyses, based on $\pi^+\pi^- \to \pi^+\pi^-$ data, two solutions for δ_0^0 were found in the 700–900 MeV region. This ambiguity could lead to either a resonance under the ρ meson with mass and width similar to those of the ρ meson [the old $\epsilon(800)$] or to an approximately energy-independent phase shift of about 90°, showing no resonant behavior. Today a narrow $\epsilon(800)$ seems to be ruled out: our present knowledge of the low (and high) energy behavior of δ_0^0 can still be summarized by Figure 1 which shows the CERN-Munich phase shift data (GRAYER 74) together with a fit of AU 87.

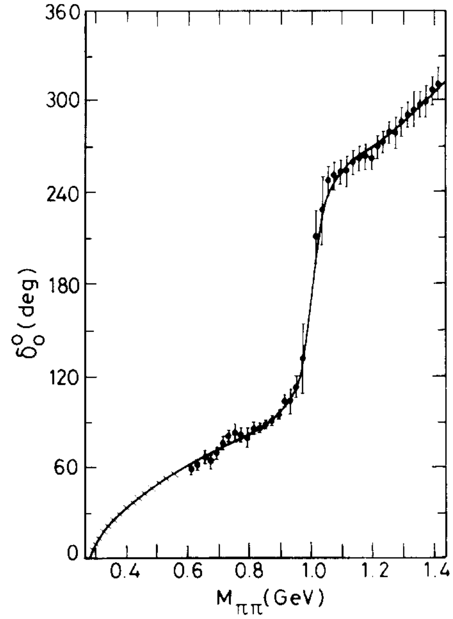


Figure 1. (From AU 87.) The $I = 0$ S-wave phase shift δ_0^0 for $\pi\pi$ scattering from the CERN-Munich group (GRAYER 74). The hatched band represents the continuation down to the threshold provided by the Roy equations. The curve shows a fit typical of all the AU 87 solutions.

Without polarization information, reactions of the type $\pi N \to \pi\pi N$ cannot be analyzed unambiguously since there are more helicity amplitudes than observables. Thus one is obliged to make additional assumptions.

No evidence for a narrow ϵ resonance is obtained in an amplitude analysis (ESTABROOKS 74) of the largest $\pi^- p$ (unpolarized) $\to \pi^+\pi^- n$ experiment (HYAMS 73, GRAYER 74); the analysis assumes both spin and phase coherence. The advent of $\pi^- p$ (polarized) $\to \pi^+\pi^- n$ data (BECKER 79) has made both assumptions unnecessary. Analyzing their data, BECKER 79B also confirms that there is no resonant structure in the phase-shift δ_0^0 below 900 MeV.

CASON 83 disagrees with these results: performing an amplitude analysis of the reaction $\pi^+\pi^- \to \pi^0\pi^0$, with the assumption of one-pion exchange dominance, he concludes that the only way to make $\pi^+\pi^- \to \pi^0\pi^0$ and $\pi^+\pi^- \to \pi^+\pi^-$ data self-consistent is a resonant phase-shift solution; however the phase variation is not well represented by a narrow Breit-Wigner resonance. It should be finally pointed out that this conclusion is in disagreement with several other unextrapolated $\pi^0\pi^0$ data which appear to rule out the existence of the $\epsilon(800)$.

The region of elastic $\pi\pi$ scattering is known to extend to about 990 MeV, near the $K\overline{K}$ threshold; beyond 1 GeV we therefore have to consider the two channels $\pi\pi$ and $K\overline{K}$, and beyond 1100 MeV the $\eta\eta$ channel also opens up. In addition, the solutions have inherent ambiguities related to the Barrelet zeroes of the amplitudes. Thus HYAMS 75 finds four solutions in the region 1.0 to 1.8 GeV, ESTABROOKS 74 finds eight solutions and CORDEN 79, extending the $\pi\pi$ analysis to 2.08 GeV, finds another set of eight solutions. Many of these solutions have been ruled out imposing continuity in various forms as well as analyticity and unitarity (FROGGATT 75 77, COMMON 76, MARTIN 78C).

One notes that a model-independent partial-wave analysis (BECKER 79B on polarized targets) agrees qualitatively with solutions β and β' (of MARTIN 78C).

The β and β' amplitudes describe the experimental moments in each bin without any explicit smoothing: they are analytic in s and approximately analytic in $\cos\theta$. They take into account all waves up to $L = 4$. The β solution has a highly elastic S wave, whereas the S wave of solution β' is somewhat inelastic (MARTIN 78C). The unique solution of FROGGATT 77, which has explicit smoothness built in and which takes into account only $L \leq 3$ waves, is rather similar to β. However, it has problems with unitarity, apparently because of the neglected G wave (MARTIN 78C).

The S wave is clearly resonant in the data of BECKER 79B. In the 1150–1400 MeV region both the S-P and S-D phase differences show the presence of a broad resonance, and the intensity of the S wave confirms this by exhibiting a peak at about 1300 MeV with a width of about 300 MeV.

The amplitude analysis of the $\pi^- p \to \pi^+\pi^- n$ experiment of CORDEN 79 has two preferred solutions which are close to β and β', giving some support for an $f_0(1400)$.

The results on $\pi^+\pi^- \to \pi^0\pi^0$ (CASON 83) establish that the only solutions consistent with the data are β and β', in agreement with BECKER 79B.

A partial wave analysis performed by AKESSON 86 on the exclusive final state $pp \to pp\pi^+\pi^-$, with the two pions produced centrally, shows that the $\pi\pi$ S wave dominates up to 1.6 GeV; furthermore, no room is left for other scalar mesons besides $f_0(975)$ and $f_0(1400)$. However, using the same data and a smaller sample of K^+K^- exclusive events, a coupled channel analysis ($\pi\pi$ and $K\overline{K}$) together with $\pi\pi$ scattering data has led AU 87 to conclude that a trio of resonances near 1 GeV is required, where the naive quark model expects just two (evidence for the lightest scalar glueball?) (see Figure 2 for a typical Argand plot).

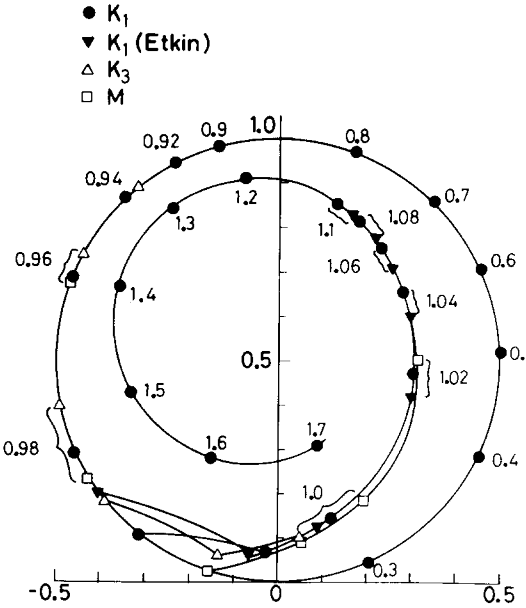


Figure 2. (From AU 87.) The $\pi\pi$ $I = 0$ S-wave amplitude $\rho_1\mathcal{F}_{11}$ shown in an Argand plot comparing the solutions K_1 (•), K_1 (Etkin) (▼), K_3 (△), and M (□). The last three are shown only where they differ from solution K_1. The corresponding energies in GeV are displayed on the plot.

Independent evidence for the $f_0(1400)$ comes from studies of the $K\overline{K}$ and $\eta\eta$ systems. In the reaction $\pi^-p \to K^0_SK^0_Sn$, the S wave has a large intensity in the 1300 MeV region (WETZEL 76, LOVERRE 80, ETKIN 82B) with evidence for a bump. Moreover, the Y^2_0 moment shows a large negative excursion, indicating S-D interference (CASON 76, WETZEL 76, POLYCHRONAKOS 79, GOTTESMAN 80, LOVERRE 80, ETKIN 82B). The main problem is the isospin of the bump; if OPE were the only mechanism, $I = 0$ would be assured. The high statistics experiment (ETKIN 82B) in the restricted t' region below 0.1 GeV^2 strongly argues in favor of OPE dominance and assigns the observed effects to the $I^G = 0^+$ state. A simplified scheme of amplitude analysis in the range 1.6–2.4 GeV has been recently applied to the same reaction $\pi^-p \to K^0_SK^0_Sn$ at 40 GeV (BOLONKIN 88). The S-wave intensity clearly shows evidence for a large structure at about 1400 MeV together with another small signal in the region of the $f_2(1720)$. The mass of the $f_0(1400)$ agrees with the finding of ETKIN 82B in the same channel.

The reaction $\pi^-p \to \eta\eta N$ at 100 GeV has been analyzed in a search for scalar glueball candidates (ALDE 86D). A partial wave analysis shows a bump near threshold in the S-wave amplitude which is naturally associated with the $f_0(1400)$, although its mass is somewhat lower than that of the state decaying into $\pi\pi$ and $K\overline{K}$.

The interpretation of the 0^{++} mesons as members of the $q\overline{q}$ 0^{++} nonet may appear controversial, due to some unconventional experimental properties of such states; to solve this problem, several extensive coupled-channel analyses of $I = 0$ S-wave $\pi\pi$ and $K\overline{K}$ final states have been performed. Rather standard properties for the scalar mesons are obtained by TORNQVIST 82 who finds that they can be understood as conventional $q\overline{q}$ states; the $f_0(975)$ and $f_0(1400)$ have large components of $q\overline{q}q\overline{q}$ in the form of virtual two-meson continuum (mainly $K\overline{K}$). ACHASOV 84 disagrees with these conclusions and finds instead that the two scalar mesons can both be interpreted as $q\overline{q}q\overline{q}$ states. WEINSTEIN 83B 89 on the other hand interpret the $f_0(975)$ as a $K\overline{K}$ molecule bound by hyperfine interaction, leaving the $f_0(1400)$ as a $^3P_0$ $q\overline{q}$ state.

From the experimental point of view, the mass and the width of the $f_0(1400)$ are difficult to extract from these partial wave analyses and also to define in any simple way, since its Breit-Wigner shape is completely distorted by hadronic mass renormalization effects from the $\pi\pi$, $K\overline{K}$, and $\eta\eta$ channels.

$f_0(1400)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
~ 1400 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1440 ±50	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_SK^0_Sn$
1420.0±20.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
1220.0±40.0	ALDE	86D	GAM4	$100\ \pi^-p \to n2\eta$
1463.0± 9.0	ETKIN	82B	MPS	$23\ \pi^-p \to n2K^0_S$
1470.0±10 ±20	[1] ETKIN	82C	MPS	$23\ \pi^-p \to n2K^0_S$
~ 1237	TORNQVIST	82	RVUE	
1425 ±15	WICKLUND	80	SPEC	$6\ \pi N \to K^+K^-N$
~ 1300	POLYCHRO...	79	STRC	$7\ \pi^-p \to n2K^0_S$
1256.0	FROGGATT	77	RVUE	$\pi^+\pi^-$ channel

[1] Fit includes interference with the $f_0(1240)$ resonance.

$f_0(1400)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
150 to 400 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
250 ± 80	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_SK^0_Sn$
460.0± 50.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
320.0± 40.0	ALDE	86D	GAM4	$100\ \pi^-p \to n2\eta$
$118.0^{+138.0}_{-16.0}$	ETKIN	82B	MPS	$23\ \pi^-p \to n2K^0_S$
140.0± 10 ±20	[2] ETKIN	82C	MPS	$23\ \pi^-p \to n2K^0_S$
~ 1400	TORNQVIST	82	RVUE	
160 ± 30	WICKLUND	80	SPEC	$6\ \pi N \to K^+K^-N$
~ 150	POLYCHRO...	79	STRC	$7\ \pi^-p \to n2K^0_S$
~ 400	[3] FROGGATT	77	RVUE	$\pi^+\pi^-$ channel

[2] Fit includes interference with the $f_0(1240)$ resonance.

[3] Width defined as distance between 45 and 135° phase shift.

$f_0(1400)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	$(93.6^{+1.9}_{-1.5})$ %
Γ_2	$K\overline{K}$	(7.5 ± 0.9) %
Γ_3	$\eta\eta$	seen
Γ_4	e^+e^-	not seen

$f_0(1400)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_4

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<20	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(1400)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.936^{+0.019}_{-0.015}$	GORLICH	80	ASPK	17,18 $\pi^- p$ polarized
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.93	TORNQVIST	82	RVUE	
0.93	LOVERRE	80	HBC	4 $\pi^- p \to K\overline{K}N$
0.73	HYAMS	75	ASPK	17.2 $\pi^- p \to n\pi^+\pi^-$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.01	COSTA...	80	OMEG	10 $\pi^- p \to K^+K^-n$

$f_0(1400)$ REFERENCES

BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
VOROBYEV	88	YAF 48 436	+Golubev, Dolinsky, Druzhinin+	(NOVO)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
TORNQVIST	82	PRL 49 624		(HELS)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH) IJP
WICKLUND	80	PRL 45 1469	+Ayres, Cohen, Diebold, Pawlicki	(ANL)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL) IJP
FROGGATT	77	NP B129 89	+Petersen	(GLAS, NORD)
HYAMS	75	NP B100 205	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)

OTHER RELATED PAPERS

WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ALDE	88	PL B201 160	+Bellazini, Binon+	(SERP, BELG, LANL, LAPP, PISA)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
ACHASOV	84	ZPHY C22 53	+Devyanin, Shestakov	(NOVO)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
GOTTESMAN	80	PR D22 1503	+Jacobs+	(SYRA, BRAN, BNL, CINC)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
BECKER	79B	NP B150 301	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
MARTIN	78C	ANP 114 1	+Pennington	(CERN)
CASON	76	PRL 36 1485	+Polychronakos, Bishop, Biswas+	(NDAM, ANL) IJ
COMMON	76	NP B103 109		(KENT) JP
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
FROGGATT	75	NP B91 454	+Petersen	(GLAS, NORD)
ESTABROOKS	74	NP B79 301	+Martin	(DURH)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)

$\hat{\rho}(1405)$

$I^G(J^{PC}) = 1^-(1^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by ALDE 88B in $\pi^- p \to \eta\pi^0 n$ amplitude analysis. Needs confirmation.

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\hat{\rho}(1405)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1406±20	ALDE[1]	88B	GAM4	0	100 $\pi^- p \to \eta\pi^0 n$

[1] Seen in the P_0-wave intensity of the $\eta\pi^0$ system.

$\hat{\rho}(1405)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
180±20	ALDE[2]	88B	GAM4	0	100 $\pi^- p \to \eta\pi^0 n$

[2] Seen in the P_0-wave intensity of the $\eta\pi^0$ system.

$\hat{\rho}(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\rho\pi$	not seen
Γ_3	$\eta'\pi$	

$\hat{\rho}(1405)$ BRANCHING RATIOS

$\Gamma(\eta\pi^0)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ALDE[3]	88B	GAM4	0	100 $\pi^- p \to \eta\pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen	APEL[4]	81	NICE	0	40 $\pi^- p \to \eta\pi^0 n$

[3] Seen in the P_0-wave intensity of the $\eta\pi^0$ system.

[4] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\rho\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		COMMENT
not seen	ZIELINSKI[5]	86	200 π^+ Cu,Pb $\to \pi^+\pi^+\pi^-$ X

[5] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\eta'\pi)/\Gamma(\eta\pi^0)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.80	95	POULET	90	GAM4	100 $\pi^- p \to 4\gamma n$

$\hat{\rho}(1405)$ REFERENCES

POULET	90	Hadron 89 Conf.	+Boutemeur	(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	88B	PL B205 397	+Binon, Boutemeur+	(SERP, BELG, LANL, LAPP) IGJPC
ZIELINSKI	86	Berkeley HEP 1 736	+Berg+	(ROCH, MINN, FNAL)
APEL	81	NP B193 269	+Augenstein, Bertolucci, Donskov+	(SERP, CERN)

OTHER RELATED PAPERS

IDDIR	88	PL B205 564	+Le Yaouanc, Ono+	(LPTP, TOKY)
TUAN	88	PL B213 537	+Ferbel, Dalitz	(HAWA, ROCH, OXF)
ZIELINSKI	87	ZPHY C34 255		(ROCH)
ZIELINSKI	86	Berkeley HEP 1 736	+Berg+	(ROCH, MINN, FNAL)

$f_1(1420)$
was $E(1420)$

$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

NOTE ON $f_1(1420)$

In hadron-induced reactions, the $f_1(1420)$ is observed in centrally produced $K\overline{K}\pi$ systems (DIONISI 80, ARMSTRONG 84, 89) obtained with π and p beams. A Dalitz-plot analysis gives its quantum numbers and the dominant decay mode. For instance, ARMSTRONG 89 finds that the signal is totally consistent with being an 1^{++} state, with a dominant quasi-two-body S-wave decay mode into $K^*(892)\overline{K}$; furthermore, no 0^{-+} or 1^{+-} waves are required to describe the data. A G-parity $= +1$ is suggested by the positive interference between the two $K^*(892)$ (ARMSTRONG 84). No significant signals in the $\eta\pi\pi$ or 4π decay modes are found by ARMSTRONG 89G in centrally produced 4π systems.

In $\gamma\gamma$ fusion from e^+e^- annihilations, a signal at $\approx$ 1420 MeV is seen only in single tag events (AIHARA 86C, GIDAL 87B, BEHREND 89, HILL 89) where one of the two photons is off the mass shell; on the contrary, it is totally absent in the untagged events where both photons are real and hence they cannot produce a spin-1 meson because of the Yang-Landau theorem. This clearly implies $J = 1$ and $C = +1$. As for the parity, AIHARA 88B, 88C (same analysis as AIHARA 86C, with 25% more statistics) and BEHREND 89 all find from the angular distributions that positive parity is preferred, but negative cannot be excluded.

Although some uncertainties still remain, these two experimental observations (the state seen in hadronic interactions and the one observed in spacelike virtual photon fusion from e^+e^- annihilations) are often identified since there are more similarities than differences. In particular, all experiments agree that this state shows up only in $K^*(892)\overline{K}$.

BITYUKOV 88 has studied the radiative decay $1^{++} \to \phi\gamma$. Since the ϕ is (almost) a pure $s\overline{s}$ state, the $\phi\gamma$ decay seems to be a good analyser to extract the $s\overline{s}$ component in the wave function of the decaying meson. From the observation of an $f_1(1285)$ and the absence of an $f_1(1420)$ signal in the $\phi\gamma$ mass spectrum, BITYUKOV 88 concludes that the $f_1(1420)$ cannot be the $s\overline{s}$ isoscalar member of the axial-vector $q\overline{q}$ nonet of the $f_1(1285)$. On the other hand AIHARA 88C argues that, with the assumption that they both belong to the same nonet and using several hypotheses, the obtained octet-singlet mixing angle turns out to be compatible with the $f_1(1420)$ being mostly $s\overline{s}$, and $f_1(1285)$ mostly $(u\overline{u} + d\overline{d})/\sqrt{2}$, although both requiring large admixtures of other $q\overline{q}$ components.

Arguments in favor of the possibility that the $f_1(1420)$ is a hybrid $q\overline{q}g$ meson or a four-quark state are put forward by ISHIDA 89 and CALDWELL 90 respectively.

$f_1(1420)$ MASS

PRODUCED IN $p\overline{p}$ ANNIHILATION

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1414.9± 3.5 OUR AVERAGE		Error includes scale factor of 1.2.		
1417.5± 4		NACASCH 78	HBC	0.7,0.76 $\overline{p}p$
1398 ±10	170	DEFOIX 72	HBC	0.7 $\overline{p}p \to 7\pi$
1406 ± 7	280	DUBOC 72	HBC	1.2 $\overline{p}p \to 2K4\pi$
1420 ± 7	310	LORSTAD 69	HBC	0.7 $\overline{p}p$
1423.0±10.0		FRENCH 67	HBC	3–4 $\overline{p}p$

PRODUCED IN OTHER REACTIONS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1425.3± 1.3 OUR AVERAGE				
1429 ± 3	389 ± 27	ARMSTRONG 89	OMEG	300 $pp \to K\overline{K}\pi pp$
1425 ±10	17	BEHREND 89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
1442 ± $5.0^{+10.0}_{-17.0}$	111^{+31}_{-26}	BECKER 87	MRK3	e^+e^-, $\omega K\overline{K}\pi$
1423 ± 4		GIDAL 87B	MRK2	$e^+e^- \to e^+e^- K\overline{K}\pi$
1417.0±13.0	13	AIHARA 86C	TPC	$e^+e^- \to e^+e^- K\overline{K}\pi$
1425.0± 2.0	1520	ARMSTRONG 84	OMEG	85 π^+p, $pp \to (\pi^+, p)(K\overline{K}\pi)$
1422.0± 3.0		CHAUVAT 84	SPEC	ISR 31.5 pp
1440.0±10.0		[1] BROMBERG 80	SPEC	100 $\pi^-p \to K\overline{K}\pi X$
1426.0± 6.0	221	DIONISI 80	HBC	4 $\pi^-p \to K\overline{K}\pi n$
1420 ±20		DAHL 67	HBC	1.6–4.2 π^-p

[1] Mass error increased to account for $a_0(980)$ mass cut uncertainties.

$f_1(1420)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
55.3± 3.0 OUR AVERAGE				
58 ± 8	389 ± 27	ARMSTRONG 89	OMEG	300 $pp \to K\overline{K}\pi pp$
42 ±22	17	BEHREND 89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
40 $^{+17}_{-13}$ ±5	111^{+31}_{-26}	BECKER 87	MRK3	e^+e^-, $\omega K\overline{K}\pi$
$35.0^{+47.0}_{-20.0}$	13	AIHARA 86C	TPC	$e^+e^- \to e^+e^- K\overline{K}\pi$
62.0± 5.0	1520	ARMSTRONG 84	OMEG	85 π^+p, $pp \to (\pi^+, p)(K\overline{K}\pi)$
47.0±10.0		CHAUVAT 84	SPEC	ISR 31.5 pp
62.0±14.0		BROMBERG 80	SPEC	100 $\pi^-p \to K\overline{K}\pi X$
40.0±15.0	221	DIONISI 80	HBC	4 $\pi^-p \to K\overline{K}\pi n$
53 ±20.0		NACASCH 78	HBC	0.7,0.76 $\overline{p}p$
50 ±10	170	DEFOIX 72	HBC	0.7 $\overline{p}p \to 7\pi$
50 ±12	280	DUBOC 72	HBC	1.2 $\overline{p}p \to 2K4\pi$
60 ±20	310	LORSTAD 69	HBC	0.7 $\overline{p}p$
60.0±20.0		DAHL 67	HBC	1.6–4.2 π^-p
45 ±20		FRENCH 67	HBC	3–4 $\overline{p}p$

$f_1(1420)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}\pi$	dominant
Γ_2	$\eta\pi\pi$	possibly seen
Γ_3	$a_0(980)\pi$	possibly seen
Γ_4	$\pi\pi\rho$	
Γ_5	$K\overline{K}^*(892)$ + c.c.	
Γ_6	4π	
Γ_7	$\gamma\gamma$	

$f_1(1420)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.5±0.4 OUR AVERAGE				
$2.3^{+1.0}_{-0.9}$±0.8		HILL 89	JADE	$e^+e^- \to e^+e^- K^\pm K^0_S \pi^\mp$
1.3±0.5±0.3		AIHARA 88B	TPC	$e^+e^- \to e^+e^- K^\pm K^0_S \pi^\mp$
1.6±0.7±0.3		[2,3] GIDAL 87B	MRK2	$e^+e^- \to e^+e^- K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.0	95	JENNI 83	MRK2	$e^+e^- \to e^+e^- K\overline{K}\pi$

[2] Assume a ρ-pole form factor.
[3] Published value divided by 2.

$f_1(1420)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(K\overline{K}\pi)$ — Γ_5/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.76±0.06	BROMBERG 80	SPEC	100 $\pi^-p \to K\overline{K}\pi X$
0.86±0.12	DIONISI 80	HBC	4 $\pi^-p \to K\overline{K}\pi n$

$\Gamma(\pi\pi\rho)/\Gamma(K\overline{K}\pi)$ — Γ_4/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.3	95	CORDEN 78	OMEG	12–15 π^-p
<2.0		DAHL 67	HBC	1.6–4.2 π^-p

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ — Γ_2/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.6	90	GIDAL 87	MRK2	$e^+e^- \to e^+e^- \eta\pi^+\pi^-$
<0.5	95	CORDEN 78	OMEG	12–15 π^-p
1.5±0.8		DEFOIX 72	HBC	0.7 $\overline{p}p$
<1.5	95	FOSTER 68B	HBC	0.0 $\overline{p}p$

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ — Γ_3/Γ_2

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
not seen in either mode	ANDO 86	SPEC	8 π^-p
not seen in either mode	CORDEN 78	OMEG	12–15 π^-p
0.4±0.2	DEFOIX 72	HBC	0.7 $\overline{p}p \to 7\pi$

$\Gamma(4\pi)/\Gamma(K\overline{K}^*(892) + \text{c.c.})$ — Γ_6/Γ_5

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.90	95	DIONISI 80	HBC	4 π^-p

$\Gamma(K\overline{K}\pi)/[\Gamma(a_0(980)\pi) + \Gamma(K\overline{K}^*(892) + \text{c.c.})]$ $\Gamma_1/(\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.65 ± 0.27	[4] DIONISI	80	HBC	$4\ \pi^- p$

[4] Calculated using $\Gamma(K\overline{K})/\Gamma(\eta\pi) = 0.24 \pm 0.07$ for $a_0(980)$ fractions.

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}^*(892) + \text{c.c.})$ Γ_3/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	68	ARMSTRONG	84	OMEG	$85\ \pi^+ p$

$\Gamma(4\pi)/\Gamma(K\overline{K}\pi)$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.62	95	ARMSTRONG	89G	OMEG	$85\ \pi p \to 4\pi X$

$f_1(1420)$ REFERENCES

ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP) JPC
ARMSTRONG	89G	ZPHY C43 55	+Bloodworth	(CERN, BIRM, BARI, ATHU, LPNP)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
HILL	89	ZPHY C42 355	+Olsson+	(JADE Collab.) JP
AIHARA	88B	PL B209 107	+Alston-Garnjost+	(TPC-2γ Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.) JP
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
GIDAL	87B	PRL 59 2016	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
AIHARA	86C	PRL 57 2500	+Alston-Garnjost+	(TPC-2γ Collab.) JP
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN) JP
CHAUVAT	84	PL 148B 382	+Meritet, Bonino+	(CERN, UDCF, UCLA, SACL)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
BROMBERG	80	PR D22 1513	+Haggerty, Abrams, Dzierba	(CIT, FNAL, ILLC, IND)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH) IJP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
NACASCH	78	NP B135 203	+Defoix, Dobrzynski+	(PARI, MADR, CERN)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(LPNP, LIVP)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN) JP
FOSTER	68B	NP B8 174	+Gavillet, Labrosse, Montanet+	(CERN, CDEF)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL) IJP
Also	65	PRL 14 1074	Miller, Chung, Dahl, Hess, Hardy, Kirz+	(LRL, UCB)
FRENCH	67	NC 52A 438	+Kinson, McDonald, Riddiford+	(CERN, BIRM)

OTHER RELATED PAPERS

CALDWELL	90	Hadron 89		(UCSB)
ISHIDA	89	PTP 82 119	+Oda, Sawazaki, Yamada	(TNIH)
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.) JPC
BITYUKOV	88	PL B203 327	+Borisov, Dorofeev+	(SERP)
PROTOPOP...	87B	Hadron 87 Conf.	Protopopescu, Chung	(BNL)

$f_2(1430)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

This entry lists nearby peaks observed in the D wave of the $K\overline{K}$ and $\pi^+\pi^-$ systems.

$f_2(1430)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1421\ \pm 5$	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1480.0 ± 50.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
$1436.0^{+26.0}_{-16.0}$	DAUM	84	CNTR	$17\text{–}18\ \pi^- p \to K^+K^- n$
$1412.0\pm\ 3.0$	DAUM	84	CNTR	$63\ \pi^- p \to K^0_S K^0_S n, K^+K^- n$
$1439.0^{+\ 5.0}_{-\ 6.0}$	[1] BEUSCH	67	OSPK	$5.7{,}12\ \pi^- p \to K^0_S K^0_S n$

[1] Not seen by WETZEL 76.

$f_2(1430)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$30\ \pm 9$	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
150.0 ± 40.0	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
$81.0^{+56.0}_{-29.0}$	DAUM	84	CNTR	$17\text{–}18\ \pi^- p \to K^+K^- n$
$14.0\pm\ 6.0$	DAUM	84	CNTR	$63\ \pi^- p \to K^0_S K^0_S n, K^+K^- n$
$43.0^{+17.0}_{-18.0}$	[2] BEUSCH	67	OSPK	$5.7{,}12\ \pi^- p \to K^0_S K^0_S n$

[2] Not seen by WETZEL 76.

$f_2(1430)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\pi\pi$

$f_2(1430)$ REFERENCES

AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
DAUM	84	ZPHY C23 339	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
BEUSCH	67	PL 25B 357	+Fischer, Gobbi, Astbury+	(ETH, CERN)

$\eta(1440)$
was $\iota(1440)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

NOTE ON $\eta(1440)$

The first observation of a meson with $I^GJ^{PC} = 0^+0^{-+}$ in the 1400 MeV mass region was made with $p\overline{p}$ annihilations at rest (BAILLON 67) in the channel $\eta(1440) \to K\overline{K}\pi$. It was seen to decay equally into $a_0(980)\pi$ and $\overline{K}^*(892)K$.

The $\eta(1440)$ is now observed in other hadronic reactions: in a partial-wave analysis of the $\eta\pi^+\pi^-$ system, confirming the decay $\eta(1440) \to a_0(980)\pi$ (TAKAMATSU 90), and in a partial-wave analysis of the $K\overline{K}\pi$ system (CHUNG 85, BIRMAN 88). It is also observed in 6 GeV $p\overline{p}$ annihilation (REEVES 86) and in nonperipherally selected $\pi^- p \to K^0_S K^0_S \pi^0 n$ (RATH 89). A resonance in this mass region is observed in $\overline{p}p$ annihilation at rest (DUCH 89), with no definite conclusions on its quantum numbers (although the data are incompatible with a dominant $\overline{K}^*(892)K$ decay mode).

It is, however, not observed in the $s\overline{s}$-enriched peripheral reaction $K^- p \to K\overline{K}\pi\Lambda$ at 11 GeV/c (ASTON 87). Similarly ARMSTRONG 84, 89, studying $K\overline{K}\pi$ central production in $\pi^+ p \to \pi^+(K\overline{K}\pi)p$ and $pp \to p(K\overline{K}\pi)p$ at 85 and 300 GeV/c, do not see the $\eta(1440)$, but the $f_1(1420)$ which is found to be mainly coupled to $\overline{K}^*(892)K$. This is in line with earlier results (DIONISI 80, DEFOIX 72, DUBOC 72, LORSTAD 69, etc.). Note that these earlier data were also dominated by central processes.

The $\eta(1440)$ is also present as a broad enhancement in the $J/\psi(1S)$ radiative decay. In the $K\overline{K}\pi$ channel, however, its mass is higher than observed in hadronic interactions, and its width is larger. It has been shown (TOKI 87) that a two-Breit-Wigner fit (with $M = 1420$ MeV and $M = 1500$ MeV) would give a better description of the data. Moreover, the $\eta\pi^+\pi^-$ channel peaks at 1390 MeV as well as the $\rho^0\gamma$ channel (TOKI 87). A similar conclusion is reached in a large statistics BNL experiment (ZIEMINSKA 88) from a partial-wave analysis of the $K\overline{K}\pi$ system in hadroproduction, where the $0^{-+}a_0(980)$ and the $0^{-+}(K^*(892))$ waves are found to have different mass dependence in the $\eta(1440)$ region.

Also RATH 89 favors the interpretation of two narrow η resonances in the 1410–1480 MeV region with widths of approximately 20 and 50 MeV.

In the present situation, we list under $\eta(1440)$ all the results obtained on the 0^{-+} system in the 1380–1480 MeV mass region.

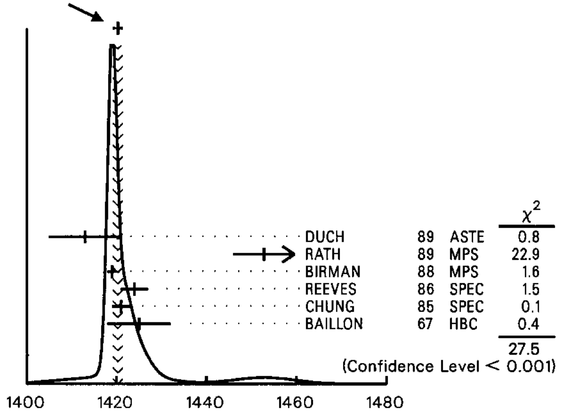
$\eta(1440)$ MASS

VALUE (MeV)	DOCUMENT ID
1440±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY HADRON BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1420.3±1.1 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
1413 ±8	500	DUCH	89	ASTE	$\overline{p}p \rightarrow \pi^+\pi^- K^\pm \pi^\mp K^0$
1452.8±6.8	170 ± 15	[1] RATH	89	MPS	$21.4\ \pi^- p \rightarrow K^0_S K^0_S \pi^0 n$
1419 ±1	8800 ± 200	[2] BIRMAN	88	MPS	$8\ \pi^- p \rightarrow K^+ \overline{K}^0 \pi^- n$
1424.0±3.0	620	REEVES	86	SPEC	$6.6\ p\overline{p} \rightarrow K K \pi X$
1421.0±2.0		CHUNG	85	SPEC	$8\ \pi^- p \rightarrow K \overline{K} \pi n$
1425 ±7		BAILLON	67	HBC	$0.0\ \overline{p}p \rightarrow K \overline{K} \pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1424 ±4		TAKAMATSU	90	SPEC	$8\ \pi^- p \rightarrow a_0(980) \pi n$
1443 ±5		TAKAMATSU	90	SPEC	$8\ \pi^- p \rightarrow K^*(892) \overline{K} n$
1388 ±4		[3] TAKAMATSU	90	SPEC	$9\ \pi^- p \rightarrow \eta \pi^+ \pi^- n$
1420 ±5		ANDO	86	SPEC	$8\ \pi^- p \rightarrow n \eta \pi^+ \pi^-$

WEIGHTED AVERAGE
1420.3 ± 1.1 (Error scaled by 1.3)



$\eta(1440)$ mass, produced by hadron beam (MeV)

PRODUCED IN $J/\psi(1S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1451.9± 2.5 OUR AVERAGE	Error includes scale factor of 1.1.				
1454 ± 3		WISNIEWSKI	87	MRK3	$J/\psi \rightarrow K \overline{K} \pi \gamma$
1444.0± 7.0		AUGUSTIN	85	DM2	$J/\psi \rightarrow K^+ K^- \pi^0 \gamma$
1454.0± 5.0		AUGUSTIN	85	DM2	$J/\psi \rightarrow K^0_S K^\pm \pi^\mp \gamma$
$1440.0^{+20.0}_{-15.0}$	174	EDWARDS	82E	CBAL	$J/\psi \rightarrow K^+ K^- \pi^0 \gamma$
$1440.0^{+10.0}_{-15.0}$		SCHARRE	80	MRK2	$J/\psi \rightarrow K^0_S K^\pm \pi^\mp \gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1420.0±15.0±20.0		[4] RICHMAN	85	MRK3	$J/\psi \rightarrow \pi^+ \pi^- 2\gamma$

[1] Best fit with a single Breit Wigner.
[2] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.
[3] This result supersedes ANDO 86.
[4] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

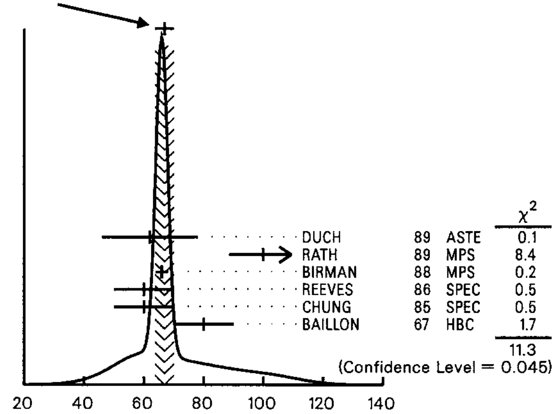
$\eta(1440)$ WIDTH

VALUE (MeV)	DOCUMENT ID
60±30 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY HADRON BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
66.9± 3.1 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.					
62 ±16	500	DUCH	89	ASTE		$\overline{p}p \rightarrow \pi^+\pi^- K^\pm \pi^\mp K^0$
99.9±11.4	170 ± 15	[5] RATH	89	MPS		$21.4\ \pi^- p \rightarrow K^0_S K^0_S \pi^0 n$
66 ± 2	8800 ± 200	BIRMAN	88	MPS		$8\ \pi^- p \rightarrow K^+ \overline{K}^0 \pi^- n$
60.0±10.0	620	REEVES	86	SPEC		$6.6\ p\overline{p} \rightarrow K K \pi X$
60.0±10.0		CHUNG	85	SPEC		$8\ \pi^- p \rightarrow K \overline{K} \pi n$
80 ±10		BAILLON	67	HBC		$0.0\ \overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
82 ± 8		TAKAMATSU	90	SPEC	0	$8\ \pi^- p \rightarrow a_0(980) \pi n$
57 ± 8		TAKAMATSU	90	SPEC	0	$8\ \pi^- p \rightarrow K^*(892) \overline{K} n$
59 ± 4		[6] TAKAMATSU	90	SPEC	0	$9\ \pi^- p \rightarrow \eta \pi^+ \pi^- n$
31 ± 7		ANDO	86	SPEC		$8\ \pi^- p \rightarrow n \eta \pi^+ \pi^-$

WEIGHTED AVERAGE
66.9 ± 3.1 (Error scaled by 1.7)



$\eta(1440)$ width, produced by hadron beam (MeV)

PRODUCED IN $J/\psi(1S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
160 ±11		WISNIEWSKI	87	MRK3	$J/\psi \rightarrow K \overline{K} \pi \gamma$
95.0±10.0		AUGUSTIN	85	DM2	$J/\psi \rightarrow K^+ K^- \pi^0 \gamma$
92.0±16.0		AUGUSTIN	85	DM2	$J/\psi \rightarrow K^0_S K^\pm \pi^\mp \gamma$
133.0±55 ±30		[7] RICHMAN	85	MRK3	$J/\psi \rightarrow \pi^+ \pi^- 2\gamma$
$55.0^{+20.0}_{-30.0}$	174	EDWARDS	82E	CBAL	$J/\psi \rightarrow K^+ K^- \pi^0 \gamma$
$50.0^{+30.0}_{-20.0}$		SCHARRE	80	MRK2	$J/\psi \rightarrow K^0_S K^\pm \pi^\mp \gamma$

[5] Best fit with a single Breit Wigner.
[6] This result supersedes ANDO 86.
[7] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

$\eta(1440)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K \overline{K} \pi$	seen
Γ_2	$\eta \pi \pi$	seen
Γ_3	$a_0(980) \pi$	seen
Γ_4	$\pi \pi \rho$	
Γ_5	$K \overline{K}^*(892)$ + c.c.	
Γ_6	4π	
Γ_7	$\gamma\gamma$	
Γ_8	$\rho^0 \gamma$	

$\eta(1440)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.2	95	BEHREND	89	CELL	$\gamma\gamma \rightarrow K^0_S K^\pm \pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	95	AIHARA	86D	TPC	$e^+ e^- \rightarrow e^+ e^- K^0_S K^\pm \pi^\mp$
<2.2	95	ALTHOFF	85B	TASS	$e^+ e^- \rightarrow e^+ e^- K \overline{K} \pi$
<8.0	95	JENNI	83	MRK2	$e^+ e^- \rightarrow e^+ e^- K \overline{K} \pi$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_2\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.3	ANTREASYAN	87	CBAL	$e^+ e^- \rightarrow e^+ e^- \eta \pi \pi$

$\Gamma(\rho^0\gamma) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_8\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5	95	ALTHOFF	84E	TASS	$e^+ e^- \rightarrow e^+ e^- \pi^+ \pi^- \gamma$

η(1440) BRANCHING RATIOS

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.5	90	EDWARDS 83B	CBAL	$J/\psi \to \eta\pi\pi\gamma$
<1.1	90	SCHARRE 80	MRK2	$J/\psi \to \eta\pi\pi\gamma$

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}\pi)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
~ 0.8	500	[8] DUCH 89	ASTE	$\bar{p}p \to \pi^+\pi^- K^\pm \pi^\mp K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.75		[8] REEVES 86	SPEC	6.6 $p\overline{p} \to K K \pi X$

[8] Assuming that the $a_0(980)$ decays only into $K\overline{K}$.

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(K\overline{K}\pi)$ Γ_5/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.50±0.10	BAILLON 67	HBC	0.0 $\overline{p}p$

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/[\Gamma(a_0(980)\pi) + \Gamma(K\overline{K}^*(892) + \text{c.c.})]$ $\Gamma_5/(\Gamma_3+\Gamma_5)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.25	90	EDWARDS 82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$

η(1440) REFERENCES

TAKAMATSU 90 Hadron 89 Conf. +Ando+ (KEK)
BEHREND 89 ZPHY C42 367 +Criegee+ (CELLO Collab.)
DUCH 89 ZPHY 45 223 +Heel, Bailey+ (ASTERIX Collab.) JP
RATH 89 PR D40 693 +Cason+ (NDAM, BRAN, BNL, CUNY, DUKE)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, SMAS) JP
ANTREASYAN 87 PR D36 2633 +Bartels, Besset+ (Crystal Ball Collab.)
WISNIEWSKI 87 CALT-68-1446 (Mark III Collab.)
AIHARA 86D PRL 57 51 +Alston-Garnjost+ (TPC-2γ Collab.)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, TOKY, TSUK+) IJP
REEVES 86 PR 34 1960 +Chung, Crittenden+ (FLOR, BNL, IND, SMAS) JP
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
AUGUSTIN 85 Moriond XX 1 479 +Calcaterra, Cosme+ (ORSA, CLER, PADO, FRAS)
CHUNG 85 PRL 55 779 +Fernow, Boehnlein+ (BNL, FLOR, IND, SMAS) JP
RICHMAN 85 Moriond XX Conf. (CIT)
ALTHOFF 84E PL 147B 487 +Braunschweig, Kirschfink, Luebelsmeyer+ (TASSO Collab.)
EDWARDS 83B PRL 51 859 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
JENNI 83 PR D27 1031 +Burke, Telnov, Abrams, Blocker+ (SLAC, LBL)
EDWARDS 82E PRL 49 259 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
Also 83 PRL 50 219 Edwards, Partridge+ (CIT, HARV, PRIN, STAN+)
SCHARRE 80 PL 97B 329 +Trilling, Abrams, Alam, Blocker+ (SLAC, LBL)
BAILLON 67 NC 50A 393 +Edwards, D'Andlau, Astier+ (CERN, CDEF, IRAD)

OTHER RELATED PAPERS

AHMAD 89 NP B (PROC.)8 50 +Amsler, Auld+ (ASTERIX Collab.)
ARMSTRONG 89 PL B221 216 +Benayoun+ (CERN, CDEF, BIRM, BARI, ATHU, LPNP)
ZIEMINSKA 88 AIP Conf. (IND)
ARMSTRONG 87 ZPHY C34 23 +Bloodworth+ (CERN, BIRM, BARI, ATHU, LPNP)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
PROTOPOP... 87B Hadron 87 Conf. Protopopescu, Chung (BNL)
TOKI 87 Hadron 87 Conf. (TOKY)
ARMSTRONG 84 PL 146B 273 +Bloodworth, Burns+ (ATHU, BARI, BIRM, CERN)
DIONISI 80 NP B169 1 +Gavillet+ (CERN, MADR, CDEF, STOH)
DEFOIX 72 NP B44 125 +Nascimento, Bizzarri+ (CDEF, CERN)
DUBOC 72 NP B46 429 +Goldberg, Makowski, Donald+ (LPNP, LIVP)
LORSTAD 69 NP B14 63 +D'Andlau, Astier+ (CDEF, CERN)

ρ(1450)

$I^G(J^{PC}) = 1^+(1^{--})$

See the mini-review under the ρ(1700).

ρ(1450) MASS

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1450± 8 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.		
1470±20	ANTONELLI 88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
1446±10	FUKUI 88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

MIXED MODES

VALUE (MeV)	DOCUMENT ID	TECN
The data in this block is included in the average printed for a previous datablock.		
1465±25	DONNACHIE 87	RVUE
• • • We do not use the following data for averages, fits, limits, etc. • • •		
1425±25	GOVORKOV 88	RVUE

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
1424±25	BISELLO 89	DM2	$e^+e^- \to \pi^+\pi^-$

$\pi^+\pi^-\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1449±4	[1] ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$

[1] Not clear whether this observation has I=1 or 0.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1250	[2] ASTON 80C	OMEG	20–70 $\gamma p \to \omega\pi^0 p$
1290±40	[2] BARBER 80C	SPEC	3–5 $\gamma p \to \omega\pi^0 p$

[2] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1480±40	[3] BITYUKOV 87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

[3] See the minireview for ρ(1700) and ACHASOV 88 for a non-exotic interpretation.

ρ(1450) WIDTH

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
237±16 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.		
230±30	ANTONELLI 88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
60±15	FUKUI 88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

MIXED MODES

VALUE (MeV)	DOCUMENT ID	TECN
The data in this block is included in the average printed for a previous datablock.		
220±25	DONNACHIE 87	RVUE
• • • We do not use the following data for averages, fits, limits, etc. • • •		
240±25	GOVORKOV 88	RVUE

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
269±31	BISELLO 89	DM2	$e^+e^- \to \pi^+\pi^-$

$\pi^+\pi^-\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
78±18	[4] ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$

[4] Not clear whether this observation has I=1 or 0.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
300	[5] ASTON 80C	OMEG	20–70 $\gamma p \to \omega\pi^0 p$
320±100	[5] BARBER 80C	SPEC	3–5 $\gamma p \to \omega\pi^0 p$

[5] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
130±60	[6] BITYUKOV 87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

[6] See the minireview for ρ(1700) and ACHASOV 88 for a non-exotic interpretation.

ρ(1450) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	4π	seen
Γ_3	e^+e^-	seen
Γ_4	$\eta\rho$	<4 %
Γ_5	$\phi\pi$	
Γ_6	$\omega\pi$	

ρ(1450) $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.12	[7] DIEKMAN 88	RVUE	$e^+e^- \to \pi^+\pi^-$

[7] Using total width = 235 MeV.

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\qquad\Gamma_4\Gamma_3/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
91±19	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$

$\Gamma(\phi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\qquad\Gamma_5\Gamma_3/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<70	90	AULCHENKO	87	ND	$e^+e^- \to K^0_S K^0_L \pi^0$

ρ(1450) BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma_{\text{total}}$ $\qquad\Gamma_4/\Gamma$

VALUE	DOCUMENT ID		TECN
<0.04	DONNACHIE	87B	RVUE

$\Gamma(\phi\pi)/\Gamma(\omega\pi)$ $\qquad\Gamma_5/\Gamma_6$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.5	95	BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

$\Gamma(\omega\pi)/\Gamma(4\pi)$ $\qquad\Gamma_6/\Gamma_2$

VALUE	DOCUMENT ID		TECN
<0.14	CLEGG	88	RVUE

ρ(1450) REFERENCES

ARMSTRONG 89E PL B228 536 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF, LPNP)
BISELLO 89 PL B220 321 +Busetto+ (DM2 Collab.)
ACHASOV 88 PL B207 199 +Kozhevnikov (NOVO)
ANTONELLI 88 PL B212 133 +Baldini+ (DM2 Collab.)
CLEGG 88 ZPHY C40 313 +Donnachie (MCHS, LANC)
DIEKMAN 88 PRPL 159 101 (BONN)
FUKUI 88 PL B202 441 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
GOVORKOV 88 SJNP 48 150 (JINR)
Translated from YAF 48 237.
AULCHENKO 87 PL B186 432 +Dolinsky, Druzhinin, Dubrovin+ (NOVO)
BITYUKOV 87 PL B188 383 +Dzhelyadin, Dorofeev, Golovkin+ (SERP)
DONNACHIE 87 ZPHY C33 407 +Mirzaie (MCHS)
DONNACHIE 87B ZPHY C34 257 +Clegg (MCHS, LANC)
ASTON 80C PL 92B 211 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BARBER 80C ZPHY C4 169 +Dainton, Brodbeck, Brookes+ (DARE, LANC, SHEF)

OTHER RELATED PAPERS

BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
KURDADZE 86 JETPL 43 643 +Lelchuk, Pakhtusova, Sidorov, Skrinskii+ (NOVO)
Translated from ZETFP 43 497.
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
BISELLO 85 LAL 85-15 +Augustin, Ajaltouni+ (PADO, LALO, CLER, FRAS)
ABE 84B PRL 53 751 +Bacon, Ballam+ (SLAC Hybrid Facility Photon Collab.)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER 82 PL 109B 129 +Bisello, Bizot, Buon, Delcourt (LALO)
DIBIANCA 81 PR D23 595 +Fickinger, Malko, Dado, Engler+ (CASE, CMU)
ASTON 80 PL 92B 215 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
COSME 79 NP B152 215 +Dudelzak, Grelaud, Jean-Marie, Jullian+ (IPN)
SIDOROV 79 Batavia Conf. 79 490 (NOVO)
QUENZER 78 PL 76B 512 +Ribes, Rumpf, Bertrand, Bizot, Chase+ (LALO)
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSA)
SCHACHT 74 NP B81 205 +Derado, Fries, Park, Yount (MPIM)
BINGHAM 72B PL 41B 635 +Rabin, Rosenfeld, Smadja+ (LBL, UCB, SLAC)
FRENKIEL 72 NP B47 61 +Ghesquiere, Lillestol, Chung+ (CDEF, CERN)
LAYSSAC 71 NC 6A 134 +Renard (MONP)

$\eta(1490)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the 4π system. Needs confirmation.

η(1490) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1489±12	3270	[1] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[1] Estimated by us from various fits.

η(1490) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
144±13	3270	[2] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[2] Estimated by us from various fits.

η(1490) REFERENCES

BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)

$f_1(1510)$

was $D(1530)$

$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

f_1(1510) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1512 ± 4	600 ± 200	[1] BIRMAN	88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1530 ±10		ASTON	88C	LASS	11 $K^- p \to K^0_S K^\pm\pi^\mp\Lambda$
1526.0± 6.0	271	GAVILLET	82	HBC	4.2 $K^- p \to \Lambda K K\pi$

[1] From partial wave analysis of $K^+\overline{K}^0\pi^-$ state.

f_1(1510) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
35 ±15	600 ± 200	[2] BIRMAN	88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
100 ±40		ASTON	88C	LASS	11 $K^- p \to K^0_S K^\pm\pi^\mp\Lambda$
107.0±15.0	271	GAVILLET	82	HBC	4.2 $K^- p \to \Lambda K K\pi$

[2] From partial wave analysis of $K^+\overline{K}^0\pi^-$ state.

f_1(1510) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)$ + c.c.	seen

f_1(1510) REFERENCES

ASTON 88C PL B201 573 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY) JP
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, SMAS) JP
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)

$f_0(1525)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

This entry contains evidence for $K\overline{K}$ S-wave intensity peaking at the mass of the $f'_2(1525)$ and with a comparable width. Needs confirmation.

f_0(1525) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1525	ASTON	88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
~ 1525	BAUBILLIER	83		8 $K^- p \to K^+K^-\Lambda$

f_0(1525) WIDTH

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 90	BAUBILLIER	83	8 $K^- p \to K^+K^-\Lambda$

f_0(1525) REFERENCES

ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)
BAUBILLIER 83 ZPHY C17 309 + (BIRM, CERN, GLAS, MSU, LPNP)

$f'_2(1525)$
was $f'(1525)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$f'_2(1525)$ MASS

VALUE (MeV)	DOCUMENT ID
1525±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY PION BEAM

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1547.0^{+10.0}_{-2.0}$		[1] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$
1496.0^{+9}_{-8}		[2] CHABAUD 81	ASPK	$6\ \pi^- p \to K^+ K^- n$
1497.0^{+8}_{-9}		CHABAUD 81	ASPK	$18.4\ \pi^- p \to K^+ K^- n$
1492.0±29.0		GORLICH 80	ASPK	$17\ \pi^- p$ polarized $\to K^+ K^- n$
1502.0±25.0		[3] CORDEN 79	OMEG	$12\text{–}15\ \pi^- p \to \pi^+ \pi^- n$
1480.0	14	CRENNELL 66	HBC	$6.0\ \pi^- p \to K^0_S K^0_S n$

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1524.5±1.4 OUR AVERAGE		Includes data from the datablock that follows this one. Error includes scale factor of 1.1.		
1526.8±4.3		ASTON 88D	LASS	$11\ K^- p \to K^0_S K^0_S \Lambda$
1529.0±3.0		ARMSTRONG 83B	OMEG	$18.5\ K^- p \to K^- K^+ \Lambda$
1521.0±6.0	650	AGUILAR-... 81B	HBC	$4.2\ K^- p \to \Lambda K^+ K^-$
1521.0±3.0	572	ALHARRAN 81	HBC	$8.25\ K^- p \to \Lambda K \bar{K}$
1522.0±6.0	123	BARREIRO 77	HBC	$4.15\ K^- p \to \Lambda K^0_S K^0_S$
1528 ±7	166	EVANGELISTA 77	OMEG	$10\ K^- p \to K^+ K^- (\Lambda,\Sigma)$
1527.0±3.0	120	BRANDENB... 76C	ASPK	$13\ K^- p \to K^+ K^- (\Lambda,\Sigma)$
1519 ±7	100	AGUILAR-... 72B	HBC	$3.9,4.6\ K^- p \to K \bar{K} (\Lambda,\Sigma)$

PRODUCED IN $e^+ e^-$ ANNIHILATION

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
1519 ± 5 OUR AVERAGE	Error includes scale factor of 1.1.		
1531.6±10.0	AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+ K^-$
1515 ± 5	[4] FALVARD 88	DM2	$J/\psi \to \phi K^+ K^-$
1525 ±10 ±10	BALTRUSAIT..87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1496 ± 2	[5] FALVARD 88	DM2	$J/\psi \to \phi K^+ K^-$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[2] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.

[3] From an amplitude analysis where the $f'_2(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\bar{K}$ channel, making the solution dubious.

[4] From an analysis ignoring interference with $f_2(1720)$.

[5] From an analysis including interference with $f_2(1720)$.

$f'_2(1525)$ WIDTH

VALUE (MeV)	DOCUMENT ID	COMMENT
76±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.	
85± 5 OUR FIT		
76±10	PDG 90	For fitting

PRODUCED BY PION BEAM

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$108.0^{+5.0}_{-2.0}$	[6] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$
69.0^{+22}_{-16}	[7] CHABAUD 81	ASPK	$6\ \pi^- p \to K^+ K^- n$
137.0^{+23}_{-21}	CHABAUD 81	ASPK	$18.4\ \pi^- p \to K^+ K^- n$
$150.0^{+83.0}_{-50.0}$	GORLICH 80	ASPK	$17\ \pi^- p$ polarized $\to K^+ K^- n$
165.0±42.0	[8] CORDEN 79	OMEG	$12\text{–}15\ \pi^- p \to \pi^+ \pi^- n$
$92.0^{+39.0}_{-22.0}$	[9] POLYCHRO... 79	STRC	$7\ \pi^- p \to n K^0_S K^0_S$

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
78 ± 5 OUR AVERAGE		Includes data from the datablock that follows this one.		
90.2±11.8		ASTON 88D	LASS	$11\ K^- p \to K^0_S K^0_S \Lambda$
83.0±15.0		ARMSTRONG 83B	OMEG	$18.5\ K^- p \to K^- K^+ \Lambda$
85.0±16.0	650	AGUILAR-... 81B	HBC	$4.2\ K^- p \to \Lambda K^+ K^-$
$80.0^{+14.0}_{-11.0}$	572	ALHARRAN 81	HBC	$8.25\ K^- p \to \Lambda K \bar{K}$
72.0±25.0	166	EVANGELISTA 77	OMEG	$10\ K^- p \to K^+ K^- (\Lambda,\Sigma)$
69 ±22	100	AGUILAR-... 72B	HBC	$3.9,4.6\ K^- p \to K \bar{K} (\Lambda,\Sigma)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$62.0^{+19.0}_{-14.0}$	123	BARREIRO 77	HBC	$4.15\ K^- p \to \Lambda K^0_S K^0_S$
61.0± 8.0	120	BRANDENB... 76C	ASPK	$13\ K^- p \to K^+ K^- (\Lambda,\Sigma)$

PRODUCED IN $e^+ e^-$ ANNIHILATION

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
67 ± 9 OUR AVERAGE			
102.6±29.7	AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+ K^-$
62 ±10	[10] FALVARD 88	DM2	$J/\psi \to \phi K^+ K^-$
85 ±35	BALTRUSAIT..87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
100 ± 3	[11] FALVARD 88	DM2	$J/\psi \to \phi K^+ K^-$

[6] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[7] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.

[8] From an amplitude analysis where the $f'_2(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\bar{K}$ channel, making the solution dubious.

[9] From a fit to the D with $f_2(1270)$-$f'_2(1525)$ interference. Mass fixed at 1516 MeV.

[10] From an analysis ignoring interference with $f_2(1720)$.

[11] From an analysis including interference with $f_2(1720)$.

$f'_2(1525)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\bar{K}$	$(71.3\ ^{+2.1}_{-2.5})\ \%$
Γ_2	$\eta\eta$	$(27.9\ ^{+2.5}_{-2.1})\ \%$
Γ_3	$\pi\pi$	$(\ 8.2\ \pm 1.6\ ) \times 10^{-3}$
Γ_4	$\gamma\gamma$	$(\ 1.27^{+0.28}_{-0.25}) \times 10^{-6}$
Γ_5	$K\bar{K}^*(892)$ + c.c.	
Γ_6	$\pi\pi\eta$	
Γ_7	$\pi K\bar{K}$	
Γ_8	$\pi^+\pi^+\pi^-\pi^-$	

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 4 partial widths, and 2 branching ratios uses 12 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 = 8.9$ for 8 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ccccc}
x_2 & -100 & & & \\
x_3 & -6 & -2 & & \\
x_4 & -17 & 17 & -1 & \\
\Gamma & 59 & -59 & 2 & -28 \\
 & x_1 & x_2 & x_3 & x_4
\end{array}$$

	Mode	Rate (MeV)
Γ_1	$K\bar{K}$	61 ±5
Γ_2	$\eta\eta$	$23.9\ ^{+2.2}_{-1.3}$
Γ_3	$\pi\pi$	0.70±0.14
Γ_4	$\gamma\gamma$	$(\ 1.08^{+0.23}_{-0.20}) \times 10^{-4}$

$f'_2(1525)$ PARTIAL WIDTHS

$\Gamma(K\bar{K})$ Γ_1

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
61 ±5 OUR FIT			
$63.0^{+6.0}_{-5.0}$	[12] LONGACRE 86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$

$\Gamma(\pi\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.70±0.14 OUR FIT				
$1.4\ ^{+1.0}_{-0.5}$	[12] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow K^0_S K^0_S n$

$\Gamma(\eta\eta)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$23.9^{+2.2}_{-1.3}$ OUR FIT				
$24.0^{+3.0}_{-1.0}$	[12] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow K^0_S K^0_S n$

$\Gamma(\gamma\gamma)$ Γ_4

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
$0.108^{+0.023}_{-0.020}$ OUR FIT				
$0.108^{+0.023}_{-0.019}$ OUR AVERAGE				
$0.11\ ^{+0.03}_{-0.02}\ \pm 0.02$	BEHREND	89C	CELL	$e^+ e^- \rightarrow e^+ e^- K^0_S K^0_S$
$0.10\ ^{+0.04}_{-0.03}\ ^{+0.03}_{-0.02}$	BERGER	88	PLUT	$e^+ e^- \rightarrow e^+ e^- K^0_S K^0_S$
$0.12\ \pm 0.07\ \pm 0.04$	[13] AIHARA	86B	TPC	$e^+ e^- \rightarrow e^+ e^- K^+ K^-$
$0.11\ \pm 0.02\ \pm 0.04$	[13] ALTHOFF	83	TASS	$e^+ e^- \rightarrow e^+ e^- K\overline{K}$

[12] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[13] Using B($f_2'(1525) \rightarrow K\overline{K}$) = 1.

$f_2'(1525)$ BRANCHING RATIOS

$\Gamma(\eta\eta)/\Gamma(K\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$0.39^{+0.05}_{-0.04}$ OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.50	BARNES	67	HBC	4.6,5.0 $K^- p$

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_3/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0082±0.0016 OUR FIT					
0.0075±0.0016 OUR AVERAGE					
0.007 ±0.002		COSTA...	80	OMEG	$10\ \pi^- p \rightarrow K^+ K^- n$
$0.027\ ^{+0.071}_{-0.013}$		[14] GORLICH	80	ASPK	$17{,}18\ \pi^- p$
0.0075±0.0025		[14,15] MARTIN	79	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	95	AGUILAR-...	81B	HBC	$4.2\ K^- p \rightarrow \Lambda K^+ K^-$
0.19 ±0.03		CORDEN	79	OMEG	$12\text{–}15\ \pi^- p \rightarrow \pi^+ \pi^- n$
<0.045	95	BARREIRO	77	HBC	$4.15\ K^- p \rightarrow \Lambda K^0_S K^0_S$
0.012 ±0.004		[14] PAWLICKI	77	SPEC	$6\ \pi N \rightarrow K^+ K^- N$
<0.063	90	BRANDENB...	76C	ASPK	$13\ K^- p \rightarrow K^+ K^- (\Lambda,\Sigma)$
<0.0086		[14] BEUSCH	75B	OSPK	$8.9\ \pi^- p \rightarrow K^0 \overline{K}^0 n$

[14] Assuming that the $f_2'(1525)$ is produced by an one-pion exchange production mechanism.

[15] MARTIN 79 uses the PAWLICKI 77 data with different input value of the $f_2'(1525) \rightarrow K\overline{K}$ branching ratio.

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.0115±0.0022 OUR FIT				
0.075 ±0.035	AUGUSTIN	87	DM2	$J/\psi \rightarrow \gamma \pi^+ \pi^-$

$\Gamma(\pi\pi\eta)/\Gamma(K\overline{K})$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.41	95	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
<0.3	67	AMMAR	67	HBC	

$[\Gamma(K\overline{K}^*(892) + \text{c.c.}) + \Gamma(\pi K\overline{K})]/\Gamma(K\overline{K})$ $(\Gamma_5+\Gamma_7)/\Gamma_1$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.35	95	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
<0.4	67	AMMAR	67	HBC	

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K\overline{K})$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.32	95	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$

$f_2'(1525)$ REFERENCES

PDG	90	PL B239			
BEHREND	89C	ZPHY C43 91	+Criegee, Dainton+	(CELLO Collab.)	
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)	
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)	
BERGER	88	ZPHY C37 329	+Genzel, Lackas+	(PLUTO Collab.)	
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)	
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)	
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)	
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)	
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)	
ALTHOFF	83	PL 121B 216	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)	
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)	
AGUILAR-...	81B	ZPHY C8 313	Aguilar-Benitez, Albajar+	(CERN, CDEF, MADR+)	
ALHARRAN	81	NP B191 26	+Baubillier+	(BIRM, CERN, GLAS, MICH, LPNP)	
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)	
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)	
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)	
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC)	JP
MARTIN	79	NP B158 520	+Ozmutlu	(DURH)	
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)	
BARREIRO	77	NP B121 237	+Diaz, Gay, Hemingway+	(CERN, AMST, NIJM, OXF)	
EVANGELISTA	77	NP B127 384	+	(BARI, BONN, CERN, DARE, GLAS+)	
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL)	IJP
BRANDENB...	76C	NP B104 413	Brandenburg, Carnegie, Cashmore+	(SLAC)	
BEUSCH	75B	PL 60B 101	+Birman, Websdale, Wetzel	(CERN, ETH)	
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)	
AMMAR	67	PRL 19 1071	+Davis, Hwang, Dagan, Derrick+	(NWES, ANL)	JP
BARNES	67	PRL 19 964	+Dornan, Goldberg, Leitner+	(BNL, SYRA)	IJPC
CRENNELL	66	PRL 16 1025	+Kalbfleisch, Lai, Scarr, Schumann+	(BNL)	I

OTHER RELATED PAPERS

JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
ARMSTRONG	82	PL 110B 77	+Baubillier+	(BARI, BIRM, CERN, MILA, LPNP+)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
LUKE	82	DESY 82/073		(DESY)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
LAVEN	77	NP B127 43	+Otter, Klein+	(AACH, BERL, CERN, LOIC, WIEN)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN)
SCOTTER	69	NC 62A 1057	+Erskine, Paler+	(BIRM, GLAS, LOIC, MPIM, OXF)
ALITTI	68B	PRL 21 1705	+Barnes, Crennell, Flaminio, Goldberg+	(BNL)
ABRAMS	67B	PRL 18 620	+Kehoe, Glasser, Sechi-Zorn, Wolsky	(UMD)
BARNES	65	PRL 15 322	+Culwick, Guidoni, Kalbfleisch, Goz+	(BNL, SYRA)

$f_2(1565)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen in $\overline{p}p$ annihilation at rest into $\pi^+\pi^-\pi^0$. Needs confirmation. See also minireview under non-$q\overline{q}$ candidates.

$f_2(1565)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1565±10	MAY	89	ASTE		$\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1477± 5	BRIDGES	86B	DBC	0	$\overline{p}N \rightarrow 3\pi^- 2\pi^+$
1527± 5	[1] GRAY	83	DBC	0	$0.0\ \overline{p}N \rightarrow 3\pi$

[1] No fit of the Dalitz plot has been made.

$f_2(1565)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
170±20	MAY	89	ASTE		$\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
116± 9	BRIDGES	86B	DBC	0	$\overline{p}N \rightarrow 3\pi^- 2\pi^+$
101±13	[2] GRAY	83	DBC	0	$0.0\ \overline{p}N \rightarrow 3\pi$

[2] No fit of the Dalitz plot has been made.

$f_2(1565)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-$	seen
Γ_2	$\rho^0\rho^0$	

$f_2(1565)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	MAY	89	ASTE		$\overline{p}p \rightarrow \pi^+\pi^-\pi^0$
seen	GRAY	83	DBC	0	$0.0\ \overline{p}N \rightarrow 3\pi$

$\Gamma(\pi^+\pi^-)/\Gamma(\rho^0\rho^0)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.042±0.013	BRIDGES	86B	DBC	0	$\overline{p}N \rightarrow 3\pi^- 2\pi^+$

$f_2(1565)$ REFERENCES

MAY	89	PL B225 450	+Duch, Heel+	(ASTERIX Collab.)	IJP
BRIDGES	86B	PRL 56 215	+Daftari, Kalogeropoulos, Debbe+	(SYRA, CASE)	
GRAY	83	PR D27 307	+Kalogeropoulos, Nandy, Roy, Zenone	(SYRA)	

$f_0(1590)$

$I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$f_0(1590)$ MASS

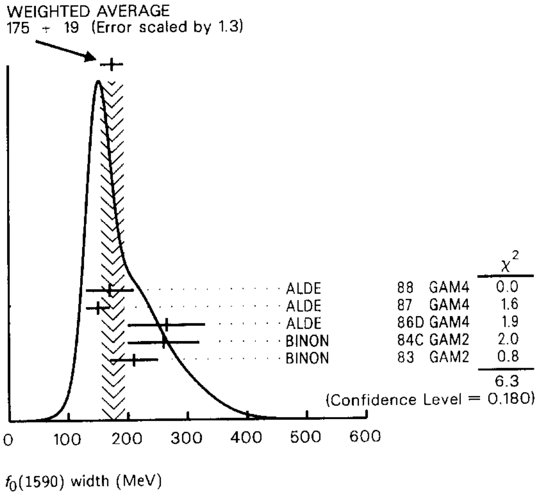
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1587 ±11 OUR AVERAGE				
1610 ±20		ALDE 88	GAM4	300 $\pi^- N \to \eta\eta\pi^- N$
1570 ±20	600 ± 70	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$
1575.0±45.0		[1] ALDE 86D	GAM4	100 $\pi^- p \to 4\gamma n$
1568.0±33.0		BINON 84C	GAM2	38 $\pi^- p \to 4\gamma n$
1592.0±25.0		BINON 83	GAM2	38 $\pi^- p \to 4\gamma n$

[1] From central value and spread of two solutions.

$f_0(1590)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
175 ±19 OUR AVERAGE		Error includes scale factor of 1.3.		See the ideogram below.
170 ±40		ALDE 88	GAM4	300 $\pi^- N \to \eta\eta\pi^- N$
150 ±20	600 ± 70	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$
265.0±65.0		[2] ALDE 86D	GAM4	100 $\pi^- p \to 4\gamma n$
260.0±60.0		BINON 84C	GAM2	38 $\pi^- p \to 4\gamma n$
210.0±40.0		BINON 83	GAM2	38 $\pi^- p \to 4\gamma n$

[2] From central value and spread of two solutions.



$f_0(1590)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta'(958)$	dominant
Γ_2	$\eta\eta$	large
Γ_3	$4\pi^0$	large
Γ_4	$\pi^0\pi^0$	
Γ_5	$K\bar{K}$	

$f_0(1590)$ BRANCHING RATIOS

$\Gamma(\eta\eta'(958))/\Gamma(\eta\eta)$ Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
2.7±0.8	BINON 84C	GAM2	38 $\pi^- p \to 4\gamma n$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
large	ALDE 88	GAM4	300 $\pi^- N \to \eta\eta\pi^- N$
large	BINON 83	GAM2	38 $\pi^- p \to 4\gamma n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.8±0.3	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta)$ Γ_4/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.3	BINON 83	GAM2	38 $\pi^- p \to 4\gamma n$

$\Gamma(K\bar{K})/\Gamma(\eta\eta)$ Γ_5/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.6	BINON 83	GAM2	38 $\pi^- p \to 4\gamma n$

$f_0(1590)$ REFERENCES

ALDE	88	PL B201 160	+Bellazini, Binon+	(SERP, BELG, LANL, LAPP, PISA) JP
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN) IGJP
BINON	84C	NC 80A 363	+Bricman, Donskov+	(BELG, LAPP, SERP, CERN)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN) IGJP
Also	83B	SJNP 38 561 Translated from YAF 38 934.	Binon, Gouanere+	(BELG, LAPP, SERP, CERN)

OTHER RELATED PAPERS

SLAUGHTER 88 MPL A3 1361 (LANL)

$\omega(1600)$

$I^G(J^{PC}) = 0^-(1^{--})$

See also $\omega(1390)$.

$\omega(1600)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1594 ±12		DONNACHIE 89	RVUE		$e^+e^- \to \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1625 ±25		GOVORKOV 88	RVUE		
1670 ±20		ATKINSON 83B	OMEG		20–70 $\gamma p \to 3\pi X$
1657 ±13		CORDIER 81	DM1		$e^+e^- \to \omega 2\pi$
1679 ±34	21	ESPOSITO 80	FRAM		$e^+e^- \to 3\pi$
1652.0±17.0		COSME 79	OSPK	0	$e^+e^- \to 3\pi$

$\omega(1600)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
100 ±30		DONNACHIE 89	RVUE		$e^+e^- \to \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
250 ±25		GOVORKOV 88	RVUE		
160 ±20		ATKINSON 83B	OMEG		20–70 $\gamma p \to 3\pi X$
136 ±46		CORDIER 81	DM1		$e^+e^- \to \omega 2\pi$
99 ±49	21	ESPOSITO 80	FRAM		$e^+e^- \to 3\pi$
42.0±17.0		COSME 79	OSPK	0	$e^+e^- \to 3\pi$

$\omega(1600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	e^+e^-	seen

$\omega(1600)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
96±35	DONNACHIE 89	RVUE	$e^+e^- \to \rho\pi$

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
56±31	DONNACHIE 89	RVUE	$e^+e^- \to \omega 2\pi$

$\omega(1600)$ REFERENCES

DONNACHIE	89	ZPHY C42 663	+Clegg	(CERN, MCHS)
GOVORKOV	88	SJNP 48 150 Translated from YAF 48 237.		(JINR)
ATKINSON	83B	PL 127B 132	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER	81	PL 106B 155	+Bisello, Bizot, Buon, Delcourt, Mane	(ORSA)
ESPOSITO	80	LNC 28 195	+Marini, Patteri+	(FRAS, NAPL, PADO, ROMA)
COSME	79	NP B152 215	+Dudelzak, Grelaud, Jean Marie, Jullian+	(IPN)

OTHER RELATED PAPERS

ATKINSON	87	ZPHY C34 157	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP)
ATKINSON	84	NP B231 15	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)

$f_2(1640)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen by ALDE 89B in $\omega\omega$ mass distribution. Needs confirmation.

$f_2(1640)$ MASS

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
1635±7		[1] SINGOVSKY 90	GAM2	$38\ \pi^- p \to n\omega\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1643±7	90	ALDE 89B	GAM2	$38\ \pi^- p \to n\omega\omega$

[1] This result supersedes ALDE 89B.

$f_2(1640)$ WIDTH

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<70	90	ALDE 89B	GAM2	$38\ \pi^- p \to n\omega\omega$

$f_2(1640)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	seen

$f_2(1640)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
seen	ALDE 89B	GAM2	$38\ \pi^- p \to n\omega\omega$

$f_2(1640)$ REFERENCES

SINGOVSKY	90	Hadron 89 Conf.		(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	89B	PL B216 451	+Binon, Bricman+	(SERP, BELG, LANL, LAPP, TBLI) IGJPC

$X(1650)$

$I^G(J^{PC}) = 1^-(?^{??})$

OMITTED FROM SUMMARY TABLE

$X(1650)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1650±50	POULET 90	GAM4	$100\ \pi^- p \to 4\gamma n$

$X(1650)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
150±50	POULET 90	GAM4	$100\ \pi^- p \to 4\gamma n$

$X(1650)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta'\pi^0$	seen

$X(1650)$ REFERENCES

POULET	90	Hadron 89 Conf.	+Boutemeur	(SERP, BELG, LANL, LAPP, PISA, KEK)

$\omega_3(1670)$

$I^G(J^{PC}) = 0^-(3^{--})$

$\omega_3(1670)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1668 ± 5 OUR AVERAGE				
1685.0±20.0	60	BAUBILLIER 79	HBC	$8.2\ K^- p$ backward
1673.0±12.0	430	[1,2] BALTAY 78E	HBC	$15\ \pi^+ p \to \Delta 3\pi$
1650.0±12.0		CORDEN 78B	OMEG	$8\text{–}12\ \pi^- p \to N 3\pi$
1669 ±11	600	[2] WAGNER 75	HBC	$7\ \pi^+ p \to \Delta^{++} 3\pi$
1678 ±14	500	DIAZ 74	DBC	$6\ \pi^+ n \to p 3\pi^0$
1660 ±13	200	DIAZ 74	DBC	$6\ \pi^+ n \to p\omega\pi^0\pi^0$
1679 ±17	200	MATTHEWS 71D	DBC	$7.0\ \pi^+ n \to p 3\pi^0$
1670 ±20		KENYON 69	DBC	$8\ \pi^+ n \to p 3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1700.0	110	[1] CERRADA 77B	HBC	$4.2\ K^- p \to \Lambda 3\pi$
1695.0±20.0		BARNES 69B	HBC	$4.6\ K^- p \to \omega 2\pi X$
1636 ±20		ARMENISE 68B	DBC	$5.1\ \pi^+ n \to p 3\pi^0$

[1] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.

[2] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
166 ±15 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.		
173 ±11 OUR AVERAGE				
160.0±80.0	60	[3] BAUBILLIER 79	HBC	$8.2\ K^- p$ backward
173.0±16.0	430	[4,5] BALTAY 78E	HBC	$15\ \pi^+ p \to \Delta 3\pi$
253.0±39.0		CORDEN 78B	OMEG	$8\text{–}12\ \pi^- p \to N 3\pi$
173 ±28	600	[3,5] WAGNER 75	HBC	$7\ \pi^+ p \to \Delta^{++} 3\pi$
167 ±40	500	DIAZ 74	DBC	$6\ \pi^+ n \to p 3\pi^0$
122 ±39	200	DIAZ 74	DBC	$6\ \pi^+ n \to p\omega\pi^0\pi^0$
155 ±40	200	[3] MATTHEWS 71D	DBC	$7.0\ \pi^+ n \to p 3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
90 ±20		BARNES 69B	HBC	$4.6\ K^- p \to \omega 2\pi$
100 ±40		KENYON 69	DBC	$8\ \pi^+ n \to p 3\pi^0$
112 ±60		ARMENISE 68B	DBC	$5.1\ \pi^+ n \to p 3\pi^0$

[3] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[4] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.

[5] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	$b_1(1235)\pi$	possibly seen

$\omega_3(1670)$ BRANCHING RATIOS

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ Γ_2/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.71±0.27	100	DIAZ 74	DBC	$6\ \pi^+ n \to p 5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
possibly seen	DIAZ 74	DBC	$6\ \pi^+ n \to p 5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\omega\pi\pi)$ Γ_3/Γ_2

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.75	68	BAUBILLIER 79	HBC	$8.2\ K^- p$ backward

$\omega_3(1670)$ REFERENCES

BAUBILLIER	79	PL 89B 131	+	(BIRM, CERN, GLAS, MSU, LPNP)
BALTAY	78E	PRL 40 87	+Cautis, Kalelkar	(COLU) JP
CORDEN	78B	NP B138 235	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF) JP
WAGNER	75	PL 58B 201	+Tabak, Chew	(LBL) JP
DIAZ	74	PRL 32 260	+Dibianca, Fickinger, Anderson+	(CASE, CMU)
MATTHEWS	71D	PR D3 2561	+Prentice, Yoon, Carroll+	(TNTO, WISC)
BARNES	69B	PRL 23 142	+Chung, Eisner, Flaminio+	(BNL)
KENYON	69	PRL 23 146	+Kinson, Scarr+	(BNL, UCND, ORNL)
ARMENISE	68B	PL 26B 336	+Forino, Cartacci+	(BARI, BGNA, FIRZ, ORSA)

OTHER RELATED PAPERS

MATTHEWS	71	LNC 1 361	+Prentice, Yoon, Carroll+	(TNTO, WISC)
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)

$\pi_2(1670)$ was $A_3(1680)$

$I^G(J^{PC}) = 1^-(2^{-+})$

Our latest mini-review on this particle can be found in the 1984 edition.

$\pi_2(1670)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1665 ±20 OUR ESTIMATE					This is only an educated guess; the error given is larger than the error on the average of the published values.
1665 ± 5 OUR AVERAGE					Error includes scale factor of 1.4. See the ideogram below.
1710 ±20	700 ± 150	ANTIPOV	87 SIGM	−	50 π^- Cu → $\mu^+\mu^-\pi^-$ Cu
1676 ± 6		[1] EVANGELISTA	81 OMEG	−	12 $\pi^- p \to 3\pi p$
1657.0±14.0		[1,2] DAUM	80D SPEC	−	63–94 $\pi p \to 3\pi X$
1662.0±10.0	2000	[1] BALTAY	77 HBC	+	15 $\pi^+ p \to p 3\pi$
1640 ±10	575	KALELKAR	75 HBC	+	15 $\pi^+ p \to p\pi^+ f_2$
1650 ±30		[1] ANTIPOV	73C CNTR	−	25,40 $\pi^- p$
1660 ±10		[1] ASCOLI	73 HBC	−	5–25 $\pi^- p \to p\pi_2$
1660 ±25	260	CASO	72 HBC	+	11.7 $\pi^+ p$
1660.0±20.0		CASO	69B HBC	−	11 $\pi^- p \to f_2\pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

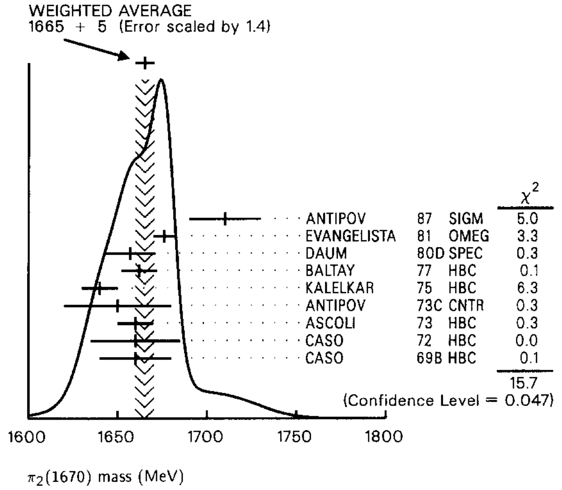
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1710.0±20.0		[3] DAUM	81B SPEC	−	63,94 $\pi^- p$
1650.0		[4] PERNEGR	78 CNTR	−	9+13+15 $\pi^- N$
1600 ±10		THOMPSON	74C HBC	+	13 $\pi^+ p \to p\pi_2^+$

[1] From a fit to $J^P = 2^-$ S-wave $f_2(1270)\pi$ partial wave.

[2] Clear phase rotation seen in 2^-S, 2^-P, 2^-D waves. We quote central value and spread of single-resonance fits to three channels.

[3] From a two-resonance fit to four 2^-0^+ waves. This should not be averaged with all the single resonance fits.

[4] Clear phase rotation seen in 2^-S and 2^-P waves.



$\pi_2(1670)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
250 ± 20 OUR ESTIMATE					This is only an educated guess; the error given is larger than the error on the average of the published values.
247 ± 11 OUR AVERAGE					
170 ± 80	700 ± 150	ANTIPOV	87 SIGM	−	50 π^- Cu → $\mu^+\mu^-\pi^-$ Cu
312.0± 50.0		[5] DAUM	81B SPEC	−	63,94 $\pi^- p$
260 ± 20		[6] EVANGELISTA	81 OMEG	−	12 $\pi^- p \to 3\pi p$
219.0± 20.0		[6,7] DAUM	80D SPEC	−	63–94 $\pi p \to 3\pi X$
285.0± 60.0	2000	[6] BALTAY	77 HBC	+	15 $\pi^+ p \to p 3\pi$
240 ± 30	575	KALELKAR	75 HBC	+	15 $\pi^+ p \to p\pi^+ f_2$
300 ± 50		[6] ANTIPOV	73C CNTR	−	25,40 $\pi^- p$
270 ± 60		[6] ASCOLI	73 HBC	−	5–25 $\pi^- p \to p\pi_2$
190 ±100	260	CASO	72 HBC	+	11.7 $\pi^+ p$
240.0± 50.0	297	ARMENISE	69 DBC	+	5.1 $\pi^+ d \to d 3\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
400.0		[8] PERNEGR	78 CNTR	−	9+13+15 $\pi^- N$
310 ± 40		THOMPSON	74C HBC	+	13 $\pi^+ p \to p\pi_2^+$
200 to 400		[6] CASO	72 HBC	+	11.7 $\pi^+ p$
130		CASO	69B HBC	−	11 $\pi^- p$
150.0		CASO	69B HBC	−	11 $\pi^- p \to f_2\pi^- p$

[5] From a two-resonance fit to four 2^-0^+ waves. This should not be averaged with all the single resonance fits.

[6] From a fit to $J^P = 2^-$ $f_2(1270)\pi$ partial wave.

[7] Clear phase rotation seen in 2^-S, 2^-P, 2^-D waves. We quote central value and spread of single-resonance fits to three channels.

[8] Clear phase rotation seen in 2^-S and 2^-P waves.

$\pi_2(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$f_2(1270)\pi$	(56.2±3.2) %	
Γ_2	$\rho\pi$	(31 ±4) %	
Γ_3	$f_0(1400)\pi$	(8.7±3.4) %	
Γ_4	$K\overline{K}^*(892)$ + c.c.	(4.2±1.4) %	
Γ_5	$\eta\pi$	< 5 %	90%
Γ_6	$\pi^\pm 2\pi^+ 2\pi^-$	< 5 %	90%
Γ_7	$\pi^\pm\pi^+\pi^-$		

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 6 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 1.9 for 3 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{cccc} x_2 & -53 & & \\ x_3 & -29 & -59 & \\ x_4 & -8 & -21 & -9 \\ & x_1 & x_2 & x_3 \end{array}$$

$\pi_2(1670)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\qquad \frac{1}{2}\Gamma_2/(.567\Gamma_1+\frac{1}{2}\Gamma_2+.624\Gamma_3)$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.29±0.04 OUR FIT				
0.29±0.05	[9] DAUM	81B SPEC		63,94 $\pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
<0.3	BARTSCH	68 HBC	+	8 $\pi^+ p \to 3\pi p$
<0.4	FERBEL	68 RVUE	±	

[9] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(f_2(1270)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\qquad .567\Gamma_1/(.567\Gamma_1+\frac{1}{2}\Gamma_2+.624\Gamma_3)$

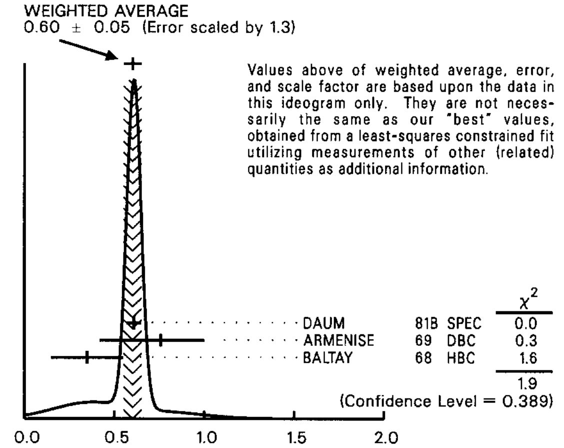
(With $f_2(1270) \to \pi^+\pi^-$.)

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.604±0.035 OUR FIT				
0.60 ±0.05 OUR AVERAGE				Error includes scale factor of 1.3. See the ideogram below.
0.61 ±0.04	[10] DAUM	81B SPEC		63,94 $\pi^- p$
0.76 $^{+0.24}_{-0.34}$	ARMENISE	69 DBC	+	5.1 $\pi^+ d \to d 3\pi$
0.35 ±0.20	BALTAY	68 HBC	+	7–8.5 $\pi^+ p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.59	BARTSCH	68 HBC	−	8 $\pi^+ p \to 3\pi p$

[10] From a two-resonance fit to four 2^-0^+ waves.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

			χ^2
DAUM	81B	SPEC	0.0
ARMENISE	69	DBC	0.3
BALTAY	68	HBC	1.6
			1.9

(Confidence Level = 0.389)

$\Gamma(f_2(1270)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$

$\Gamma(\eta\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\Gamma_5/(.567\Gamma_1+\frac{1}{2}\Gamma_2+.624\Gamma_3)$

(All η decays.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	BALTAY	68	HBC	+	7–8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	CRENNELL	70	HBC	−	6 $\pi^- p \rightarrow f_2 \pi^- N$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^-)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\Gamma_6/(.567\Gamma_1+\frac{1}{2}\Gamma_2+.624\Gamma_3)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.10	CRENNELL	70	HBC	−	6 $\pi^- p \rightarrow f_2 \pi^- N$
<0.1	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(f_0(1400)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $.624\Gamma_3/(.567\Gamma_1+\frac{1}{2}\Gamma_2+.624\Gamma_3)$

(With $f_0(1400) \rightarrow \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.04 OUR FIT				
0.10±0.05	[11] DAUM	81B	SPEC	63,94 $\pi^- p$

[11] From a two-resonance fit to four $2^- 0^+$ waves.

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(f_2(1270)\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.075±0.025 OUR FIT					
0.075±0.025	[12] ARMSTRONG	82B	OMEG	−	16 $\pi^- p \rightarrow K^+ K^- \pi^- p$

[12] From a partial-wave analysis of $K^+ K^- \pi^-$ system.

D-wave/S-wave RATIO FOR $\pi_2(1670) \rightarrow f_2(1270)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.10	[13] DAUM	81B	SPEC	63,94 $\pi^- p$

[13] From a two-resonance fit to four $2^- 0^+$ waves.

$\pi_2(1670)$ REFERENCES

ANTIPOV	87	EPL 4 403	+Batarin+	(SERP, JINR, INRM, TBLI, BGNA, MILA)
ARMSTRONG	82B	NP B202 1	+Baccari	(AACH, BARI, BONN, CERN, GLAS+)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
Also	81B	NP B186 594	Evangelista	
DAUM	80D	PL 89B 285	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
PERNEGR	78	NP B134 436	+Aebischer+	(ETH, CERN, LOIC, MILA)
BALTAY	77	PRL 39 591	+Cautis, Kalelkar	(COLU) JP
KALELKAR	75	Nevis 207 Thesis		(COLU)
THOMPSON	74C	PRL 32 331	+Badewitz, Gaidos, McIlwain, Paler+	(PURD) JP
Also	74B	NP B69 381	Thompson, Badewitz, Gaidos, McIlwain+	(PURD) JP
ANTIPOV	73C	NP B63 153	+Ascoli, Busnello, Focacci+	(CERN, SERP) JP
ASCOLI	73	PR D7 669		(ILL, TNTO, GENO, HAMB, MILA, SACL) JP
CASO	72	NP B36 349	+Maddock, Bassler+	(DURH, GENO, DESY, MILA+)
CRENNELL	70	PRL 24 781	+Karshon, Lai, Scarr, Sims	(BNL)
ARMENISE	69	LNC 2 501	+Ghidini, Forino, Cartacci+	(BARI, BGNA, FIRZ)
CASO	69B	LNC 2 437	+Conte, Tomasini, Cantore+	(GENO, MILA, SACL)
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE) I
BARTSCH	68	NP B7 345	+Keppel, Kraus+	(AACH, BERL, CERN) JP
FERBEL	68	Phil. Conf. 335		(ROCH)

OTHER RELATED PAPERS

CHEN	83B	PR D28 2304	+Fenker+	(ARIZ, FNAL, FLOR, NDAM, TUFT+)
LEEDOM	83	PR D27 1426	+DeBonte, Gaidos, Key, Wong+	(PURD, TNTO)
BELLINI	82B	NP B199 1	+	(CERN, MILA, JINR, BGNA, HELS, PAVI, WARS+)
BALTAY	78	PR D17 52	+Cautis, Cohen, Csorna, Kalelkar+	(COLU, BING)
CORDEN	78C	NP B136 77	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
ROBERTS	78B	PR D18 59	+Kruse, Edelstein+	(ILL, CMU, NWES, ROCH)
CAUTIS	77	Nevis 221 Thesis		(COLU) JP
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF) JP
BEKETOV	75	SJNP 20 379 Translated from YAF 20 709.	+Zombkovskii, Kaidalon, Konovalov+	(ITEP)
EMMS	75B	PL 60B 109	+Jones, Kinson, Bell, Dale+	(BIRM, DURH, RHEL) JP
HORNE	75	PR D11 996	+Hagopian, Hagopian, Bensinger+	(FSU, BRAN)
WAGNER	75	PL 58B 201	+Tabak, Chew	(LBL) JP
ASCOLI	74	PR D9 1963	+Cutler, Jones, Kruse, Roberts, Weinstein+	(ILL)
LICHTMAN	74	NP B81 31	+Biswas, Cason, Kenney, McGahan+	(NDAM)
OTTER	74	NP B80 1	+Rudolph+	(AACH, BERL, BONN, CERN, HEID) JP
TABAK	74	Boston Conf.	+Ronat, Rosenfeld, Lasinski+	(LBL, SLAC) JP
ANTIPOV	73B	NP B63 141	+Ascoli, Busnello, Focacci+	(CERN, SERP) JP
ASCOLI	73B	PR D8 3894	+Jones, Weinstein, Wyld	(ILL) JP
ALEXANDER	72	NP B45 29	+Bar-Nir, Benary, Dagan+	(TELA)
ARMENISE	72	LNC 4 201	+Forino, Cartacci+	(BARI, BGNA, FIRZ)
SALZBERG	72	NP B41 397	+Harrison, Heyda, Johnson, Kim, Law+	(HARV)
BEKETOV	71	SJNP 4 765 Translated from unknown journal.	+Sombkowsky, Konovalov, Krutschinin+	(ITEP) JP
PALER	71	PRL 26 1675	+Badewitz, Barton, Miller, Palfrey, Tebes	(PURD)
BRANDENB...	70	NP B16 369	Brandenburg, Brenner, Ioffredo+	(HARV)
CHIEN	70B	Phil. Conf. 275		(JHU)
MIYASHITA	70	PR D1 771	+VonKrogh, Kopelman, Libby	(COLO)
BARNES	69B	PRL 23 142	+Chung, Eisner, Flaminio+	(BNL)
CASO	68	NC 54A 983	+Conte, Cords, Diaz+	(GENO, HAMB, MILA, SACL)
IOFFREDO	68	PRL 21 1212	+Brandenburg, Brenner, Eisenstein+	(HARV)
LAMSA	68	PR 166 1395	+Cason, Biswas, Derado, Groves+	(NDAM)
DANYSZ	67B	NC 51A 801	+French, Simak	(CERN)
DUBAL	67	NP B3 435	+Focacci, Kienzle+	(CERN Missing Mass Spect. Collab.)
Also	68	Thesis 1456	Dubal	(GEVA)
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)
LUBATTI	66	Berkeley Thesis		(LRL)
VETLITSKY	66	PL 21 579	+Guszavin, Kliger, Zolganov+	(ITEP)
FORINO	65B	PL 19 68	+Gessaroli+	(BGNA, BARI, FIRZ, ORSA, SACL)

$\phi(1680)$

$I^G(J^{PC}) = 0^-(1^{--})$

First identified using Dalitz plot analysis of $e^+e^- \rightarrow K\overline{K}^*(892)$ (BIZOT 80, DELCOURT 81). We do not list anymore ω radial excitations under this particle. See also $\omega(1390)$ and $\omega(1600)$.

$\phi(1680)$ MASS

e^+e^- PRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1680±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1655±17	[1] BISELLO	88B	DM2	$e^+e^- \rightarrow K^+K^-$
1680±10	[2] BUON	82	DM1	$e^+e^- \rightarrow$ hadrons
1677±12	[3] MANE	82	DM1	$e^+e^- \rightarrow K_S^0 K\pi$

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1726±22	BUSENITZ	89	TPS	$\gamma p \rightarrow K^+K^-X$
1760±20	ATKINSON	85C	OMEG	20–70 $\gamma p \rightarrow K\overline{K}X$
1690±10	ASTON	81F	OMEG	25–70 $\gamma p \rightarrow K^+K^-X$

[1] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.

[2] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K_S^0K_L^0$, $K_S^0K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.

[3] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ WIDTH

e^+e^- PRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
207±45	[4] BISELLO	88B	DM2	$e^+e^- \rightarrow K^+K^-$
185±22	[5] BUON	82	DM1	$e^+e^- \rightarrow$ hadrons
102±36	[6] MANE	82	DM1	$e^+e^- \rightarrow K_S^0 K\pi$

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
121±47	BUSENITZ	89	TPS	$\gamma p \rightarrow K^+K^-X$
80±40	ATKINSON	85C	OMEG	20–70 $\gamma p \rightarrow K\overline{K}X$
100±40	ASTON	81F	OMEG	25–70 $\gamma p \rightarrow K^+K^-X$

[4] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.

[5] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K_S^0K_L^0$, $K_S^0K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.

[6] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)$ + c.c.	dominant
Γ_2	$K\overline{K}$	seen
Γ_3	e^+e^-	seen
Γ_4	$\omega\pi\pi$	possibly seen
Γ_5	$K^0_S K\pi$	

$\phi(1680)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\mathrm{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel (I) in e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(I)$ or the branching ratio $\Gamma(I)$/total.

$\Gamma(K\overline{K}^*(892) + \mathrm{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\mathrm{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.413±0.033	[7] BIZOT	80	DM1	e^+e^-

$\Gamma(K\overline{K}) \times \Gamma(e^+e^-)/\Gamma_{\mathrm{total}}$ $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.053±0.035	[7] BIZOT	80	DM1	e^+e^-

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\mathrm{total}}$ $\Gamma_4\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.017	[7] BIZOT	80	DM1	e^+e^-

[7] Model dependent.

$\phi(1680)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892) + \mathrm{c.c.})/\Gamma(K^0_S K\pi)$ Γ_1/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
dominant	MANE	82	DM1	$e^+e^- \to K^0_S K^\pm \pi^\mp$

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892) + \mathrm{c.c.})$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.07±0.01	BUON	82	DM1	e^+e^-

$\Gamma(\omega\pi\pi)/\Gamma(K\overline{K}^*(892) + \mathrm{c.c.})$ Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
<0.10	BUON	82	DM1	e^+e^-

$\phi(1680)$ REFERENCES

BUSENITZ 89 PR D40 1 +Olszewski, Callahan+ (ILL, FNAL)
BISELLO 88B ZPHY C39 13 +Busetto+ (PADO, CLER, FRAS, LALO)
ATKINSON 85C ZPHY C27 233 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
BUON 82 PL 118B 221 +Bisello, Bizot, Cordier, Delcourt+ (LALO, MONP)
MANE 82 PL 112B 178 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 81F PL 104B 231 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT 81 PL 99B 257 +Bisello, Bizot, Buon, Cordier, Mane (ORSA)
BIZOT 80 Madison Conf. 546 +Bisello, Buon, Cordier, Delcourt- (LALO, USTL)

OTHER RELATED PAPERS

ATKINSON 86C ZPHY C30 541 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 84B NP B231 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 83C NP B229 269 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSA)
MANE 81 PL 99B 261 +Bisello, Bizot, Buon, Cordier, Delcourt (ORSA)
ASTON 80F NP B174 269 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\rho_3(1690)$
was $g(1690)$

$I^G(J^{PC}) = 1^+(3^{--})$

$\rho_3(1690)$ MASS

We include only high statistics experiments in the average for the 2π and $K\overline{K}$ modes.

2π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1691 ± 5 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.				
1691.4± 2.7 OUR AVERAGE		Includes data from the datablock that follows this one.				
1677 ±14		EVANGELISTA	81	OMEG	−	12 $\pi^- p \to 2\pi p$
1679.0±11.0	476	BALTAY	78B	HBC	0	15 $\pi^+ p \to \pi^+\pi^- n$
1678.0±12.0	175	[1] ANTIPOV	77	CIBS	0	25 $\pi^- p \to p3\pi$
1690 ± 7	600	[1] ENGLER	74	DBC	0	6 $\pi^+ n \to \pi^+\pi^- p$
1693 ± 8		[2] GRAYER	74	ASPK	0	17 $\pi^- p \to \pi^+\pi^- n$
1678 ±12		MATTHEWS	71C	DBC	0	7 $\pi^- N$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1734.0±10.0		[3] CORDEN	79	OMEG		12–15 $\pi^- p \to n2\pi$
1692 ±12		[2,4] ESTABROOKS	75	RVUE		17 $\pi^- p \to \pi^+\pi^- n$
1737.0±23.0		ARMENISE	70	DBC	0	9 $\pi^+ N$
1650.0±35.0	122	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N2\pi$
1687 ±21		STUNTEBECK	70	HDBC	0	8 $\pi^- p$, 5.4 $\pi^+ d$
1683 ±13		ARMENISE	68	DBC	0	5.1 $\pi^+ d$
1670.0±30.0		GOLDBERG	65	HBC	0	6 $\pi^+ d$, 8 $\pi^- p$

[1] Mass errors enlarged by us to $\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[2] Uses same data as HYAMS 75

[3] From a phase shift solution containing a $f_2'(1525)$ width two times larger than the $K\overline{K}$ result.

[4] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.

$K\overline{K}$ + $K\overline{K}\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1699.0± 5.0		ALPER	80	CNTR	0	62 $\pi^- p \to K^+K^- n$
1698 ±12	6k	[5,6] MARTIN	78D	SPEC		10 $\pi p \to K^0_S K^- p$
1692 ± 6		BLUM	75	ASPK	0	18.4 $\pi^- p \to nK^+K^-$
1690.0±16.0		ADERHOLZ	69	HBC	+	8 $\pi^+ p \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1694.0± 8.0		[7] COSTA...	80	OMEG		10 $\pi^- p \to K^+K^- n$

[5] From a fit to $J^P = 3^-$ partial wave.

[6] Systematic error on mass scale subtracted.

[7] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^\pm$ MODE

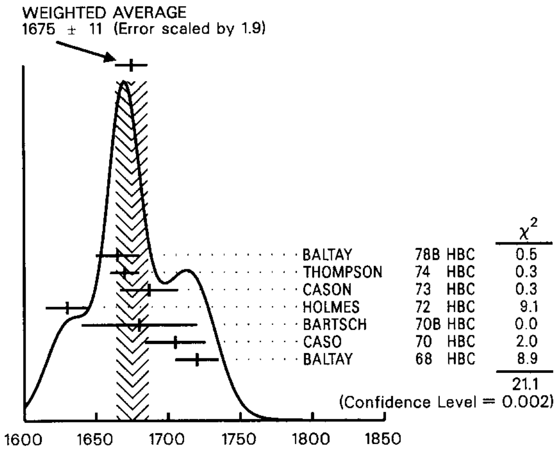
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1675 ±11 OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.				
1665.0±15.0	177	BALTAY	78B	HBC	+	15 $\pi^+ p \to p4\pi$
1670 ±10		THOMPSON	74	HBC	+	13 $\pi^+ p$
1687 ±20		CASON	73	HBC	−	8,18.5 $\pi^- p$
1630 ±15		HOLMES	72	HBC	+	10–12 $K^+ p$
1680.0±40.0	144	BARTSCH	70B	HBC	+	8 $\pi^+ p \to N4\pi$
1705.0±21.0		CASO	70	HBC	−	11.2 $\pi^- p \to n\rho2\pi$
1720 ±15		BALTAY	68	HBC	+	7, 8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1694 ± 6		[8] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p4\pi$
1718 ±10		[9] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p4\pi$
1673 ± 9		[10] EVANGELISTA	81	OMEG	−	12 $\pi^- p \to p4\pi$
1733 ± 9	66	[11] KLIGER	74	HBC	−	4.5 $\pi^- p \to p4\pi$
1685 ±14		[11] CASON	73	HBC	−	8,18.5 $\pi^- p$
1689.0±20.0	102	[11] BARTSCH	70B	HBC	+	8 $\pi^+ p \to N2\rho$

[8] From $\rho^-\rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.

[9] From $a_2(1320)^-\pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.

[10] From $a_2(1320)^0\pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.

[11] From $\rho^\pm\rho^0$ mode.



$\rho_3(1690)$ mass, $(4\pi)^{\pm}$ mode (MeV)

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1680 ± 7 OUR AVERAGE				
1690 ±15	EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
1666.0±14.0	GESSAROLI 77	HBC		$11\ \pi^- p \to \omega\pi p$
1686 ± 9	THOMPSON 74	HBC	+	$13\ \pi^+ p$
1654 ±24	BARNHAM 70	HBC	+	$10\ K^+ p \to \omega\pi X$

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1680 ±15	FUKUI 88	SPEC	0	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1700.0±47.0	[12] ANDERSON 69	MMS	−	$16\ \pi^- p$ backward
1632 ±15	[12,13] FOCACCI 66	MMS	−	$7\text{–}12\ \pi^- p \to p$ MM
1700 ±15	[12,13] FOCACCI 66	MMS	−	$7\text{–}12\ \pi^- p \to p$ MM
1748 ±15	[12,13] FOCACCI 66	MMS	−	$7\text{–}12\ \pi^- p \to p$ MM

[12] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+ 2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1976)

[13] Not seen by BOWEN 72.

$\rho_3(1690)$ WIDTH

We include only high statistics experiments in the average for the 2π and $K\overline{K}$ modes.

2π MODE

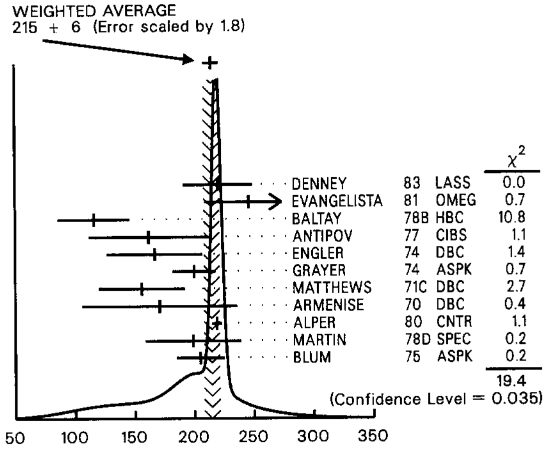
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
215 ±20 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.			
215 ± 6 OUR AVERAGE		Includes data from the datablock that follows this one. Error includes scale factor of 1.8. See the ideogram below.			
220 ±29		DENNEY 83	LASS		$10\ \pi^+ N$
246 ±37		EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to 2\pi p$
116.0±30.0	476	BALTAY 78B	HBC	0	$15\ \pi^+ p \to \pi^+\pi^- n$
162.0±50.0	175	[14] ANTIPOV 77	CIBS	0	$25\ \pi^- p \to p3\pi$
167 ±40	600	ENGLER 74	DBC	0	$6\ \pi^+ n \to \pi^+\pi^- p$
200 ±18		[15] GRAYER 74	ASPK	0	$17\ \pi^- p \to \pi^+\pi^- n$
156 ±36		MATTHEWS 71C	DBC	0	$7\ \pi^+ N$
171.0±65.0		ARMENISE 70	DBC	0	$9\ \pi^+ d$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
322.0±35.0		[16] CORDEN 79	OMEG		$12\text{–}15\ \pi^- p \to n2\pi$
240 ±30		[15,17] ESTABROOKS 75	RVUE		$17\ \pi^- p \to \pi^+\pi^- n$
180.0±30.0	122	BARTSCH 70B	HBC	+	$8\ \pi^+ p \to N2\pi$
267 $^{+72}_{-46}$		STUNTEBECK 70	HDBC	0	$8\ \pi^- p$, $5.4\ \pi^+ d$
188 ±49		ARMENISE 68	DBC	0	$5.1\ \pi^+ d$
180.0±40.0		GOLDBERG 65	HBC	0	$6\ \pi^+ d$, $8\ \pi^- p$

[14] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[15] Uses same data as HYAMS 75 and BECKER 79.

[16] From a phase shift solution containing a $f_2'(1525)$ width two times larger than the $K\overline{K}$ result.

[17] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.



$\rho_3(1690)$ width, $\pi\pi + K\overline{K} + K\overline{K}\pi$ modes (MeV)

$K\overline{K} + K\overline{K}\pi$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
219.0± 4.0		ALPER 80	CNTR	0	$62\ \pi^- p \to K^+ K^- n$
199 ±40	6000	[18] MARTIN 78D	SPEC		$10\ \pi p \to K_S^0 K^- p$
205 ±20		BLUM 75	ASPK	0	$18.4\ \pi^- p \to n K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
186.0±11.0		[19] COSTA... 80	OMEG		$10\ \pi^- p \to K^+ K^- n$
112.0±60.0		ADERHOLZ 69	HBC	+	$8\ \pi^+ p \to K\overline{K}\pi$

[18] From a fit to $J^P = 3^-$ partial wave.

[19] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^{\pm}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
119 ±13 OUR AVERAGE					
105.0±30.0	177	BALTAY 78B	HBC	+	$15\ \pi^+ p \to p4\pi$
106 ±25		THOMPSON 74	HBC	+	$13\ \pi^+ p$
169 $^{+70}_{-48}$		CASON 73	HBC	−	$8{,}18.5\ \pi^- p$
130 ±30		HOLMES 72	HBC	+	$10\text{–}12\ K^+ p$
135.0±30.0	144	BARTSCH 70B	HBC	+	$8\ \pi^+ p \to N4\pi$
100 ±35		BALTAY 68	HBC	+	$7, 8.5\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
123 ±13		[20] EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to p4\pi$
230 ±28		[21] EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to p4\pi$
184 ±33		[22] EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to p4\pi$
150	66	[23] KLIGER 74	HBC	−	$4.5\ \pi^- p \to p4\pi$
125 $^{+83}_{-35}$		[23] CASON 73	HBC	−	$8{,}18.5\ \pi^- p$
180.0±30.0	90	[23] BARTSCH 70B	HBC	+	$8\ \pi^+ p \to N a_2 \pi$
160.0±30.0	102	BARTSCH 70B	HBC	+	$8\ \pi^+ p \to N2\rho$

[20] From $\rho^- \rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.

[21] From $a_2(1320)^- \pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.

[22] From $a_2(1320)^0 \pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.

[23] From $\rho^{\pm}\rho^0$ mode.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
114 ±20 OUR AVERAGE				
190 ±65	EVANGELISTA 81	OMEG	−	$12\ \pi^- p \to \omega\pi p$
160.0±56.0	GESSAROLI 77	HBC		$11\ \pi^- p \to \omega\pi p$
89 ±25	THOMPSON 74	HBC	+	$13\ \pi^+ p$
130 $^{+73}_{-43}$	BARNHAM 70	HBC	+	$10\ K^+ p \to \omega\pi X$

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
106 ±27	FUKUI 88	SPEC	0	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$

• • • We do not use the following data for averages, fits, limits, etc. • • •				
195.0	[24] ANDERSON 69	MMS	–	16 $\pi^- p$ backward
< 21	[24,25] FOCACCI 66	MMS	–	7–12 $\pi^- p \to p$ MM
< 30	[24,25] FOCACCI 66	MMS	–	7–12 $\pi^- p \to p$ MM
< 38	[24,25] FOCACCI 66	MMS	–	7–12 $\pi^- p \to p$ MM

[24] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+ 2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ^0 band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1979)

[25] Not seen by BOWEN 72.

$\rho_3(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	4π	(71.1 ±1.9) %	
Γ_2	$\pi\pi$	(23.6 ±1.3) %	
Γ_3	$K\overline{K}\pi$	(3.8 ±1.2) %	
Γ_4	$K\overline{K}$	(1.58±0.26) %	1.2
Γ_5	$\eta\pi^+\pi^-$	seen	
Γ_6	$\pi\pi\rho$ Excluding 2ρ and $a_2(1320)\pi$.		
Γ_7	$a_2(1320)\pi$		
Γ_8	$\omega\pi$		
Γ_9	$\rho\rho$		
Γ_{10}	$\phi\pi$		
Γ_{11}	$\eta\pi$		
Γ_{12}	$\pi^\pm\pi^+\pi^-\pi^0$		
Γ_{13}	$\pi^\pm 2\pi^+ 2\pi^-\pi^0$		

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 10 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 14.7 for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−77		
x_3	−74	17	
x_4	−15	2	0
	x_1	x_2	x_3

$\rho_3(1690)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\rm total}$ $\qquad\Gamma_2/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.236±0.013 OUR FIT				
0.243±0.013 OUR AVERAGE				
$0.259^{+0.018}_{-0.019}$	BECKER 79	ASPK	0	17 $\pi^- p$ polarized
0.23 ±0.02	CORDEN 79	OMEG		12–15 $\pi^- p \to n 2\pi$
0.22 ±0.04	[26] MATTHEWS 71C	HDBC	0	7 $\pi^+ n \to \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.245±0.006	[27] ESTABROOKS 75	RVUE		17 $\pi^- p \to \pi^+\pi^- n$

[26] One-pion-exchange model used in this estimation.

[27] From phase-shift analysis of HYAMS 75 data.

$\Gamma(\pi\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ $\qquad\Gamma_2/\Gamma_{12}$

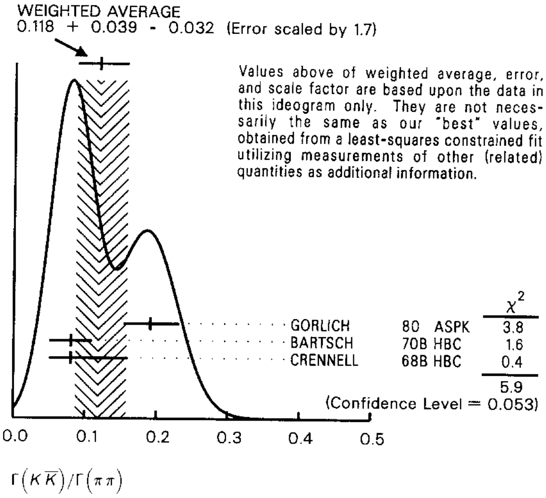
VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.35±0.11	CASON 73	HBC	–	8,18.5 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.2	HOLMES 72	HBC	+	10–12 $K^+ p$
<0.12	BALLAM 71B	HBC	–	16 $\pi^- p$

$\Gamma(\pi\pi)/\Gamma(4\pi)$ $\qquad\Gamma_2/\Gamma_1$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.332±0.026 OUR FIT	Error includes scale factor of 1.1.			
0.30 ±0.10	BALTAY 78B	HBC	0	15 $\pi^+ p \to p 4\pi$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ $\qquad\Gamma_4/\Gamma_2$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.067±0.011 OUR FIT	Error includes scale factor of 1.2.			
$0.118^{+0.039}_{-0.032}$ OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.			
$0.191^{+0.040}_{-0.037}$	GORLICH 80	ASPK	0	17,18 $\pi^- p$ polarized
0.08 ±0.03	BARTSCH 70B	HBC	+	8 $\pi^+ p$
$0.08\ ^{+0.08}_{-0.03}$	CRENNELL 68B	HBC		6.0 $\pi^- p$



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(K\overline{K}\pi)/\Gamma(\pi\pi)$ $\qquad\Gamma_3/\Gamma_2$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.16±0.05 OUR FIT				
0.16±0.05	[28] BARTSCH 70B	HBC	+	8 $\pi^+ p$

[28] Increased by us to correspond to B($\rho_3(1690) \to \pi\pi$)=0.24.

$\left[\Gamma(\pi\pi\rho) + \Gamma(a_2(1320)\pi) + \Gamma(\rho\rho)\right]/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ $\qquad(\Gamma_6+\Gamma_7+\Gamma_9)/\Gamma_{12}$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.94±0.09 OUR AVERAGE				
0.96±0.21	BALTAY 78B	HBC	+	15 $\pi^+ p \to p 4\pi$
0.88±0.15	BALLAM 71B	HBC	–	16 $\pi^- p$
1 ±0.15	BARTSCH 70B	HBC	+	8 $\pi^+ p$
consistent with 1	CASO 68	HBC	–	11 $\pi^- p$

$\Gamma(\rho\rho)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ $\qquad\Gamma_9/\Gamma_{12}$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.12±0.11		BALTAY 78B	HBC	+	15 $\pi^+ p \to p 4\pi$
0.56	66	KLIGER 74	HBC	–	4.5 $\pi^- p \to p 4\pi$
0.13±0.09		[29] THOMPSON 74	HBC	+	13 $\pi^+ p$
0.7 ±0.15		BARTSCH 70B	HBC	+	8 $\pi^+ p$

[29] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\rho\rho)/\left[\Gamma(\pi\pi\rho) + \Gamma(a_2(1320)\pi) + \Gamma(\rho\rho)\right]$ $\qquad\Gamma_9/(\Gamma_6+\Gamma_7+\Gamma_9)$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.48±0.16	CASO 68	HBC	–	11 $\pi^- p$

$\Gamma(a_2(1320)\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ $\qquad\Gamma_7/\Gamma_{12}$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.66±0.08	BALTAY 78B	HBC	+	15 $\pi^+ p \to p 4\pi$
0.36±0.14	[30] THOMPSON 74	HBC	+	13 $\pi^+ p$
not seen	CASON 73	HBC	–	8,18.5 $\pi^- p$
0.6 ±0.15	BARTSCH 70B	HBC	+	8 $\pi^+ p$
0.6	BALTAY 68	HBC	+	7,8.5 $\pi^+ p$

[30] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\omega\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ $\qquad\Gamma_8/\Gamma_{12}$

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.23±0.05 OUR AVERAGE		Error includes scale factor of 1.2.			
0.33±0.07		THOMPSON 74	HBC	+	13 $\pi^+ p$
0.12±0.07		BALLAM 71B	HBC	–	16 $\pi^- p$
0.25±0.10		BALTAY 68	HBC	+	7,8.5 $\pi^+ p$
0.25±0.10		JOHNSTON 68	HBC	–	7.0 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	95	BALTAY 78B	HBC	+	15 $\pi^+ p \to p 4\pi$
<0.09		KLIGER 74	HBC	–	4.5 $\pi^- p \to p 4\pi$

$\Gamma(\phi\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ $\qquad\Gamma_{10}/\Gamma_{12}$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.11	BALTAY 68	HBC	+	7,8.5 $\pi^- p$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^- \pi^0)/\Gamma(\pi^\pm \pi^+ \pi^- \pi^0)$ Γ_{13}/Γ_{12}

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.15	BALTAY 68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\pi^\pm \pi^+ \pi^- \pi^0)$ Γ_{11}/Γ_{12}

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	THOMPSON 74	HBC	+	13 $\pi^+ p$

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.0158±0.0026 OUR FIT Error includes scale factor of 1.2.				
0.0130±0.0024 OUR AVERAGE				
0.013 ±0.003	COSTA... 80	OMEG	0	10 $\pi^- p \to K^+ K^- n$
0.013 ±0.004	[31] MARTIN 78B	SPEC	–	10 $\pi p \to K^0_S K^- p$

[31] From $(\Gamma_2\Gamma_4)^{1/2} = 0.056 \pm 0.034$ assuming $B(\rho_3(1690) \to \pi\pi) = 0.24$.

$\Gamma(\omega\pi)/[\Gamma(\omega\pi) + \Gamma(\rho\rho)]$ $\Gamma_8/(\Gamma_8+\Gamma_9)$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.08	CASON 73	HBC	–	8,18.5 $\pi^- p$

$\Gamma(\eta\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	FUKUI 88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\rho_3(1690)$ REFERENCES

FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)
MARTIN	78B	NP B140 158	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)
MARTIN	78D	PL 74B 417	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
GESSAROLI	77	NP B126 382	+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM) JP
ESTABROOKS	75	NP B95 322	+Martin	(DURH)
HYAMS	75	NP B100 205	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
KLIGER	74	SJNP 19 428 Translated from YAF 19 839.	+Beketov, Grechko, Guzhavin, Dubovikov+	(ITEP)
OREN	74	NP B71 189	+Cooper, Fields, Rhines, Allison+	(ANL, OXF)
THOMPSON	74	NP B69 220	+Gaidos, McIlwain, Miller, Mulera+	(PURD)
CASON	73	PR D7 1971	+Biswas, Kenney, Madden+	(NDAM)
BOWEN	72	PRL 29 890	+Earles, Faissler, Blieden+	(NEAS, STON)
HOLMES	72	PR D6 3336	+Ferbel, Slattery, Werner	(ROCH)
BALLAM	71B	PR D3 2606	+Chadwick, Guiragossian, Johnson+	(SLAC)
MATTHEWS	71C	NP B33 1	+Prentice, Yoon, Carroll+	(TNTO, WISC) JP
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)
BARNHAM	70	PRL 24 1083	+Colley, Jobes, Kenyon, Pathak, Riddiford	(BIRM)
BARTSCH	70B	NP B22 109	+Kraus, Tsanos, Grote+	(AACH, BERL, CERN)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
STUNTEBECK	70	PL 32B 391	+Kenney, Deery, Biswas, Cason+	(NDAM)
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH, BERL, CERN, JAGL, WARS)
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSA) I
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE) I
CASO	68	NC 54A 983	+Conte, Cords, Diaz+	(GENO, HAMB, MILA, SACL)
CRENNELL	68B	PL 28B 136	+Karshon, Lai, Scarr, Skillicorn	(BNL)
JOHNSTON	68	PRL 20 1414	+Prentice, Steenberg, Yoon	(TNTO, WISC) IJP
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)
GOLDBERG	65	PL 17 354	+	(CERN, EPOL, ORSA, MILA, CEA, SACL)

OTHER RELATED PAPERS

BARNETT	83B	PL 120B 455	+Blockus, Burka, Chien, Christian+	(JHU)
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
FORINO	78	NP B139 413	+Cartacci+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI) JP
MARTIN	78C	ANP 114 1	+Pennington	(CERN)
KALELKAR	75	Nevis 207 Thesis		(COLU) I
DUBOVIKOV	74	SJNP 19 568 Translated from YAF 19 1109.	+Matsyuk, Nilov, Sokolov	(ITEP)
OREN	74	NP B71 189	+Cooper, Fields, Rhines, Allison+	(ANL, OXF)
ARNOLD	73	LNC 6 707	+Engel, Escoubes, Kurtz, Lloret, Paty+	(STRB)
CASON	73B	NP B64 14	+Madden, Bishop, Biswas, Kenney+	(NDAM)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
ROBERTSON	73	PR D7 2554	+Walker, Davis	(DUKE, WISC)
ARMENISE	72B	LNC 4 205	+Forino, Cartacci+	(BARI, BGNA, FIRZ)
Also	75	LNC 14 177	Armenise, Fogli-Muciaccia+	(BARI, BGNA, FIRZ) JP
BOWEN	72	PRL 29 890	+Earles, Faissler, Blieden+	(NEAS, STON)
CLAYTON	72	NP B47 81	+Mason, Muirhead, Rigopoulos+	(LIVP, PATR)
GRAYER	72B	Phil. Conf. 5	+Hyams, Jones, Schlein+	(CERN, MPIM)
GRAYER	71B	PL 35B 610	+Hyams, Jones, Schlein, Blum+	(CERN, MPIM) JP
KRAMER	70	PRL 25 396	+Barton, Gutay, Lichtman, Miller+	(PURD)
BARISH	69	PR 184 1375	+Selove, Biswas, Cason+	(PENN, NDAM, ROCH)
CASO	69	NC 62A 755	+Conte, Benz+	(GENO, DESY, HAMB, MILA, SACL)
VETLITSKY	69	SJNP 9 461 Translated from YAF 9 789.	+Guzhavin, Kliger, Kolganov, Lebedev+	(ITEP)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
CRENNELL	68B	PL 28B 136	+Karshon, Lai, Scarr, Skillicorn	(BNL)
ABRAMS	67B	PRL 18 620	+Kehoe, Glasser, Sechi-Zorn, Wolsky	(UMD)
DUBAL	67	NP B3 435	+Focacci, Kienzle+	(CERN Missing Mass Spect. Collab.)
Also	68	Thesis 1456	Dubal	(GEVA)
FRENCH	67	NC 52A 438	+Kinson, McDonald, Riddiford+	(CERN, BIRM)
EHRLICH	66	PR 152 1194	+Selove, Yuta	(PENN)
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)
SEGUINOT	66	PL 19 712	+Martin+	(CERN Missing Mass Spect. Collab.)
BELLINI	65	NC 40A 948	+DiCorato, Duimio, Fiorini	(MILA)
DEUTSCH...	65	PL 18 351	Deutschmann+	(AACH, BERL, CERN)
FORINO	65	PL 19 65	+Gessaroli+	(BGNA, ORSA, SACL)

$\rho(1700)$

$I^G(J^{PC}) = 1^+(1^{--})$

NOTE ON $\rho(1450)$ AND $\rho(1700)$

In the 1988 edition we replaced the old $\rho(1600)$ entry by two new ones, the $\rho(1450)$ and the $\rho(1700)$, because there was emerging evidence that the 1600 MeV mass region may actually contain two ρ-like resonances. ERKAL 86 had pointed out this possibility with a theoretical analysis on the consistency of 2π and 4π electromagnetic form factors and of the $\pi\pi$ scattering length. DONNACHIE 87, with a full analysis of the data available in the annihilation reactions $e^+e^- \to \pi^+\pi^-$, $2\pi^+2\pi^-$, $\pi^+\pi^-\pi^0\pi^0$ and in the photoproduction reactions $\gamma p \to \pi^+\pi^- p$, $2\pi^+2\pi^- p$, $\pi^+\pi^-\pi^0\pi^0 p$, had also argued that to obtain a consistent picture it was necessary to postulate two resonances, whose masses and widths could be fixed reasonably well. This picture is supported by the analysis of DONNACHIE 87B of the $J^P = 1^-$ $\eta\rho^0$ mass spectra obtained in photoproduction and in e^+e^- annihilation; the analysis shows the need for a contribution from a ρ meson with a mass of about 1.47 GeV, while this data can say very little about a higher mass resonance (actually the data can be explained without it).

The analysis of DONNACHIE 87 is extended by CLEGG 88 to include new data on 4π systems, produced in e^+e^- annihilation and τ-decay (note that 4π τ-lepton decays and 4π annihilation reactions can be related by the Conserved Vector Current assumption). These systems are successfully analysed in terms of interfering contributions from two ρ-like states and from the tail of the $\rho(770)$ decaying into two-body states. While specific conclusions on $\rho(1450) \to 4\pi$ are obtained, the quality of the data used by CLEGG 88 prevents any conclusion on the $\rho(1700) \to 4\pi$ decay.

Independent supporting evidence for two 1^- states is provided by KILLIAN 80 [4π electroproduction at $\langle Q^2 \rangle = 1$ $(\text{GeV}/c)^2$] and FUKUI 88 (high statistics sample of the $\eta\pi\pi$ system in the $\pi^- p$ charge exchange reaction).

This scenario with two overlapping resonances has recently been confirmed by new experimental data. BISELLO 89 has measured the pion form factor in the energy interval 1.35–2.4 GeV with significant statistics (280 $e^+e^- \to \pi^+\pi^-$ events with very low background); a deep minimum is observed around 1.6 GeV, and the best fit to the form factor is obtained with the hypothesis of two ρ-like resonances ≈ 0.25 GeV wide with 1.42 and 1.77 GeV masses. ANTONELLI 88 also finds that the $e^+e^- \to \eta\pi^+\pi^-$ cross section (with three different η

decay modes) is better fitted with two fully interfering Breit-Wigners, whose parameters are in fair agreement with those of DONNACHIE 87 and BISELLO 89.

These new experimental results (although ANTONELLI 88 is statistically less significant than BISELLO 89) have also solved the previous disagreement between DONNACHIE 87 and FUKUI 88 on the $\rho(1450)$ width in favor of the DONNACHIE 87 value. From this point of view, the two experiments can be considered as a solid confirmation of the $\rho(1450)$.

Several observations in the $\omega\pi$ system in the 1200 MeV mass region (FRENKIEL 72, COSME 76, BARBER 80C, ATKINSON 84C, BRAU 88) may be interpreted either in terms of $J^P = 1^-$ $\rho(770) \to \pi\omega$ production (LAYSSAC 71) or in terms of $J^P = 1^+$ $b_1(1235)$ production (BRAU 88). We argue that no special entry for a $\rho(1250)$ is needed. For completeness the relevant observations are listed under $\rho(1450)$.

$\rho(1700)$ MASS

VALUE (MeV)	DOCUMENT ID
1700±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

MIXED MODES

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1712±13 OUR AVERAGE	Includes data from the datablock that follows this one. Error includes scale factor of 1.2.		
1700±25	DONNACHIE 87	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1625±25	GOVORKOV 88	RVUE	
1580±20	[1] BUON 82	DM1	$e^+ e^- \to$ hadrons

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
1740±20	ANTONELLI 88	DM2	$e^+ e^- \to \eta\pi^+\pi^-$
1701±15	FUKUI 88	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1768 ±21	BISELLO 89	DM2	$e^+ e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1546 ±26	GESHKENBEIN 89	RVUE	
1650	[2] ERKAL 85	RVUE	$20\text{–}70\ \gamma p \to \gamma\pi$
1550 ±70	ABE 84B	HYBR	$20\ \gamma p \to \pi^+\pi^- p$
1590 ±20	[3] ASTON 80	OMEG	$20\text{–}70\ \gamma p \to p 2\pi$
1600.0±10.0	[4] ATIYA 79B	SPEC	$50\ \gamma C \to C 2\pi$
$1598.0^{+24.0}_{-22.0}$	BECKER 79	ASPK	$17\ \pi^- p$ polarized
1659 ±25	[2] LANG 79	RVUE	
1575	[2] MARTIN 78C	RVUE	$17\ \pi^- p \to \pi^+\pi^- n$
1610 ±30	[2] FROGGATT 77	RVUE	$17\ \pi^- p \to \pi^+\pi^- n$
1590 ±20	[5] HYAMS 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1582±36	1600	CLELAND 82B	SPEC	+	$50\ \pi p \to K^0_S K^{\pm} p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1520± 30		[3] ASTON 81E	OMEG	$20\text{–}70\ \gamma p \to p 4\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1570± 20		[6] CORDIER 82	DM1	$e^+ e^- \to 2(\pi^+\pi^-)$
1654± 25		[7] DIBIANCA 81	DBC	$\pi^+ d \to p p 2(\pi^+\pi^-)$
1666± 39		[6] BACCI 80	FRAG	$e^+ e^- \to 2(\pi^+\pi^-)$
1780	34	KILLIAN 80	SPEC	$11\ e^- p \to 2(\pi^+\pi^-)$
1500		[8] ATIYA 79B	SPEC	$50\ \gamma C \to C 4\pi^{\pm}$
1570± 60	65	[9] ALEXANDER 75	HBC	$7.5\ \gamma p \to p 4\pi$
1550± 60		[3] CONVERSI 74	OSPK	$e^+ e^- \to 2(\pi^+\pi^-)$
1550± 50	160	SCHACHT 74	STRC	$5.5\text{–}9\ \gamma p \to p 4\pi$
1450±100	340	SCHACHT 74	STRC	$9\text{–}18\ \gamma p \to p 4\pi$
1430± 50	400	BINGHAM 72B	HBC	$9.3\ \gamma p \to p 4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1660±30	ATKINSON 85B	OMEG	$20\text{–}70\ \gamma p$

[1] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^{\pm}\pi^{\mp}$.

[2] From phase shift analysis of HYAMS 73 data.

[3] Simple relativistic Breit-Wigner fit with constant width.

[4] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.

[5] Included in BECKER 79 analysis.

[6] Simple relativistic Breit-Wigner fit with model dependent width.

[7] One peak fit result.

[8] Parameters roughly estimated, not from a fit.

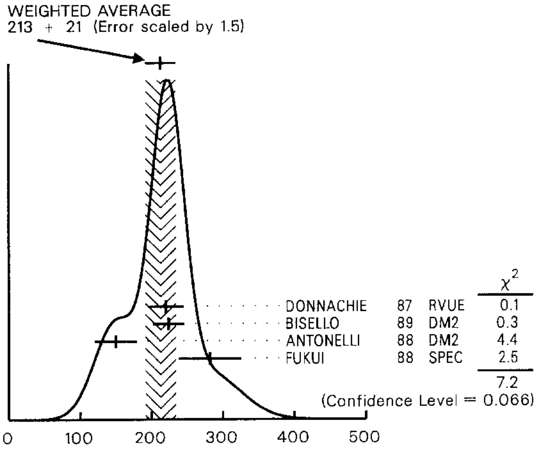
[9] Skew mass distribution compensated by Ross-Stodolsky factor.

$\rho(1700)$ WIDTH

VALUE (MeV)	DOCUMENT ID
235±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

MIXED MODES

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
213±21 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.5. See the ideogram below.		
220±25	DONNACHIE 87	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
250±25	GOVORKOV 88	RVUE	
340±80	[10] BUON 82	DM1	$e^+ e^- \to$ hadrons



$\rho(1700)$ width, mixed modes (MeV)

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
150±30	ANTONELLI 88	DM2	$e^+ e^- \to \eta\pi^+\pi^-$
282±44	FUKUI 88	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
224 ± 22	BISELLO 89	DM2	$e^+ e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
620 ± 60	GESHKENBEIN 89	RVUE	
<315	[11] ERKAL 85	RVUE	$20\text{–}70\ \gamma p \to \gamma\pi$
$280\ ^{+30}_{-80}$	ABE 84B	HYBR	$20\ \gamma p \to \pi^+\pi^- p$
230.0± 80.0	[12] ASTON 80	OMEG	$20\text{–}70\ \gamma p \to p 2\pi$
283.0± 14.0	[13] ATIYA 79B	SPEC	$50\ \gamma C \to C 2\pi$
$175.0^{+98.0}_{-53.0}$	BECKER 79	ASPK	$17\ \pi^- p$ polarized
232 ± 34	[11] LANG 79	RVUE	
340	[11] MARTIN 78C	RVUE	$17\ \pi^- p \to \pi^+\pi^- n$
300 +100	[11] FROGGATT 77	RVUE	$17\ \pi^- p \to \pi^+\pi^- n$
180 ± 50	[14] HYAMS 73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
265±120	1600	CLELAND 82B	SPEC	±	$50\ \pi p \to K^0_S K^{\pm} p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
400± 50		[12] ASTON	81E	OMEG	20–70 $\gamma p \to p4\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
510± 40		[15] CORDIER	82	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
400±146		[16] DIBIANCA	81	DBC	$\pi^+ d \to pp2(\pi^+\pi^-)$
700±160		[15] BACCI	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$
100	34	KILLIAN	80	SPEC	11 $e^- p \to 2(\pi^+\pi^-)$
600		[17] ATIYA	79B	SPEC	50 $\gamma C \to C4\pi^\pm$
340±160	65	[18] ALEXANDER	75	HBC	7.5 $\gamma p \to p4\pi$
360±100		[12] CONVERSI	74	OSPK	$e^+e^- \to 2(\pi^+\pi^-)$
400±120	160	[19] SCHACHT	74	STRC	5.5–9 $\gamma p \to p4\pi$
850±200	340	[19] SCHACHT	74	STRC	9–18 $\gamma p \to p4\pi$
650±100	400	BINGHAM	72B	HBC	9.3 $\gamma p \to p4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300±50	ATKINSON	85B	OMEG	20–70 γp

[10] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm \pi^\mp$.

[11] From phase shift analysis of HYAMS 73 data.

[12] Simple relativistic Breit-Wigner fit with constant width.

[13] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.

[14] Included in BECKER 79 analysis.

[15] Simple relativistic Breit-Wigner fit with model-dependent width.

[16] One peak fit result.

[17] Parameters roughly estimated, not from a fit.

[18] Skew mass distribution compensated by Ross-Stodolsky factor.

[19] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

$\rho(1700)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi\pi$	dominant
Γ_2	$\rho^0\pi^+\pi^-$	large
Γ_3	$\rho^0\pi^0\pi^0$	
Γ_4	$\rho^\pm\pi^\mp\pi^0$	large
Γ_5	$2(\pi^+\pi^-)$	large
Γ_6	$\pi^+\pi^-$	seen
Γ_7	$K\overline{K}^*(892)$ + c.c.	seen
Γ_8	$\eta\rho$	seen
Γ_9	$K\overline{K}$	seen
Γ_{10}	e^+e^-	seen
Γ_{11}	$\rho^0\rho^0$	
Γ_{12}	$\pi\omega$	

$\rho(1700)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the cross-section into channel$_i$ in e^+e^- annihilation.

$\Gamma(2(\pi^+\pi^-)) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_5\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
2.64±0.18 OUR AVERAGE				
2.6 ±0.2	DELCOURT	81B	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
2.83±0.42	BACCI	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$

$\Gamma(\pi^+\pi^-) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_6\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13	[20] DIEKMAN	88	RVUE	$e^+e^- \to \pi^+\pi^-$

[20] Using total width = 220 MeV.

$\Gamma(K\overline{K}^*(892) + \text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_7\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.305±0.071	[21] BIZOT	80	DM1	e^+e^-

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_8\Gamma_{10}/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
7±3	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$

$\Gamma(K\overline{K}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_9\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035±0.029	[21] BIZOT	80	DM1	e^+e^-

$\Gamma(\rho\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.510±0.090	[21] BIZOT	80	DM1	e^+e^-

[21] Model dependent.

$\rho(1700)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.287^{+0.043}_{-0.042}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
0.15 to 0.30	[22] MARTIN	78C	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
<0.20	[23] COSTA...	77B	RVUE	$e^+e^- \to 2\pi, 4\pi$
0.30 ±0.05	[22] FROGGATT	77	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
<0.15	[24] EISENBERG	73	HBC	5 $\pi^+ p \to \Delta^{++}2\pi$
0.25 ±0.05	[25] HYAMS	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
0.20 ±0.05	MONTANET	73	HBC	0.0 $\overline{p}p$

[22] From phase shift analysis of HYAMS 73 data.

[23] Estimate using unitarity, time reversal invariance, Breit-Wigner.

[24] Estimated using one-pion-exchange model.

[25] Included in BECKER 79 analysis.

$\Gamma(\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13±0.05	ASTON	80	OMEG	20–70 $\gamma p \to p2\pi$
<0.14	[26] DAVIER	73	STRC	6–18 $\gamma p \to p4\pi$
<0.2	[27] BINGHAM	72B	HBC	9.3 $\gamma p \to p2\pi$

[26] Upper limit is estimate.

[27] 2σ upper limit.

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(2(\pi^+\pi^-))$ Γ_7/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15±0.03	[28] DELCOURT	81B	DM1	$e^+e^- \to \overline{K}K\pi$

[28] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(\eta\rho)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04		DONNACHIE	87B	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	58	ATKINSON	86B	OMEG	20–70 γp

$\Gamma(\eta\rho)/\Gamma(2(\pi^+\pi^-))$ Γ_8/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.123±0.027	DELCOURT	82	DM1	$e^+e^- \to \pi^+\pi^-$ MM
~ 0.1	ASTON	80	OMEG	20–70 γp

$\Gamma(\pi^+\pi^-\text{ neutrals})/\Gamma(2(\pi^+\pi^-))$ $(\Gamma_3+\Gamma_4+.709\Gamma_8)/\Gamma_5$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.6±0.4	[29] BALLAM	74	HBC	9.3 γp

[29] Upper limit. Background not subtracted.

$\Gamma(K\overline{K})/\Gamma(2(\pi^+\pi^-))$ Γ_9/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.015±0.010		[30] DELCOURT	81B	DM1		$e^+e^- \to \overline{K}K$
<0.04	95	BINGHAM	72B	HBC	0	9.3 γp

[30] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892) + \text{c.c.})$ Γ_9/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.052±0.026	BUON	82	DM1	$e^+e^- \to$ hadrons

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ Γ_2/Γ_5

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1.0		DELCOURT	81B	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
0.7 ±0.1	500	SCHACHT	74	STRC	5.5–18 $\gamma p \to p4\pi$
0.80		[31] BINGHAM	72B	HBC	9.3 $\gamma p \to p4\pi$

[31] The $\pi\pi$ system is in S-wave.

$\Gamma(\rho^0\pi^0\pi^0)/\Gamma(\rho^\pm\pi^\mp\pi^0)$ Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	ATKINSON	85B	OMEG		20–70 γp
<0.15	ATKINSON	82	OMEG	0	20–70 $\gamma p \to p4\pi$

$\rho(1700)$ REFERENCES

BISELLO 89 PL B220 321 +Busetto+ (DM2 Collab.)
GESHKENBEIN 89 ZPHY 45 351 (ITEP)
ANTONELLI 88 PL B212 133 +Baldini+ (DM2 Collab.)
DIEKMAN 88 PRPL 159 101 (BONN)
FUKUI 88 PL B202 441 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
GOVORKOV 88 SJNP 48 150 (JINR)
Translated from YAF 48 237.
DONNACHIE 87 ZPHY C33 407 +Mirzaie (MCHS)
DONNACHIE 87B ZPHY C34 257 +Clegg (MCHS, LANC)
ATKINSON 86B ZPHY C30 531 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 85B ZPHY C26 499 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ERKAL 85 ZPHY C29 485 +Olsson (WISC)
ABE 84B PRL 53 751 +Bacon, Ballam+ (SLAC Hybrid Facility Photon Collab.)
ATKINSON 82 PL 108B 55 + (BONN, CERN, GLAS, LANC, MCHS, CURI+)
BUON 82 PL 118B 221 +Bisello, Bizot, Cordier, Delcourt+ (LALO, MONP)
CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
CORDIER 82 PL 109B 129 +Bisello, Bizot, Buon, Delcourt (LALO)
DELCOURT 82 PL 113B 93 +Bisello, Bizot, Buon, Cordier, Mane (LALO)
ASTON 81E NP B189 15 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT 81B Bonn Conf. 205 (ORSA)
Also 82 PL 109B 129 Cordier, Bisello, Bizot, Buon, Delcourt (LALO)
DIBIANCA 81 PR D23 595 +Fickinger, Malko, Dado, Engler+ (CASE, CMU)
ASTON 80 PL 92B 215 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BACCI 80 PL 95B 139 +DeZorzi, Penso, Baldini-Celio+ (ROMA, FRAS)
BIZOT 80 Madison Conf. 546 +Bisello, Buon, Cordier, Delcourt+ (LALO, USTL)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
ATIYA 79B PRL 43 1691 +Holmes, Knapp, Lee, Seto+ (COLU, ILL, FNAL)
BECKER 79 NP B151 46 +Blanar, Blum+ (MPIM, CERN, ZEEM, CRAC)
LANG 79 PR D19 956 +Mas-Parareda (GRAZ)
MARTIN 78C ANP 114 1 +Pennington (CERN)
COSTA... 77B PL 71B 345 Costa De Beauregard, Pire, Truong (EPOL)
FROGGATT 77 NP B129 89 +Petersen (GLAS, NORD)
ALEXANDER 75 PL 57B 487 +Benary, Gandsman, Lissauer+ (TELA)
BALLAM 74 NP B76 375 +Chadwick, Bingham, Fretter+ (SLAC, LBL, MPIM)
CONVERSI 74 PL 52B 493 +Paoluzi, Ceradini, Grilli+ (ROMA, FRAS)
SCHACHT 74 NP B81 205 +Derado, Fries, Park, Yount (MPIM)
DAVIER 73 NP B58 31 +Derado, Fries, Liu, Mozley, Odian, Park+ (SLAC)
EISENBERG 73 PL 43B 149 +Karshon, Mikenberg, Pitluck+ (REHO)
HYAMS 73 NP B64 134 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
MONTANET 73 Erice School 518 (CERN)
BINGHAM 72B PL 41B 635 +Rabin, Rosenfeld, Smadja+ (LBL, UCB, SLAC) IGJP

OTHER RELATED PAPERS

ACHASOV 88C PLB 209 373 +Kozhevnikov (NOVO)
BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.) JP
CLEGG 88 ZPHY C40 313 +Donnachie (MCHS, LANC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
ERKAL 86 ZPHY C31 615 +Olsson (WISC)
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
BISELLO 85 LAL 85-15 +Augustin, Ajaltouni+ (PADO, LALO, CLER, FRAS)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+) JP
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
ATKINSON 83C NP B229 269 + (BONN, CERN, GLAS, LANC, MCHS, LPNP+)
AUGUSTIN 83 LAL 83-21 +Ayach, Bisello, Baldini+ (LALO, PADO, FRAS)
SHAMBROO 82 PR D26 1 +Wilson, Anderson, Francis+ (HARV, EFI, ILL, OXF)
ASTON 81F PL 104B 231 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT 81 PL 99B 257 +Bisello, Bizot, Buon, Cordier, Mane (ORSA)
ASTON 80F NP B174 269 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BARBER 80C ZPHY C4 169 +Dainton, Brodbeck, Brookes+ (DARE, LANC, SHEF)
HEYN 80 ZPHY C7 169 +Lang (GRAZ)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
O'DONNELL 80 PR D22 711 (TNTO)
BACCI 79 PL 86B 234 +DeZorzi, Penso, Stella+ (ROMA, BGNA, FRAS)
CORDEN 79 NP B157 250 +Dowell, Garvey+ (BIRM, RHEL, TELA, LOWC) JP
CORDIER 79 PL 81B 389 +Delcourt, Eschstruth, Fulda+ (LALO)
COSME 79 NP B152 215 +Dudelzak, Grelaud, Jean-Marie, Jullian+ (IPN)
RICHARD 79 Fermilab Symp. 469 (LALO)
SIDOROV 79 Batavia Conf. 79 490 (NOVO)
GENSINI 78 PR D17 1368 (SLAC)
QUENZER 78 PL 76B 512 +Ribes, Rumpf, Bertrand, Bizot, Chase+ (LALO)
BUDNEV 77 PL 70B 365 +Budnev, Serebryakov (NOVO)
COSTA... 77 PL 67B 213 Costa De Beauregard, Pham, Pire+ (EPOL)
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
BASSOMPIE... 76 PL 65B 397 Bassompierre, Binder+ (MULH, STRB, TORI)
COMMON 76 NP B103 109 (KENT) JP
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSA)
JOHNSON 76 PL 63B 95 +Martin, Pennington (DURH, CERN) JP
ALLES-... 75 NC 30A 136 Alles-Borelli, Bernardini+ (CERN, BGNA, FRAS)
CHUNG 75C PR D11 2436 +Protopopescu, Lynch, Flatte+ (BNL, LBL, USC)
ESTABROOKS 75 NP B95 322 +Martin (DURH)
FROGGATT 75 NP B91 454 +Petersen (GLAS, NORD)
HYAMS 75 NP B100 205 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
LANG 75 PL 58B 450 +Stefanescu (KARL)
LANGACKER 75 PR D13 697 +Segre (PENN)
LEE 75 Stanford Conf. 213 (COLU)
ROOS 75 NP B97 165 (HELS)
BERNABEI 74 LNC 11 261 +Angelo, Spillantini, Valente (ROMA, FRAS)
CHALOUPKA 74 PL 51B 407 +Ferrando, Losty, Montanet (CERN)
ESTABROOKS 74 NP B79 301 +Martin (DURH)
FERBEL 74 PR D9 824 +Slattery (ROCH)
GRAYER 74 NP B75 189 +Hyams, Blum, Dietl+ (CERN, MPIM)
HIRSHFELD 74 NP B74 211 +Kramer (HAMB)
CERADINI 73 PL 43B 341 +Conversi, Ekstrand, Grilli+ (ROMA, FRAS, PADO) IGJP
CHUNG 73 PL 47B 526 +Protopopescu, Lynch, Flatte+ (BNL, LBL, UCSC)
KREUZER 73 PR D8 1431 +Kamal (ALBE)
OCHS 73 Thesis (MPIM)
PARK 73 NP B58 45 (MPIM) JP
BACCI 72 PL 38B 551 +Penso, Salvini, Stella, Baldini-Celio (ROMA, FRAS) JPC
BARBARINO 72 LNC 3 689 +Ceradini+ (FRAS, ROMA, PADO, UMD) IGJP
BARTOLI 72 PR D6 2374 +Felicetti, Ogren+ (FRAS, ROMA, NAPL) IGJP
BRAMON 72 LNC 3 693 +Greco (FRAS)
DIEBOLD 72 Batavia Conf. 3 1 (ANL)
EISENBERG 72 PR D5 15 +Ballam, Dagan+ (REHO, SLAC, TELA)
FRENKIEL 72 NP B47 61 +Ghesquiere, Lillestol, Chung+ (CDEF, CERN)
LAYSSAC 72 NC 10A 407 +Renard (MONP)
SMADJA 72 Phil. Conf. 349 +Bingham, Fretter, Ballam, Chadwick+ (LBL, SLAC)
ALVENSLEBEN 71 PRL 26 273 +Becker, Bertram, Chen+ (DESY, MIT) G
BRAUN 71 NP B30 213 +Fridman, Gerber, Givernaud+ (STRB) G
BULOS 71 PRL 26 149 +Busza, Kehoe, Beniston+ (SLAC, UMD, IBM, LBL) G
LAYSSAC 71 NC 6A 134 +Renard (MONP)

$X(1700)$
was $\eta(1700)$

$I^G(J^{PC}) = \text{EVEN}^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

Enhancement seen in the $\eta\pi\pi$ system produced in the radiative decay of the $J/\psi(1S)$. May contain significant substructure. Relation to other enhancements seen in radiative $J/\psi(1S)$ decay unclear (see HITLIN 83). Tentatively called $X(1700)$ by us.

$X(1700)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1700.0±45	EDWARDS	83B	CBAL	$J/\psi \to \eta\gamma 2\pi$

$X(1700)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
520±110	EDWARDS	83B	CBAL	$J/\psi \to \eta\gamma 2\pi$

$X(1700)$ REFERENCES

EDWARDS 83B PRL 51 859 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
HITLIN 83 Cornell Conf. 746 (CIT)

$f_2(1720)$
was $\theta(1690)$

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

NOTE ON $f_2(1720)$

The $f_2(1720)$ is seen in the "gluon rich" radiative decay $J/\psi(1S) \to \gamma f_2(1720)$, therefore $C = +$. It decays into 2η, which implies $I^G = 0^+$. From the decay angular distribution, $J^P = 0^-$ is ruled out, $J^P = 2^+$ being strongly favored (ARMSTRONG 89D). It is also observed in $K\overline{K}$ systems recoiling against ϕ and ω in hadronic $J/\psi(1S)$ decay [FALVARD 88: however $J/\psi(1S) \to \omega f_2(1720)$ is rather controversial]. The $f_2(1720)$ is not seen in the radiative decay $J/\psi(1S) \to \gamma\rho^0\rho^0$ (BISELLO 89B), in agreement with the indication (BALTRUSAITIS 85G) that the $\rho\rho$ enhancement in this region is $J^P = 0^-$, hence unrelated to the $f_2(1720)$.

Clear evidence is seen for the first time in hadroproduction (ARMSTRONG 89D, 300 GeV/c pp central production of the $K\overline{K}$ system), both in K^+K^- and $K^0_SK^0_S$. Mass and width determinations are complicated since the mass spectra are dominated by the overlap with $f'_2(1525)$. The apparent large disagreement between the widths found by ARMSTRONG 89D in the two different channels ($\approx$ 180 MeV in K^+K^- and $\approx$ 100 MeV in $K^0_SK^0_S$) can be explained by the arbitrariness of the polynomial-exponential background shape which leads to a large systematic error on the width. Note that the $f_2(1720)$ is not observed in the exclusive hypercharge-exchange reaction $K^-p \to K^0_SK^0_S\Lambda$ (ASTON 88D).

A partial-wave analysis of the $K^0_SK^0_S$ system (BOLONKIN 88) finds a D_0 wave ($J^{PC} = 2^{++}$) behavior consistent with $f_2(1720)$, but its width ($\approx$ 30 MeV) is much narrower than the width observed in $J/\psi(1S)$ decays and in hadroproduction.

See also the minireview under non-$q\overline{q}$ candidates.

$f_2(1720)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$1713.2^{+1.9}_{-4.5}$ OUR AVERAGE			
1713 ±10	ARMSTRONG 89D	OMEG	$300\ pp \to ppK^+K^-$
1706 ±10	ARMSTRONG 89D	OMEG	$300\ pp \to ppK^0_SK^0_S$
1707.0±10.0	AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+K^-$
1698 ±15	AUGUSTIN 87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1720 ±10 ±10	BALTRUSAIT..87	MRK3	$J/\psi \to \gamma K^+K^-$
$1730\ {}^{+\ 2}_{-10}$	[1,2] LONGACRE 86	MPS	$22\ \pi^-p \to n2K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1700 ±15	BOLONKIN 88	SPEC	$40\ \pi^-p \to K^0_SK^0_Sn$
1638 ±10	[3] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$
1690 ± 4	[4] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$
1670 ±50	BLOOM 83	CBAL	$J/\psi \to \gamma 2\eta$
1650 ±50	BURKE 82	MRK2	$J/\psi \to \gamma 2\rho$
1708.0±30.0	FRANKLIN 82	MRK2	$e^+e^- \to \gamma K^+K^-$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[2] Fit with constrained inelasticity.

[3] From an analysis ignoring interference with $f_2'(1525)$.

[4] From an analysis including interference with $f_2'(1525)$.

$f_2(1720)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$138\ {}^{+12}_{-\ 9}$ OUR AVERAGE			
181 ± 30	ARMSTRONG 89D	OMEG	$300\ pp \to ppK^+K^-$
104 ± 30	ARMSTRONG 89D	OMEG	$300\ pp \to ppK^0_SK^0_S$
166.4± 33.2	AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+K^-$
136 ± 28	AUGUSTIN 87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
130 ± 20	BALTRUSAIT..87	MRK3	$J/\psi \to \gamma K^+K^-$
$122\ {}^{+74}_{-15}$	[5,6] LONGACRE 86	MPS	$22\ \pi^-p \to n2K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
30 ± 20	BOLONKIN 88	SPEC	$40\ \pi^-p \to K^0_SK^0_Sn$
148 ± 17	[7] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$
184 ± 6	[8] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$
160 ± 80	BLOOM 83	CBAL	$J/\psi \to \gamma 2\eta$
200 ±100	BURKE 82	MRK2	$J/\psi \to \gamma 2\rho$
156.0± 60.0	FRANKLIN 82	MRK2	$e^+e^- \to \gamma K^+K^-$

[5] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[6] Fit with constrained inelasticity.

[7] From an analysis ignoring interference with $f_2'(1525)$.

[8] From an analysis including interference with $f_2'(1525)$.

$f_2(1720)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	$(38\ {}^{+\ 9}_{-19})\ \%$
Γ_2	$\eta\eta$	$(18.0\ {}^{+\ 3.0}_{-13.0})\ \%$
Γ_3	$\pi\pi$	$(\ 3.90^{+\ 0.20}_{-\ 2.40})\ \%$
Γ_4	$\rho\rho$	possibly seen
Γ_5	$\gamma\gamma$	

$f_2(1720)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\qquad \Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.11	95	[9] BEHREND 89C	CELL	$\gamma\gamma \to K^0_SK^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.28	95	[9] ALTHOFF 85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[9] Assuming helicity 2.

$f_2(1720)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ $\qquad \Gamma_1/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$0.38^{+0.09}_{-0.19}$	[10,11] LONGACRE 86	MPS	$22\ \pi^-p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ $\qquad \Gamma_2/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$0.18^{+0.03}_{-0.13}$	[10,11] LONGACRE 86	MPS	$22\ \pi^-p \to n2K^0_S$

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ $\qquad \Gamma_3/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$0.039^{+0.002}_{-0.024}$	[10,11] LONGACRE 86	MPS	$22\ \pi^-p \to n2K^0_S$

[10] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

[11] Fit with constrained inelasticity.

$f_2(1720)$ REFERENCES

ARMSTRONG 89D PL B227 186 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF)
BEHREND 89C ZPHY C43 91 +Criegee, Dainton+ (CELLO Collab.)
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)
BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
FALVARD 88 PR D38 2706 +Ajaltouni+ (CLER, FRAS, LALO, PADO)
AUGUSTIN 87 ZPHY C36 369 +Cosme+ (LALO, CLER, FRAS, PADO)
BALTRUSAIT... 87 PR D35 2077 Baltrusaitis, Coffman, Dubois+ (Mark III Collab.)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
BLOOM 83 ARNS 33 143 +Peck (SLAC, CIT)
BURKE 82 PRL 49 632 +Trilling, Abrams, Alam, Blocker+ (LBL, SLAC)
FRANKLIN 82 SLAC-254 (SLAC)

OTHER RELATED PAPERS

BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
ARMSTRONG 86B PL 167B 133 +Bloodworth, Carney+ (ATHU, BARI, BIRM, CERN)
BALTRUSAIT... 85G PR D33 1222 Baltrusaitis+ (CIT, UCSC, ILL, SLAC, WASH)
ALTHOFF 83 PL 121B 216 +Brandelik, Boerner, Burkhardt+ (TASSO Collab.)
BARNETT 83B PL 120B 455 +Blockus, Burka, Chien, Christian+ (JHU)
ALTHOFF 82 ZPHY C16 13 +Boerner, Burkhardt+ (TASSO Collab.)
BARNES 82 PL 116B 365 +Close (RHEL)
BARNES 82B NP B198 360 +Close, Monaghan (RHEL, OXF)
TANIMOTO 82 PL 116B 198 (BIEL)

$f_0(1750)$
was $S(1730)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Seen in phase-shift analysis of $K^0_SK^0_S$ system and in $\eta\eta$ mass distribution. We also include ALDE 86C here although the quantum numbers are not certain. Needs confirmation.

$f_0(1750)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1720 ±60	BOLONKIN 88	SPEC	$40\ \pi^-p \to K^0_SK^0_Sn$
1755.0± 8.0	ALDE 86C	GAM2	$38\ \pi^-p \to n2\eta$
1742.0±15.0	WILLIAMS 84	MPSF	$200\ \pi^-N \to 2K^0_SX$
1730.0±10 ±20	[1] ETKIN 82C	MPS	$23\ \pi^-p \to n2K^0_S$

[1] From an amplitude analysis of the $K^0_SK^0_S$ system.

$f_0(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
350 ±150	BOLONKIN 88	SPEC	$40\ \pi^-p \to K^0_SK^0_Sn$
50.0± 8.0	ALDE 86C	GAM2	$38\ \pi^-p \to n2\eta$
57.0± 38.0	WILLIAMS 84	MPSF	$200\ \pi^-N \to 2K^0_SX$
$200.0^{+156.0}_{-\ \ 9.0}$	[2] ETKIN 82B	MPS	$23\ \pi^-p \to n2K^0_S$

[2] From an amplitude analysis of the $K^0_SK^0_S$ system.

$f_0(1750)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\eta\eta$

$f_0(1750)$ REFERENCES

BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
ALDE 86C PL B182 105 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)
WILLIAMS 84 PR D30 877 +Diamond+ (VAND, NDAM, TUFT, ARIZ, FNAL+)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFT, VAND) JP
ETKIN 82C PR D25 2446 +Foley, Lai+ (BNL, CUNY, TUFT, VAND)

$\eta(1760)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the 4π system. Needs confirmation.

$\eta(1760)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1760±11	320	[1] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[1] Estimated by us from various fits.

$\eta(1760)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
60±16	320	[2] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[2] Estimated by us from various fits.

$\eta(1760)$ REFERENCES

BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)

$\pi(1770)$

$I^G(J^{PC}) = 1^-(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the diffractively produced 3π system. Needs confirmation.

$\pi(1770)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1770±30	1100	BELLINI	82	SPEC	−	$40\ \pi^- A \to 3\pi A$

$\pi(1770)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
310±50	1100	BELLINI	82	SPEC	−	$40\ \pi^- A \to 3\pi A$

$\pi(1770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$f_0(1400)\pi$	dominant
Γ_2	$\rho\pi$	not seen

$\pi(1770)$ BRANCHING RATIOS

$\Gamma(f_0(1400)\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
dominant	BELLINI	82	SPEC	−	$40\ \pi^- A \to 3\pi A$

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
not seen	BELLINI	82	SPEC	−	$40\ \pi^- A \to 3\pi A$

$\pi(1770)$ REFERENCES

BELLINI 82 PRL 48 1697 +Frabetti, Ivanshin, Litkin+ (MILA, BGNA, JINR)

$f_2(1810)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

From an amplitude analysis of the K^+K^- system seen in $\pi^- p \to K^+K^- n$ at 10 GeV/c. Confirmed by LONGACRE 86. Seen also in $\pi^+\pi^- \to 2\pi^0$ amplitude analysis (CASON 82), in the partial-wave analysis of the $\eta\eta$ system (ALDE 86D) and in the $4\pi^0$ mass spectrum (ALDE 88).

$f_2(1810)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1806 ± 10	1600 ± 100	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
1870 ± 40		[1] ALDE	86D	GAM4	$100\ \pi^- p \to 4\gamma n$
$1858.0^{+18.0}_{-71.0}$		[2] LONGACRE	86	MPS	Compilation
1799.0 ± 15.0		CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$
$1857.0^{+35.0}_{-24.0}$		[3] COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^- n$

[1] Seen in only one solution.

[2] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.

[3] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.

$f_2(1810)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
190 ± 20	1600 ± 100	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
250 ± 30		[4] ALDE	86D	GAM4	$100\ \pi^- p \to 4\gamma n$
$388.0^{+15.0}_{-21.0}$		[5] LONGACRE	86	MPS	Compilation
$280.0^{+42.0}_{-35.0}$		CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$
$185.0^{+102.0}_{-139.0}$		[6] COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^- n$

[4] Seen in only one solution.

[5] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.

[6] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.

$f_2(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	$(21.0^{+2.0}_{-3.0})$ %
Γ_2	$\eta\eta$	$(8.0^{+28.0}_{-3.0}) \times 10^{-3}$
Γ_3	$4\pi^0$	$(6.4^{+23.0}_{-3.4}) \times 10^{-3}$
Γ_4	K^+K^-	$(3.0^{+19.0}_{-2.0}) \times 10^{-3}$

$f_2(1810)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.21^{+0.02}_{-0.03}$	[7] LONGACRE	86	MPS	Compilation
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ± 0.03	[8] CASON	82	STRC	$8\ \pi^+ p \to p\pi^+ 2\pi^0$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.008^{+0.028}_{-0.003}$	[7] LONGACRE	86	MPS	Compilation

$\Gamma(\pi\pi)/\Gamma(4\pi^0)$ Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.75	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.8 ± 0.3	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.003^{+0.019}_{-0.002}$	[7] LONGACRE	86	MPS	Compilation
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^- n$

[7] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.

[8] Included in LONGACRE 86 global analysis.

$f_2(1810)$ REFERENCES

ALDE 88 PL B201 160 +Bellazini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
CASON 82 PRL 48 1316 +Biswas, Baumbaugh, Bishop+ (NDAM, ANL)
COSTA... 80 NP B175 402 Costa De Beauregard+ (BARI, BONN, CERN+)

OTHER RELATED PAPERS

CASON 83 PR D28 1586 +Cannata, Baumbaugh, Bishop+ (NDAM, ANL)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFT, VAND)

$\phi_3(1850)$

was $X(1850)$

was $\phi_J(1850)$

$I^G(J^{PC}) = 0^-(3^{--})$

Seen in the $K\overline{K}$ and $K\overline{K}\pi$ mass distributions.

$\phi_3(1850)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1854 ± 7	**OUR AVERAGE**				
1855 ±10		ASTON	88E	LASS	$11\ K^- p \to K^-K^+\Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
$1870.0^{+30.0}_{-20.0}$	430	ARMSTRONG	82	OMEG	$18.5\ K^- p \to K^-K^+\Lambda$
1850.0±10.0	123	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$87\ ^{+28}_{-23}$	**OUR AVERAGE**	Error includes scale factor of 1.2.			
64 ±31		ASTON	88E	LASS	$11\ K^- p \to K^-K^+\Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
$160.0^{+90.0}_{-50.0}$	430	ARMSTRONG	82	OMEG	$18.5\ K^- p \to K^-K^+\Lambda$
$80.0^{+40.0}_{-30.0}$	123	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$K\overline{K}^*(892)$ + c.c.	seen

$\phi_3(1850)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892) + \text{c.c.})/\Gamma(K\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$0.55^{+0.85}_{-0.45}$	ASTON	88E	LASS	$11\ K^- p \to K^-K^+\Lambda$, $K^0_S K^\pm \pi^\mp \Lambda$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8 ±0.4	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\pi\Lambda$

$\phi_3(1850)$ REFERENCES

ASTON 88E PL B208 324 +Awaji, Biewz+ (SLAC, NAGO, CINC, TOKY) IGJPC
ARMSTRONG 82 PL 110B 77 +Baubillier+ (BARI, BIRM, CERN, MILA, LPNP+) JP
ALHARRAN 81B PL 101B 357 +Amirzadeh+ (BIRM, CERN, GLAS, MICH, LPNP)

OTHER RELATED PAPERS

CORDIER 82B PL 110B 335 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 80B PL 92B 219 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$f_2(1920)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen by ALDE 89B in $\omega\omega$ mass distribution. Needs confirmation.

$f_2(1920)$ MASS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
1924±14		[2] SINGOVSKY	90	GAM2	$38\ \pi^- p \to n\omega\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1956±20	90	[1] ALDE	89B	GAM2	$38\ \pi^- p \to n\omega\omega$

[1] Signal seen as superimposition of $f_2(1920)$ and $f_4(2050)$.

[2] This result supersedes ALDE 89B.

$f_2(1920)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
91±50		[4] SINGOVSKY	90	GAM2	$38\ \pi^- p \to n\omega\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
220±60	90	[3] ALDE	89B	GAM2	$38\ \pi^- p \to n\omega\omega$

[3] Signal seen as superimposition of $f_2(1920)$ and $f_4(2050)$.

[4] This result supersedes ALDE 89B.

$f_2(1920)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	seen

$f_2(1920)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ALDE	89B	GAM2	$38\ \pi^- p \to n\omega\omega$

$f_2(1920)$ REFERENCES

SINGOVSKY 90 Hadron 89 Conf. (SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE 89B PL B216 451 +Binon, Bricman+ (SERP, BELG, LANL, LAPP, TBLI) IGJPC

$X(1920)$

$I^G(J^{PC}) = 0^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

Seen by (ALDE 89) in $\eta\eta'$ mass distribution. Needs confirmation.

$X(1920)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1911±10	[1] PROKOSHKIN	90	GAM2	$38\ \pi^- p \to \eta\eta' n$

[1] These results supersede ALDE 89 and ALDE 86C.

$X(1920)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
90±35	[2] PROKOSHKIN	90	GAM2	$38\ \pi^- p \to \eta\eta' n$

[2] These results supersede ALDE 89 and ALDE 86C.

$X(1920)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta'$	seen
Γ_2	$\eta\eta$	
Γ_3	$\pi^0\pi^0$	
Γ_4	$K^0_S K^0_S$	

$X(1920)$ BRANCHING RATIOS

$\Gamma(\eta\eta')/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ALDE	89	GAM2	$38\pi^- p \to n\eta\eta'$

$\Gamma(\eta\eta)/\Gamma(\eta\eta')$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	[3] PROKOSHKIN 90	GAM2	$38\ \pi^- p \rightarrow \eta\eta' n$

[3] These results supersede ALDE 89 and ALDE 86C.

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta')$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.1	90	ALDE 89	GAM2	$38\pi^- p \rightarrow n\eta\eta'$

$\Gamma(K_S^0 K_S^0)/\Gamma(\eta\eta')$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.066	90	BALOSHIN 86	SPEC	$40\pi p \rightarrow K_S^0 K_S^0 n$

$X(1920)$ REFERENCES

PROKOSHKIN	90	Hadron 89 Conf.		(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	89	PL B216 447	+Binon, Bricman, Donskov+	(SERP, BELG, LANL, LAPP) IG
ALDE	86C	PL B182 105	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
BALOSHIN	86	SJNP 43 959 Translated from YAF 43 1487.	+Barkov, Bolonkin, Vladimirskii, Grigoriev+	(ITEP)

$f_2(2010)$

was $g_T(2010)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2010)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$2011\ ^{+62}_{-76}$	[1] ETKIN 88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1980 ± 20	[2] BOLONKIN 88	SPEC	$40\ \pi^- p \rightarrow K_S^0 K_S^0 n$
$2050.0^{+90.0}_{-50.0}$	ETKIN 85	MPS	$22\ \pi^- p \rightarrow 2\phi n$
$2120.0^{+20.0}_{-120.0}$	LINDENBAUM 84	RVUE	
2160.0 ± 50.0	ETKIN 82	MPS	$16\ \pi^- p \rightarrow 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi\ 2^{++}\ S_2$, D_2, and D_0 is 98^{+1}_{-3}, 0^{+1}_{-0}, and 2^{+2}_{-1}, respectively.

[2] Statistically very weak, only 1.4 sigma.

$f_2(2010)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$202\ ^{+67}_{-62}$	[3] ETKIN 88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
145 ± 50	[4] BOLONKIN 88	SPEC	$40\ \pi^- p \rightarrow K_S^0 K_S^0 n$
$200.0^{+160.0}_{-50.0}$	ETKIN 85	MPS	$22\ \pi^- p \rightarrow 2\phi n$
$300.0^{+150.0}_{-50.0}$	LINDENBAUM 84	RVUE	
310.0 ± 70.0	ETKIN 82	MPS	$16\ \pi^- p \rightarrow 2\phi n$

[3] Includes data of ETKIN 85.

[4] Statistically very weak, only 1.4 sigma.

$f_2(2010)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2010)$ REFERENCES

BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
Also	83	Brighton Conf. 351	Lindenbaum	(BNL, CUNY)

OTHER RELATED PAPERS

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$a_4(2040)$

$I^G(J^{PC}) = 1^-(4^{++})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K\overline{K}$ and $\pi^+\pi^-\pi^0$ systems. Needs confirmation.

$a_4(2040)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2037 ±26 OUR AVERAGE				
2040.0 ± 30.0	[1] CLELAND 82B	SPEC	±	$50\ \pi p \rightarrow K_S^0 K^\pm p$
2030.0 ± 50.0	[2] CORDEN 78C	OMEG	0	$15\ \pi^- p \rightarrow 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1903.0 ± 10.0	[3] BALDI 78	SPEC	−	$10\ \pi^- p \rightarrow p K_S^0 K^-$

[1] From an amplitude analysis.

[2] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.

[3] From a fit to the Y_8^0 moment. Limited by phase space.

$a_4(2040)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
427 ±120 OUR AVERAGE				
380.0 ± 150.0	[4] CLELAND 82B	SPEC	±	$50\ \pi p \rightarrow K_S^0 K^\pm p$
510.0 ± 200.0	[5] CORDEN 78C	OMEG	0	$15\ \pi^- p \rightarrow 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
166.0 ± 43.0	[6] BALDI 78	SPEC	−	$10\ \pi^- p \rightarrow p K_S^0 K^-$

[4] From an amplitude analysis.

[5] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.

[6] From a fit to the Y_8^0 moment. Limited by phase space.

$a_4(2040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\pi^+\pi^-\pi^0$	seen

$a_4(2040)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	BALDI 78	SPEC	±	$10\ \pi^- p \rightarrow K_S^0 K^- p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
seen	CORDEN 78C	OMEG	0	$15\ \pi^- p \rightarrow 3\pi n$

$a_4(2040)$ REFERENCES

CLELAND	82B	NP B208 228	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
BALDI	78	PL 74B 413	+Bohringer, Dorsaz, Hungerbuhler+	(GEVA) JP
CORDEN	78C	NP B136 77	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP

OTHER RELATED PAPERS

DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)

$a_3(2050)$ was $A(2050)$

$I^G(J^{PC}) = 1^-(3^{++})$

OMITTED FROM SUMMARY TABLE

Formerly called A_4 or π. Needs confirmation.

$a_3(2050)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2080±40	208	KALELKAR	75	HBC	+	15 $\pi^+ p \to p \pi^+ \rho_3$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
~ 2100		ANTIPOV	77	CIBS	−	25 $\pi^- p \to p \pi^- \rho_3$
2214±15		BALTAY	77	HBC	0	15 $\pi^- p \to \Delta^{++} 3\pi$

$a_3(2050)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
340±80	208	KALELKAR	75	HBC	+	15 $\pi^+ p \to p \pi^+ \rho_3$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
~ 500		ANTIPOV	77	CIBS	−	25 $\pi^- p \to p \pi^- \rho_3$
355±21		BALTAY	77	HBC	0	15 $\pi^- p \to \Delta^{++} 3\pi$

$a_3(2050)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	
Γ_2	$\rho_3(1690)\pi$	dominant

$a_3(2050)$ BRANCHING RATIOS

$\Gamma(\rho_3(1690)\pi)/\Gamma(3\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
dominant	KALELKAR	75	HBC	+	15 $\pi^+ p \to p 3\pi$

$a_3(2050)$ REFERENCES

ANTIPOV 77 NP B119 45 +Busnello, Damgaard, Kienzle+ (SERP, GEVA)
BALTAY 77 PRL 39 591 +Cautis, Kalelkar (COLU) JP
KALELKAR 75 Nevis 207 Thesis (COLU)

OTHER RELATED PAPERS

HARRIS 81 ZPHY C9 275 +Dunn, Lubatti, Moriyasu, Podolsky+ (SEAT, UCB)
BALTAY 78 PR D17 52 +Cautis, Cohen, Csorna, Kalelkar+ (COLU, BING)
CAUTIS 77 Nevis 221 Thesis (COLU) JP
DEUTSCH... 75 NP B99 397 Deutschmann, Kirk, Sixel, Boeckmann+(ABBCCHW Collab.)
OREN 74 NP B71 189 +Cooper, Fields, Rhines, Allison+ (ANL, OXF)
BASTIEN 73 Uppsala Conf. 73 +Dunn, Harris, Lubatti, Bingham+ (SEAT, UCB)
CLAYTON 72 NP B47 81 +Mason, Muirhead, Rigopoulos+ (LIVP, PATR)
HARRISON 72 PRL 28 775 +Heyda, Johnson, Kim, Law, Mueller+ (HARV)
SALZBERG 72 NP B41 397 +Harrison, Heyda, Johnson, Kim, Law+ (HARV)
BEMPORAD 71 NP B33 397 +Beusch, Melissinos+ (CERN, ETH, LOIC, MILA)
HUSON 68 PL 28B 208 +Lubatti, Six, Veillet+ (ORSA, MILA, UCLA)
DANYSZ 67B NC 51A 801 +French, Simak (CERN)

$f_4(2050)$ was $h(2030)$

$I^G(J^{PC}) = 0^+(4^{++})$

$f_4(2050)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2049 ±10	**OUR AVERAGE**	Error includes scale factor of 1.2.			
2060 ±20		SINGOVSKY	90	GAM2	38 $\pi^- p \to n\omega\omega$
2038 ±30		AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
2086 ±15		BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
2000.0±60.0		ALDE	86D	GAM4	100 $\pi^- p \to n 2\eta$
2020.0±20.0	40k	[1] BINON	84B	GAM2	38 $\pi^- p \to n 2\pi^0$
2015.0±28.0		[1] CASON	82	STRC	8 $\pi^+ p \to p\pi^+ 2\pi^0$
2031.0^{+25}_{-36}		ETKIN	82B	MPS	23 $\pi^- p \to n 2K^0_S$
2020 ±30	700	APEL	75	CNTR	40 $\pi^- p \to n 2\pi^0$
2050 ±25		BLUM	75	ASPK	18.4 $\pi^- p \to n K^+ K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1978.0± 5.0		[2] ALPER	80	CNTR	62 $\pi^- p \to K^+ K^- n$
2040.0±10.0		[2] ROZANSKA	80	SPRK	18 $\pi^- p \to p\overline{p}n$
1935.0±13.0		[2] CORDEN	79	OMEG	12–15 $\pi^- p \to n 2\pi$
1988.0± 7.0		EVANGELISTA	79B	OMEG	10 $\pi^- p \to K^+ K^- n$
1922.0±14.0		[3] ANTIPOV	77	CIBS	25 $\pi^- p \to p 3\pi$

[1] From amplitude analysis of reaction $\pi^+\pi^- \to 2\pi^0$.

[2] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.

[3] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

$f_4(2050)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
203 ± 12	**OUR AVERAGE**				
170 ± 60		SINGOVSKY	90	GAM2	38 $\pi^- p \to n\omega\omega$
304 ± 60		AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
210 ± 63		BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
400.0±100.0		ALDE	86D	GAM4	100 $\pi^- p \to n 2\eta$
240.0± 40.0	40k	[4] BINON	84B	GAM2	38 $\pi^- p \to n 2\pi^0$
190.0± 14.0		DENNEY	83	LASS	10 $\pi^+ n/\pi^+ p$
$186.0^{+103.0}_{-58.0}$		[4] CASON	82	STRC	8 $\pi^+ p \to p\pi^+ 2\pi^0$
305.0^{+36}_{-119}		ETKIN	82B	MPS	23 $\pi^- p \to n 2K^0_S$
180 ± 60	700	APEL	75	CNTR	40 $\pi^- p \to n 2\pi^0$
$225\ ^{+120}_{-70}$		BLUM	75	ASPK	18.4 $\pi^- p \to n K^+ K^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
243.0± 16.0		[5] ALPER	80	CNTR	62 $\pi^- p \to K^+ K^- n$
140.0± 15.0		[5] ROZANSKA	80	SPRK	18 $\pi^- p \to p\overline{p}n$
263.0± 57.0		[5] CORDEN	79	OMEG	12–15 $\pi^- p \to n 2\pi$
100.0± 28.0		EVANGELISTA	79B	OMEG	10 $\pi^- p \to K^+ K^- n$
107.0± 56.0		[6] ANTIPOV	77	CIBS	25 $\pi^- p \to p 3\pi$

[4] From amplitude analysis of reaction $\pi^+\pi^- \to 2\pi^0$.

[5] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.

[6] Width errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

$f_4(2050)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	(25 ±6) %
Γ_2	$\pi\pi$	(17.0±1.5) %
Γ_3	$K\overline{K}$	$(6.8^{+3.4}_{-1.8}) \times 10^{-3}$
Γ_4	$\eta\eta$	$(2.1\pm0.8) \times 10^{-3}$
Γ_5	$4\pi^0$	< 1.2 %
Γ_6	$\gamma\gamma$	

$f_4(2050)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_3\Gamma_6/\Gamma$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.29	95	ALTHOFF	85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

$f_4(2050)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma(\pi\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.5±0.3	SINGOVSKY	90	GAM2	38 $\pi^- p \to n\omega\omega$

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.170±0.015 OUR AVERAGE				
0.18 ±0.03	[7] BINON	83C	GAM2	38 $\pi^- p \to n4\gamma$
0.16 ±0.03	[7] CASON	82	STRC	8 $\pi^+ p \to p\pi^+ 2\pi^0$
0.17 ±0.02	[7] CORDEN	79	OMEG	12–15 $\pi^- p \to n2\pi$

[7] Assuming one pion exchange.

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
$0.04^{+0.02}_{-0.01}$	ETKIN	82B	MPS	23 $\pi^- p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.1±0.8	ALDE	86D	GAM4	100 $\pi^- p \to n4\gamma$

$\Gamma(4\pi^0)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.012	ALDE	87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$f_4(2050)$ REFERENCES

SINGOVSKY	90	Hadron 89 Conf.		(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
BINON	84B	LNC 39 41	+Donskov, Duteil, Gouanere+	(SERP, BELG, LAPP)
BINON	83C	SJNP 38 723 Translated from YAF 38 1199.	+Gouanere, Donskov, Duteil+	(SERP, BRUX+)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
ROZANSKA	80	NP B162 505	+Blum, Dietl, Grayer, Lorenz+	(MPIM, CERN)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
APEL	75	PL 57B 398	+Augenstein+	(KARL, PISA, SERP, WIEN, CERN) JP
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM) JP

OTHER RELATED PAPERS

CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
GOTTESMAN	80	PR D22 1503	+Jacobs+	(SYRA, BRAN, BNL, CINC)
WAGNER	74	London Conf. 2 27		(MPIM)

$\eta(2100)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the 4π system. Needs confirmation.

$\eta(2100)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2103±50	586	[1] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[1] Estimated by us from various fits.

$\eta(2100)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
187±75	586	[2] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[2] Estimated by us from various fits.

$\eta(2100)$ REFERENCES

BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)

$\pi_2(2100)$
was $A(2100)$

$I^G(J^{PC}) = 1^-(2^{-+})$

OMITTED FROM SUMMARY TABLE

Seen in the $\rho\pi$, $f_0(1400)\pi$, and $f_2(1270)\pi$ $J^P = 2^-$ waves of the diffractively produced 3π system. Needs confirmation.

$\pi_2(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100±150	[1] DAUM	81B	CNTR	63,94 $\pi^- p \to 3\pi X$

[1] From a two-resonance fit to four $2^- 0^+$ waves.

$\pi_2(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
651±50	[2] DAUM	81B	CNTR	63,94 $\pi^- p \to 3\pi X$

[2] From a two-resonance fit to four $2^- 0^+$ waves.

$\pi_2(2100)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	seen
Γ_2	$\rho\pi$	seen
Γ_3	$f_2(1270)\pi$	seen
Γ_4	$f_0(1400)\pi$	seen

$\pi_2(2100)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(3\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.19±0.05	[3] DAUM	81B	CNTR	63,94 $\pi^- p$

$\Gamma(f_2(1270)\pi)/\Gamma(3\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.36±0.09	[3] DAUM	81B	CNTR	63,94 $\pi^- p$

$\Gamma(f_0(1400)\pi)/\Gamma(3\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.45±0.07	[3] DAUM	81B	CNTR	63,94 $\pi^- p$

D-wave/S-wave RATIO FOR $\pi_2(2100) \to f_2(1270)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
0.39±0.23	[3] DAUM	81B	CNTR	63,94 $\pi^- p$

[3] From a two-resonance fit to four $2^- 0^+$ waves.

$\pi_2(2100)$ REFERENCES

DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$f_2(2150)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

This entry was previously called T_0. Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $\rho_3(2250)$, $f_4(2300)$, $\rho_5(2350)$.

$f_2(2150)$ MASS

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2170.0	[1] MARTIN	80B	RVUE	
~ 2150.0	[1] MARTIN	80C	RVUE	
~ 2150.0	[2] DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[1] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[2] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\bar{p}p$ or $\bar{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190.0	[3] CUTTS	78B	CNTR		0.97–$3\ \bar{p}p \to \bar{N}N$
2155.0±15.0	[3,4] COUPLAND	77	CNTR	0	0.7–$2.4\ \bar{p}p \to \bar{p}p$
2193 ± 2	[3,5] ALSPECTOR	73	CNTR		$\bar{p}p$ S channel

[3] Isospins 0 and 1 not separated.
[4] From a fit to the total elastic cross section.
[5] Referred to as T or T region by ALSPECTOR 73.

$f_2(2150)$ WIDTH

$\bar{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 250.0	[6] MARTIN	80B	RVUE	
~ 250.0	[6] MARTIN	80C	RVUE	
~ 250.0	[7] DULUDE	78B	OSPK	1–$2\ \bar{p}p \to \pi^0\pi^0$

[6] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\bar{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[7] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\bar{p}p$ or $\bar{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135.0±75.0	[8,9] COUPLAND	77	CNTR	0	0.7–$2.4\ \bar{p}p \to \bar{p}p$
98 ± 8	[9] ALSPECTOR	73	CNTR		$\bar{p}p$ S channel

[8] From a fit to the total elastic cross section.
[9] Isospins 0 and 1 not separated.

$f_2(2150)$ DECAY MODES

	Mode
Γ_1	$\pi\pi$

$f_2(2150)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)

OTHER RELATED PAPERS

BOWCOCK	80	LNC 28 21	+Hodgson	(BIRM)
MARTIN	79B	PL 86B 93	+Pennington	(DURH)
DULUDE	78	PL 79B 329	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
GAY	76	NC 31A 593	+Jeanneret, Bogdanski+	(NEUC, LAUS, LIVP, LPNP)
BACON	73	PR D7 577	+Butterworth+	(RHEL, LIVP)
DONALD	73	NP B61 333	+Edwards, Gibbins, Briand, Duboc+	(LIVP, LPNP)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
DONALD	72	PL 40B 586	+Galletly, Edwards, DeBilly+	(LIVP, LPNP)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)

$\rho(2150)$

$I^G(J^{PC}) = 1^+(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $T_1(2190)$. Contains results only from formation experiments. For production experiments see the $\bar{N}N(1100$–$3600)$ entry. See also $f_2(2150)$, $\rho_3(2250)$, $f_4(2300)$, $\rho_5(2350)$.

Our latest mini-review on this particle can be found in the 1984 edition.

$\rho(2150)$ MASS

$\bar{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 2170.0	[1] MARTIN	80B	RVUE
~ 2100.0	[1] MARTIN	80C	RVUE

S-CHANNEL $\bar{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190.0	[2] CUTTS	78B	CNTR		0.97–$3\ \bar{p}p \to \bar{N}N$
2155.0±15.0	[2,3] COUPLAND	77	CNTR	0	0.7–$2.4\ \bar{p}p \to \bar{p}p$
2193 ± 2	[2,4] ALSPECTOR	73	CNTR		$\bar{p}p$ S channel
2190 ±10	[5] ABRAMS	70	CNTR		S channel $\bar{p}N$

[1] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\bar{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] Isospins 0 and 1 not separated.
[3] From a fit to the total elastic cross section.
[4] Referred to as T or T region by ALSPECTOR 73.
[5] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\bar{p}p$ results of ABRAMS 70, no narrow structure.

$\rho(2150)$ WIDTH

$\bar{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 250.0	[6] MARTIN	80B	RVUE
~ 200.0	[6] MARTIN	80C	RVUE

S-CHANNEL $\bar{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135.0±75.0	[7,8] COUPLAND	77	CNTR	0	0.7–$2.4\ \bar{p}p \to \bar{p}p$
98 ± 8	[8] ALSPECTOR	73	CNTR		$\bar{p}p$ S channel
~ 85	[9] ABRAMS	70	CNTR		S channel $\bar{p}N$

[6] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\bar{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[7] From a fit to the total elastic cross section.
[8] Isospins 0 and 1 not separated.
[9] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\bar{p}p$ results of ABRAMS 70, no narrow structure.

$\rho(2150)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

OTHER RELATED PAPERS

MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
CARTER	78B	NP B141 467		(LOQM)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
JONES	77	NP B119 476	+Plano	(RUTG)
MONTANET	77	Boston Conf. 260		(CERN)
GAY	76	NC 31A 593	+Jeanneret, Bogdanski+	(NEUC, LAUS, LIVP, LPNP)
ZEMANY	76	NP B103 537	+MingMa, Mountz, Smith	(MSU)
DONNACHIE	75	NC 26A 317	+Thomas	(MCHS)
EISENHAND...	75	NP B96 109	Eisenhandler, Gibson+	(LOQM, LIVP, DARE, RHEL)
HANDLER	75	NP B101 35	+Jacques, Jones, Pandoulas+	(RUTG, STEV, ALBA)
HUESMAN	75	NC 25A 91	+Alston-Garnjost, Ross+	(LBL, PADO, PISA, TORI)
BERTANZA	74	NC 23A 209	+Bigi, Casali, Lariccia+	(PISA, PADO, TORI)
HYAMS	74	NP B73 202	+Jones, Weilhammer, Blum+	(CERN, MPIM)
BACON	73	PR D7 577	+Butterworth+	(RHEL, LIVP)
BETTINI	73	NC 15A 563	+Alston-Garnjost, Bigi+	(PADO, LBL, PISA, TORI)
DONALD	73	NP B61 333	+Edwards, Gibbins, Briand, Duboc+	(LIVP, LPNP)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
ALEXANDER	72	NP B45 29	+Bar-Nir, Benary, Dagan+	(TELA)
DONALD	72	PL 40B 586	+Galletly, Edwards, DeBilly+	(LIVP, LPNP)
BACON	71	NP B32 66	+Butterworth, Miller, Phelan+	(RHEL, LIVP)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$f_2(2175)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen in central production of $\eta\eta$ system.

$f_2(2175)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2175±20	PROKOSHKIN 90	GAM4	$300\ \pi^- p \to \pi^- p\eta\eta$

$f_2(2175)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
150±35	PROKOSHKIN 90	GAM4	$300\ \pi^- p \to \pi^- p\eta\eta$

$f_2(2175)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta$	seen

$f_2(2175)$ BRANCHING RATIOS

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID
• • • We do not use the following data for averages, fits, limits, etc. • • •	
seen	PROKOSHKIN 90

$f_2(2175)$ REFERENCES

PROKOSHKIN 90 Hadron 89 Conf. (SERP, BELG, LANL, LAPP, PISA, KEK)

$X(2200)$

$I^G(J^{PC}) = ?^?(\text{EVEN}^{++})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the $K^0_S K^0_S$ system. Not seen in Υ radiative decays (BARU 89). Needs confirmation.

$X(2200)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2197±17	AUGUSTIN	88	DM2	0	$J/\psi \to \gamma K^0_S K^0_S$

$X(2200)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
201±51	AUGUSTIN	88	DM2	0	$J/\psi \to \gamma K^0_S K^0_S$

$X(2200)$ REFERENCES

BARU 89 ZPHY C42 505 +Beilin, Blinov+ (NOVO)
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)

$f_4(2220)$
was $\xi(2220)$

$I^G(J^{PC}) = 0^+(4^{++})$

OMITTED FROM SUMMARY TABLE

This state has been seen at SPEAR in the $K\overline{K}$ systems (K^+K^- and $K^0_S K^0_S$) produced in the radiative decay of $J/\psi(1S)$. Seen in $\eta\eta'$ (ALDE 86B) and in $K^0_S K^0_S$ (ASTON 88D). Needs confirmation. Not seen in Υ radiative decays nor in B inclusive decay (BEHRENDS 84). Not seen in $\overline{p}p \to K^+K^-$ formation experiment (SCULLI 87). Not seen at DCI in either K^+K^- or $K^0_S K^0_S$ systems (AUGUSTIN 88).

$f_4(2220)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2225± 6 OUR AVERAGE					
$2209^{+17}_{-15}\pm10$		ASTON	88F	LASS	$11\ K^-p \to K^+K^-\Lambda$
2230±20		BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
2220±10	41	ALDE	86B	GAM4	$38\text{–}100\ \pi p \to n\eta\eta'$
2230± 6±14	93	BALTRUSAIT...	86D	MRK3	$e^+e^- \to \gamma K^+K^-$
2232± 7± 7	23	BALTRUSAIT...	86D	MRK3	$e^+e^- \to \gamma K^0_S K^0_S$

$f_4(2220)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
38^{+15}_{-13} OUR AVERAGE					
60^{+107}_{-57}		ASTON	88F	LASS	$11\ K^-p \to K^+K^-\Lambda$
80± 30		BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
$26^{+20}_{-16}\pm17$	93	BALTRUSAIT...	86D	MRK3	$e^+e^- \to \gamma K^+K^-$
$18^{+23}_{-15}\pm10$	23	BALTRUSAIT...	86D	MRK3	$e^+e^- \to \gamma K^0_S K^0_S$

$f_4(2220)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\gamma\gamma$
Γ_3	$\eta\eta'(958)$

$f_4(2220)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_2/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.0	95	[1] ALTHOFF	85B	TASS	$\gamma\gamma$, $K\overline{K}\pi$

[1] True for $J^P = 0^+$ and $J^P = 2^+$.

$f_4(2220)$ REFERENCES

ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY)
ASTON 88F PL B215 199 +Awaji+ (SLAC, NAGO, CINC, TOKY) JP
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)
BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
SCULLI 87 PRL 58 1715 +Christenson, Kreiter, Nemethy, Yamin (NYU, BNL)
ALDE 86B PL B177 120 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)
BALTRUSAIT... 86D PRL 56 107 Baltrusaitis (CIT, UCSC, ILL, SLAC, WASH)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
BEHRENDS 84 PL 137B 277 +Chadwich, Chauveau, Gentile+ (CLEO Collab.)

OTHER RELATED PAPERS

BARDIN 87 PL B195 292 +Burgun+ (SACL, FERR, CERN, PADO, TORI)
YAOUANC 85 ZPHY C28 309 +Oliver, Pene, Raynal, Ono (ORSA, TOKY)
GODFREY 84 PL 141B 439 +Kokoski, Isgur (TNTO)
SHATZ 84 PL 138B 209 (CIT)
WILLEY 84 PRL 52 585 (PITT)
EINSWEILER 83 Brighton Conf. 348 (Mark III Collab.)
HITLIN 83 Cornell Conf. 746 (CIT)

$\rho_3(2250)$

$I^G(J^{PC}) = 1^+(3^{--})$

OMITTED FROM SUMMARY TABLE

Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $f_4(2300)$, $\rho_5(2350)$.

$\rho_3(2250)$ MASS

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2250.0	[1] MARTIN	80B	RVUE		
~ 2300.0	[1] MARTIN	80C	RVUE		
~ 2140.0	[2] CARTER	78B	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to K^-K^+$
~ 2150.0	[3] CARTER	77	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to \pi\pi$

[1] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.
[3] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190.0	[4] CUTTS	78B	CNTR		$0.97\text{–}3\ \overline{p}p \to \overline{N}N$
2155.0±15.0	[4,5] COUPLAND	77	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to \overline{p}p$
2193 ± 2	[4,6] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
2190 ±10	[7] ABRAMS	70	CNTR		S channel $\overline{p}N$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as T or T region by ALSPECTOR 73.
[7] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ WIDTH

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	[8] MARTIN	80B	RVUE		
~ 200.0	[8] MARTIN	80C	RVUE		
~ 150.0	[9] CARTER	78B	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to K^-K^+$
~ 200.0	[10] CARTER	77	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to \pi\pi$

[8] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[9] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.
[10] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135.0±75.0	[11,12] COUPLAND	77	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to \overline{p}p$
98 ± 8	[12] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
~ 85	[13] ABRAMS	70	CNTR		S channel $\overline{p}N$

[11] From a fit to the total elastic cross section.
[12] Isospins 0 and 1 not separated.
[13] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

OTHER RELATED PAPERS

MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
MONTANET	77	Boston Conf. 260		(CERN)
ZEMANY	76	NP B103 537	+MingMa, Mountz, Smith	(MSU)
BERTANZA	74	NC 23A 209	+Bigi, Casali, Lariccia+	(PISA, PADO, TORI)
BETTINI	73	NC 15A 563	+Alston-Garnjost, Bigi+	(PADO, LBL, PISA, TORI)
DONNACHIE	73	LNC 7 285	+Thomas	(MCHS)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$f_2(2300)$
was $g'_T(2300)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2300)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2297 ±28	[1] ETKIN	88	MPS	$22\ \pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2220 ±15 ±20	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^+ 2K^- \gamma$
2206 ±20 ±25	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^0 K^+ K^- \gamma$
2231.0±10.0	BOOTH	86	OMEG	$85\ \pi^-$ Be $\to 2\phi$Be
$2220.0^{+90.0}_{-20.0}$	LINDENBAUM	84	RVUE	
2320.0±40.0	ETKIN	82	MPS	$16\ \pi^- p \to 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi\ 2^{++}\ S_2$, D_2, and D_0 is 6^{+15}_{-5}, 25^{+18}_{-14}, and 69^{+16}_{-27}, respectively.

$f_2(2300)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
149 ±41	[2] ETKIN	88	MPS	$22\ \pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114 ±45 ±35	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^+ 2K^- \gamma$
150 ±46 ±35	WISNIEWSKI	87	MRK3	$J/\psi \to 2K^0 K^+ K^- \gamma$
133.0±50.0	BOOTH	86	OMEG	$85\ \pi^-$ Be $\to 2\phi$Be
200.0±50.0	LINDENBAUM	84	RVUE	
220.0±70.0	ETKIN	82	MPS	$16\ \pi^- p \to 2\phi n$

[2] Includes data of ETKIN 85.

$f_2(2300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2300)$ REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
WISNIEWSKI	87	CALT-68-1446		(Mark III Collab.)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
Also	83	Brighton Conf. 351	Lindenbaum	(BNL, CUNY)

OTHER RELATED PAPERS

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$f_4(2300)$

$I^G(J^{PC}) = 0^+(4^{++})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_0(2350)$. Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $\rho_5(2350)$.

$f_4(2300)$ MASS

$\overline{p}p \to \pi\pi$ or $\overline{K}K$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2300	[1] MARTIN	80B	RVUE	
~ 2300	[1] MARTIN	80C	RVUE	
~ 2340	[2] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \to K^- K^+$
~ 2330	DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$
~ 2310	[3] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \to \pi\pi$

[1] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[2] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.

[3] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2380.0	[4] CUTTS	78B	CNTR	0.97–3 $\overline{p}p \to \overline{N}N$
2345 ±15.0	[4,5] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \to \overline{p}p$
2359 ± 2	[4,6] ALSPECTOR	73	CNTR	$\overline{p}p$ S channel
2375 ±10	ABRAMS	70	CNTR	S channel $\overline{N}N$

[4] Isospins 0 and 1 not separated.

[5] From a fit to the total elastic cross section.

[6] Referred to as U or U region by ALSPECTOR 73.

$f_4(2300)$ WIDTH

$\overline{p}p \to \pi\pi$ or $\overline{K}K$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 200	[7] MARTIN	80C	RVUE	
~ 150	[8] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \to K^- K^+$
~ 210	[9] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \to \pi\pi$

[7] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.

[8] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.

[9] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$135.0^{+150.0}_{-65.0}$	[10,11] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \to \overline{p}p$
$165\ ^{+18}_{-8}$	[11] ALSPECTOR	73	CNTR	$\overline{p}p$ S channel
~ 190	ABRAMS	70	CNTR	S channel $\overline{N}N$

[10] From a fit to the total elastic cross section.

[11] Isospins 0 and 1 not separated.

$f_4(2300)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

OTHER RELATED PAPERS

BOWCOCK	80	LNC 28 21	+Hodgson	(BIRM)
MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
DULUDE	78	PL 79B 329	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
MONTANET	77	Boston Conf. 260		(CERN)
DONNACHIE	75	NC 26A 317	+Thomas	(MCHS)
EISENHAND...	75	NP B96 109	Eisenhandler, Gibson+	(LOQM, LIVP, DARE, RHEL)
HYAMS	74	NP B73 202	+Jones, Weilhammer, Blum+	(CERN, MPIM)
MINGMA	74	NP B68 214	+Mountz, Zemany, Smith	(MICH)
DONNACHIE	73	LNC 7 285	+Thomas	(MCHS)
EASTMAN	73	NP B51 29	+MingMa, Oh, Parker, Smith, Sprafka	(MSU)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)

$f_2(2340)$ was $g''_T(2340)$

$I^G(J^{PC}) = 0^+(2^{-+})$

See also the mini-review under non-$q\bar{q}$ candidates. (See the index for the page number.)

$f_2(2340)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2339 ±55	[1] ETKIN	88	MPS	22 $\pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2392.0±10.0	BOOTH	86	OMEG	85 π^- Be $\to 2\phi$Be
2360.0±20.0	LINDENBAUM	84	RVUE	

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 37 ± 19, 4^{+12}_{-4}, and 59^{+21}_{-19}, respectively.

$f_2(2340)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
319^{+81}_{-69}	[2] ETKIN	88	MPS	22 $\pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
198.0± 50.0	BOOTH	86	OMEG	85 π^- Be $\to 2\phi$Be
$150.0^{+150.0}_{-50.0}$	LINDENBAUM	84	RVUE	

[2] Includes data of ETKIN 85.

$f_2(2340)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2340)$ REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)

OTHER RELATED PAPERS

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$\rho_5(2350)$

$I^G(J^{PC}) = 1^+(5^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_1(2400)$. Contains results only from formation experiments. For production experiments see the $\bar{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $f_4(2300)$.

$\rho_5(2350)$ MASS

$\bar{p}p \to \pi\pi$ or $\bar{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2300	[1] MARTIN	80B	RVUE		
~ 2250	[1] MARTIN	80C	RVUE		
~ 2500	[2] CARTER	78B	CNTR	0	0.7–2.4 $\bar{p}p \to K^- K^+$
~ 2480	[3] CARTER	77	CNTR	0	0.7–2.4 $\bar{p}p \to \pi\pi$

[1] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\bar{p} \to \pi^- \pi^+$ and $\pi^0\pi^0$.

[2] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.

[3] $I(J^P) = 1(5^-)$ from amplitude analysis.

S-CHANNEL $\bar{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2380	[4] CUTTS	78B	CNTR		0.97–3 $\bar{p}p \to \bar{N}N$
2345.0±15.0	[4,5] COUPLAND	77	CNTR	0	0.7–2.4 $\bar{p}p \to \bar{p}p$
2359 ± 2	[4,6] ALSPECTOR	73	CNTR		$\bar{p}p$ S channel
2350 ±10	[7] ABRAMS	70	CNTR		S channel $\bar{N}N$
2360.0±25.0	[8] OH	70B	HDBC	−0	$\bar{p}(pn)$, $K^* K 2\pi$

[4] Isospins 0 and 1 not separated.

[5] From a fit to the total elastic cross section.

[6] Referred to as U or U region by ALSPECTOR 73.

[7] For $I = 1$ $\bar{N}N$.

[8] No evidence for this bump seen in the $\bar{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ WIDTH

$\bar{p}p \to \pi\pi$ or $\bar{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	[9] MARTIN	80B	RVUE		
~ 300	[9] MARTIN	80C	RVUE		
~ 150	[10] CARTER	78B	CNTR	0	0.7–2.4 $\bar{p}p \to K^- K^+$
~ 210	[11] CARTER	77	CNTR	0	0.7–2.4 $\bar{p}p \to \pi\pi$

[9] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\bar{p} \to \pi^- \pi^+$ and $\pi^0\pi^0$.

[10] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.

[11] $I(J^P) = 1(5^-)$ from amplitude analysis.

S-CHANNEL $\bar{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$135.0^{+150.0}_{-65.0}$	[12,13] COUPLAND	77	CNTR	0	0.7–2.4 $\bar{p}p \to \bar{p}p$
165^{+18}_{-8}	[13] ALSPECTOR	73	CNTR		$\bar{p}p$ S channel
< 60.0	[14] OH	70B	HDBC	−0	$\bar{p}(pn)$, $K^* K 2\pi$
~ 140	ABRAMS	67C	CNTR		S channel $\bar{p}N$

[12] From a fit to the total elastic cross section.

[13] Isospins 0 and 1 not separated.

[14] No evidence for this bump seen in the $\bar{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ REFERENCES

MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
OH	73	NP B51 57	+Eastman, MingMa, Parker, Smith+	(MSU)
CHAPMAN	71B	PR D4 1275	+Green, Lys, Murphy, Ring+	(MICH)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
OH	70B	PRL 24 1257	+Parker, Eastman, Smith, Sprafka, Ma	(MSU)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

OTHER RELATED PAPERS

BOWCOCK	80	LNC 28 21	+Hodgson	(BIRM)
MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
MONTANET	77	Boston Conf. 260		(CERN)
DONNACHIE	75	NC 26A 317	+Thomas	(MCHS)
EISENHAND...	75	NP B96 109	Eisenhandler, Gibson+	(LOQM, LIVP, DARE, RHEL)
HYAMS	74	NP B73 202	+Jones, Weilhammer, Blum+	(CERN, MPIM)
MINGMA	74	NP B68 214	+Mountz, Zemany, Smith	(MICH)
EASTMAN	73	NP B51 29	+MingMa, Oh, Parker, Smith, Sprafka	(MSU)
MINGMA	73	NP B51 77	+Eastman, Oh, Parker, Smith, Sprafka	(MSU)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
OH	73	NP B51 57	+Eastman, MingMa, Parker, Smith+	(MSU)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)

$a_6(2450)$

$I^G(J^{PC}) = 1^-(6^{+-})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K\bar{K}$ system. Needs confirmation.

$a_6(2450)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2450±130	[1] CLELAND	82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

[1] From an amplitude analysis.

$a_6(2450)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
400±250	[2] CLELAND	82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

[2] From an amplitude analysis.

$a_6(2450)$ DECAY MODES

	Mode
Γ_1	$K\bar{K}$

$a_6(2450)$ REFERENCES

CLELAND	82B	NP B208 228	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)

$f_6(2510)$ was $r(2510)$

$I^G(J^{PC}) = 0^+(6^{++})$

OMITTED FROM SUMMARY TABLE

Seen in $\pi^0\pi^0$. Needs confirmation.

$f_6(2510)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2510.0±30.0	BINON 84B	GAM2	$38\ \pi^- p \to n 2\pi^0$

$f_6(2510)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
240.0±60.0	BINON 84B	GAM2	$23\ \pi^- p \to n 2\pi^0$

$f_6(2510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	(6.0 ± 1.0) %

$f_6(2510)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.06±0.01	[1] BINON 83C	GAM2	$38\ \pi^- p \to n 4\gamma$

[1] Assuming one pion exchange.

$f_6(2510)$ REFERENCES

BINON 84B LNC 39 41 +Donskov, Duteil, Gouanere+ (SERP, BELG, LAPP) JP
BINON 83C SJNP 38 723 +Gouanere, Donskov, Duteil+ (SERP, BRUX+)
Translated from YAF 38 1199.

$X(3100)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Narrow peak observed in several ($\Lambda\overline{p}$ + pions) and ($\overline{\Lambda}p$ + pions) states. If due to strong decays, this state has exotic quantum numbers (B=0,Q=+1,S=−1 for $\Lambda\overline{p}\pi^+\pi^+$ and $I \geq 3/2$ for $\Lambda\overline{p}\pi^-$). See also under non-$q\overline{q}$ candidates. (See the index for the page number.)

$X(3100)$ MASS

3-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3060±30	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^+$
3040±30	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^-$
3070±30	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^-$
3040±30	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^+$

4-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3060±25	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^+\pi^\pm$
3045±25	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^-\pi^\pm$
3105±30	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+$
3115±30	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3095±30	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+\pi^-$

$X(3100)$ WIDTH

3-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
55±15	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^+$
40±15	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^-$
70±25	KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^-$
35±15	KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^+$

4-BODY DECAYS

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30±10		KEKELIDZE 90	BIS2	$X(3100) \to \Lambda\overline{p}\pi^+\pi^\pm$
30±15		KEKELIDZE 90	BIS2	$X(3100) \to \overline{\Lambda}p\pi^-\pi^\pm$
<30	90	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+$
<80	90	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<30	90	BOURQUIN 86	SPEC	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+\pi^-$

$X(3100)$ DECAY MODES

	Mode
Γ_1	$X(3100)^0 \to \Lambda\overline{p}\pi^+$
Γ_2	$X(3100) \to \Lambda\overline{p}\pi^-$
Γ_3	$X(3100) \to \Lambda\overline{p}\pi^+\pi^-$
Γ_4	$X(3100) \to \Lambda\overline{p}\pi^+\pi^+$
Γ_5	$X(3100)^0 \to \Lambda\overline{p}\pi^+\pi^+\pi^-$

$X(3100)$ REFERENCES

KEKELIDZE 90 Hadron 89 Conf. +Aleev+ (BIS-2 Collab.)
BOURQUIN 86 PL B172 113 +Brown+ (GEVA, RAL, HEID, LAUS, BRIS, CERN)

$X(3250)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE

Narrow peak observed in several final states with hidden strangeness ($\Lambda\overline{p}K^+$, $\Lambda\overline{p}K^+\pi^\pm$, $K^0 p\overline{p}K^\pm$). See also under non-$q\overline{q}$ candidates. (See the index for the page number.)

$X(3250)$ MASS

3-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3230±30	KEKELIDZE 90	SPEC	$X(3250) \to \Lambda\overline{p}K^+$
3250±30	KEKELIDZE 90	SPEC	$X(3250) \to \overline{\Lambda}pK^-$

4-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3240±30	KEKELIDZE 90	SPEC	$X(3250) \to \Lambda\overline{p}K^+\pi^\pm$
3220±30	KEKELIDZE 90	SPEC	$X(3250) \to \overline{\Lambda}pK^-\pi^\pm$
3270±30	KEKELIDZE 90	SPEC	$X(3250) \to K^0 p\overline{p}K^\pm$

$X(3250)$ WIDTH

3-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
35±15	KEKELIDZE 90	SPEC	$X(3250) \to \Lambda\overline{p}K^+$
20±10	KEKELIDZE 90	SPEC	$X(3250) \to \overline{\Lambda}pK^-$

4-BODY DECAYS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
25±10	KEKELIDZE 90	SPEC	$X(3250) \to \Lambda\overline{p}K^+\pi^\pm$
55±20	KEKELIDZE 90	SPEC	$X(3250) \to \overline{\Lambda}pK^-\pi^\pm$
50±20	KEKELIDZE 90	SPEC	$X(3250) \to K^0 p\overline{p}K^\pm$

$X(3250)$ DECAY MODES

	Mode
Γ_1	$\Lambda\overline{p}K^+$
Γ_2	$\Lambda\overline{p}K^+\pi^\pm$
Γ_3	$K^0 p\overline{p}K^\pm$

$X(3250)$ REFERENCES

KEKELIDZE 90 Hadron 89 Conf. +Aleev+ (BIS-2 Collab.)

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3535.0±20.0	BAUD	70	MMS	–	14–15.5 $\pi^- p$
~ 30.0	BAUD	70	MMS	–	14–15.5 $\pi^- p$

[1] Seen in $J = 2$ wave in one of the two ambiguous solutions.

[2] Seen in $J = 0$ wave in one of the two ambiguous solutions.

[3] Seen in $\rho^- \pi^+ \pi^-$ (ω and η antiselected in 4π system).

[4] Dominant decay into $\rho^0 \rho^0 \pi^+$. BALTAY 78 finds confirmation in $2\pi^+ \pi^- 2\pi^0$ events which contain $\rho^+ \rho^0 \pi^0$ and $2\rho^+ \pi^-$.

[5] Seen in $(K \overline{K} \pi \pi)$ mass distribution.

$X(1900\text{–}3600)$ REFERENCES

ARMSTRONG	89E	PL B228 536	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF, LPNP)
ATKINSON	88	ZPHY C38 535	+Axon+	(BONN, CERN, GLAS, LANC, MCHS, LPNP)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFT, VAND+)
ATKINSON	85	ZPHY C29 333	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
ATKINSON	84F	NP B239 1	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH) J
CHLIAPNIK...	80	ZPHY C3 285	Chliapnikov, Gerdyukov+	(SERP, BRUX, MONS)
BALTAY	78	PR D17 52	+Cautis, Cohen, Csorna, Kalelkar+	(COLU, BING)
BALTAY	75	PRL 35 891	+Cautis, Cohen, Kalelkar, Pisello+	(COLU, BING)
THOMPSON	74	NP B69 220	+Gaidos, McIlwain, Miller, Mulera+	(PURD)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHO, PENN, NDAM, ANL)
SABAU	71	LNC 1 514	+Uretsky	(BUCH, ANL)
BAUD	70	PL 31B 549	+Benz+	(CERN Boson Spectrometer Collab.)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)
BAUD	69	PL 30B 129	+Benz+	(CERN Boson Spectrometer Collab.)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
CLAYTON	67	Heidelberg Conf. 57	+Mason, Muirhead, Filippas+	(LIVP, ATHU)
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)

OTHER RELATED PAPERS

BALTAY	78	PR D17 52	+Cautis, Cohen, Csorna, Kalelkar+	(COLU, BING)
ANTIPOV	72	PL 40 147	+Kienzle, Landsberg+	(SERP)
CHIKOVANI	66	PL 22 233	+Kienzle, Maglich+	(SERP)

STRANGE MESONS
$(S = \pm 1,\ C = B = 0)$

$K^+ = u\overline{s}$, $K^0 = d\overline{s}$, $\overline{K}^0 = \overline{d}s$, $K^- = \overline{u}s$, similarly for K^*'s

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

$K^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
493.646±0.009 OUR FIT					
493.646±0.009 OUR AVERAGE					
493.636±0.011	GALL	88	CNTR	–	Kaonic atoms
493.640±0.054	LUM	81	CNTR	–	Kaonic atoms
493.670±0.029	BARKOV	79	EMUL	±	$e^+ e^- \rightarrow K^+ K^-$
493.657±0.020	CHENG	75	CNTR	–	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	–	Kaonic atoms
• • • We do not use the following data for averages, fits, limits, etc. • • •					
493.662±0.19	KUNSELMAN	74	CNTR	–	Kaonic atoms
493.78 ±0.17	GREINER	65	EMUL	+	
493.7 ±0.3	BARKAS	63	EMUL	–	
493.9 ±0.2	COHEN	57	RVUE	+	

$K^+ - K^-$ MASS DIFFERENCE

Test of *CPT*.

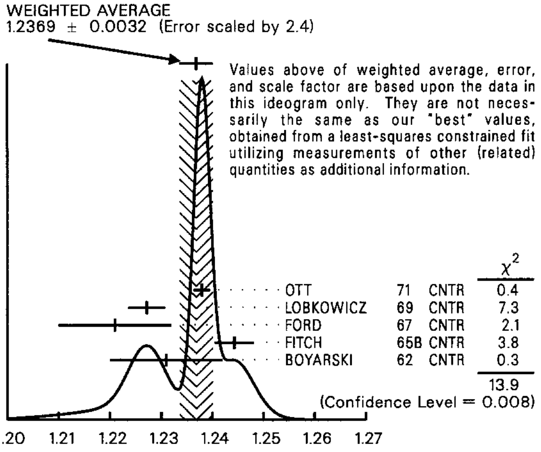
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG
–0.032±0.090	1.5M	[1] FORD	72	ASPK	±

[1] FORD 72 uses $m(\pi^+) - m(\pi^-) = +28 \pm 70$ keV.

$K^{\pm}$ MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.2371±0.0029 OUR FIT Error includes scale factor of 2.2.						
1.2369±0.0032 OUR AVERAGE Error includes scale factor of 2.4. See the ideogram below.						
1.2380±0.0016	3M	OTT	71	CNTR	+	Stopping *K*
1.2272±0.0036		LOBKOWICZ	69	CNTR	+	*K* in flight
1.221 ±0.011		FORD	67	CNTR	±	
1.2443±0.0038		FITCH	65B	CNTR	+	*K* at rest
1.231 ±0.011		BOYARSKI	62	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.25 $^{+0.22}_{-0.17}$		[2] BARKAS	61	EMUL		
1.27 $^{+0.36}_{-0.23}$	51	[2] BHOWMIK	61	EMUL		
1.31 ±0.08	293	NORDIN	61	HBC	–	
1.24 ±0.07		NORDIN	61	RVUE	–	
1.38 ±0.24	33	[2] FREDEN	60B	EMUL		
1.21 ±0.06		BURROWES	59	CNTR		
1.60 ±0.3	52	[2] EISENBERG	58	EMUL		
0.95 $^{+0.36}_{-0.25}$		[2] ILOFF	56	EMUL		

[2] Old experiments with large errors excluded from averaging.



$K^{\pm}$ mean life (10^{-8} s)

$(K^+ - K^-)$ / AVERAGE, MEAN LIFE DIFFERENCE

This quantity is a measure of *CPT* invariance in weak interactions.

VALUE (%)	DOCUMENT ID		TECN
0.11 ±0.09 OUR AVERAGE Error includes scale factor of 1.2.			
0.090±0.078	LOBKOWICZ	69	CNTR
0.47 ±0.30	FORD	67	CNTR

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\mu^+ \nu_\mu$	(63.51±0.19) %	S=1.2
Γ_2	$e^+ \nu_e$	(1.55±0.07) × 10^{-5}	
Γ_3	$\pi^+ \pi^0$	(21.17±0.16) %	S=1.1
Γ_4	$\pi^+ \pi^+ \pi^-$	(5.59±0.05) %	S=2.0
Γ_5	$\pi^+ \pi^0 \pi^0$	(1.73±0.04) %	S=1.2
Γ_6	$\pi^0 \mu^+ \nu_\mu$ Called $K_{\mu3}$.	(3.18±0.08) %	S=1.6
Γ_7	$\pi^0 e^+ \nu_e$ Called K_{e3}.	(4.82±0.06) %	S=1.3
Γ_8	$\pi^0 \pi^0 e^+ \nu_e$	(2.1 ±0.4) × 10^{-5}	
Γ_9	$\pi^+ \pi^- e^+ \nu_e$	(3.91±0.17) × 10^{-5}	
Γ_{10}	$\pi^+ \pi^- \mu^+ \nu_\mu$	(1.4 ±0.9) × 10^{-5}	
Γ_{11}	$\pi^+ \gamma \gamma$	[a] < 8.4 × 10^{-6}	CL=90%
Γ_{12}	$\pi^+ 3\gamma$	[a] < 1.0 × 10^{-4}	CL=90%
Γ_{13}	$e^+ \nu_e \nu \overline{\nu}$	< 6 × 10^{-5}	CL=90%
Γ_{14}	$\mu^+ \nu_\mu \nu \overline{\nu}$	< 6.0 × 10^{-6}	CL=90%
Γ_{15}	$\mu^+ \nu_\mu e^+ e^-$	(1.06±0.32) × 10^{-6}	
Γ_{16}	$e^+ \nu_e e^+ e^-$	(2.1 $^{+2.1}_{-1.1}$) × 10^{-7}	
Γ_{17}	$\mu^+ \nu_\mu \mu^+ \mu^-$	< 4.1 × 10^{-7}	CL=90%
Γ_{18}	$\mu^+ \nu_\mu \gamma$	[a,b] (5.46±0.28) × 10^{-3}	
Γ_{19}	$\mu^+ \nu_\mu \gamma$ (SD$^+$)	[c,d] < 3.0 × 10^{-5}	CL=90%
Γ_{20}	$\mu^+ \nu_\mu \gamma$ (SD$^+$INT)	[c,d] < 2.7 × 10^{-5}	CL=90%
Γ_{21}	$\mu^+ \nu_\mu \gamma$ (SD$^-$ + SD$^-$INT)	[c,d] < 2.6 × 10^{-4}	CL=90%
Γ_{22}	$e^+ \nu_e \gamma$ (SD$^+$)	[c,d] (1.52±0.23) × 10^{-5}	
Γ_{23}	$e^+ \nu_e \gamma$ (SD$^-$)	[c,d] < 1.6 × 10^{-4}	CL=90%

Γ_{24}	$\pi^+\pi^0\gamma$	[a,b]	$(2.75\pm0.15)\times10^{-4}$	
Γ_{25}	$\pi^+\pi^0\gamma$ (DE)	[a,e]	$(1.8\pm0.4)\times10^{-5}$	
Γ_{26}	$\pi^+\pi^+\pi^-\gamma$	[a,b]	$(1.0\pm0.4)\times10^{-4}$	
Γ_{27}	$\pi^+\pi^0\pi^0\gamma$	[a,b]	$(7.4\ ^{+5.5}_{-2.9})\times10^{-6}$	
Γ_{28}	$\pi^0\mu^+\nu_\mu\gamma$	[a,b]	$< 6.1\times10^{-5}$	CL=90%
Γ_{29}	$\pi^0 e^+\nu_e\gamma$	[a,b]	$(2.72\pm0.19)\times10^{-4}$	
Γ_{30}	$\pi^0 e^+\nu_e\gamma$ (SD)	[c,d]	$< 5.3\times10^{-5}$	CL=90%

$\Delta S = \Delta Q$ (*SQ*), Lepton number (*L*), Lepton Family number (*LF*) violating modes or Flavor-Changing neutral current (*FC*) modes

Γ_{31}	$\pi^+\pi^+e^-\overline{\nu}_e$	*SQ*	$< 1.2\times10^{-8}$	CL=90%
Γ_{32}	$\pi^+\pi^+\mu^-\overline{\nu}_\mu$	*SQ*	$< 3.0\times10^{-6}$	CL=95%
Γ_{33}	$\pi^+e^+e^-$	*FC*	$(2.7\pm0.5)\times10^{-7}$	
Γ_{34}	$\pi^+\mu^+\mu^-$	*FC*	$< 2.3\times10^{-7}$	CL=90%
Γ_{35}	$\pi^+\nu\overline{\nu}$	*FC*	$< 3.4\times10^{-8}$	CL=90%
Γ_{36}	$\mu^-\nu e^+e^+$	*LF*	$< 2.0\times10^{-8}$	CL=90%
Γ_{37}	$\mu^+\nu_e$	*LF*	$< 4\times10^{-3}$	CL=90%
Γ_{38}	$\pi^+\mu^+e^-$	*LF*	$< 2.1\times10^{-10}$	CL=90%
Γ_{39}	$\pi^\pm\mu^\mp e^+$	*LF,L* [f]	$< 7\times10^{-9}$	CL=90%
Γ_{40}	$\pi^-e^+e^+$	*L*	$< 1.0\times10^{-8}$	CL=90%
Γ_{41}	$\mu^+\overline{\nu}_e$	*L*	$< 3.3\times10^{-3}$	CL=90%
Γ_{42}	$\pi^0e^+\overline{\nu}_e$	*L*	$< 3\times10^{-3}$	CL=90%
Γ_{43}	$\pi^+\gamma$			
Γ_{44}	$\pi^+e^+\mu^-$			

[a] See the Listings below for the energy limits used in this measurement.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] Structure-dependent part with positive (SD$^+$) and negative (SD$^-$) photon helicity. Interference terms between structure-dependent parts and inner bremsstrahlung (SD$^+$INT and SD$^-$INT).

[d] See the Note on $\pi^\pm \rightarrow \ell^\pm\nu\gamma$ and $K^\pm \rightarrow \ell^\pm\nu\gamma$ Form Factors in the $\pi^\pm$ Full Listings for definitions and details.

[e] Direct-emission branching fraction.

[f] Value is for the sum of the charge states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 2 partial widths, and 20 branching ratios uses 59 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 74.9$ for 52 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−63						
x_4	−36	−15					
x_5	−24	−5	21				
x_6	−43	−20	13	0			
x_7	−44	−19	35	5	40		
x_8	−3	−1	2	0	2	6	
Γ	7	3	−20	−4	−3	−7	0
	x_1	x_3	x_4	x_5	x_6	x_7	x_8

	Mode	Rate (10^8 s^{-1})	Scale factor
Γ_1	$\mu^+\nu_\mu$	0.5134 ± 0.0020	1.4
Γ_3	$\pi^+\pi^0$	0.1711 ± 0.0013	1.1
Γ_4	$\pi^+\pi^+\pi^-$	0.0452 ± 0.0004	1.9
Γ_5	$\pi^+\pi^0\pi^0$	0.01400 ± 0.00032	1.2
Γ_6	$\pi^0\mu^+\nu_\mu$ Called $K_{\mu3}$.	0.0257 ± 0.0007	1.6
Γ_7	$\pi^0e^+\nu_e$ Called K_{e3}.	0.0390 ± 0.0005	1.3
Γ_8	$\pi^0\pi^0e^+\nu_e$	$(1.70\ ^{+0.34}_{-0.29})\times10^{-5}$	

$K^\pm$ DECAY RATES

$\Gamma(\mu^+\nu_\mu)$ Γ_1

VALUE (10^6 s^{-1})	DOCUMENT ID	TECN	CHG
51.34±0.20 OUR FIT Error includes scale factor of 1.4.			
51.2 ±0.8	FORD 67	CNTR	±

$\Gamma(\pi^+\pi^+\pi^-)$ Γ_4

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID	TECN	CHG
4.52 ±0.04 OUR FIT	Error includes scale factor of 1.9.			
4.511±0.024		[3] FORD 70	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.529±0.032	3.2M	[3] FORD 70	ASPK	
4.496±0.030		[3] FORD 67	CNTR	±

[3] First FORD 70 value is second FORD 70 combined with FORD 67.

$(\Gamma(K^+) - \Gamma(K^-)) / \Gamma(K)$

$K^+ \rightarrow \mu^+\nu_\mu$ RATE DIFFERENCE

Test of *CPT* conservation.

VALUE (%)	DOCUMENT ID	TECN
−0.54±0.41	FORD 67	CNTR

$K^+ \rightarrow \pi^+\pi^+\pi^-$ RATE DIFFERENCE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID	TECN	CHG
0.07±0.12 OUR AVERAGE				
0.08±0.12		[4] FORD 70	ASPK	
−0.50±0.90		FLETCHER 67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.02±0.16		[5] SMITH 73	ASPK	±
0.10±0.14	3.2M	[4] FORD 70	ASPK	
−0.04±0.21		[4] FORD 67	CNTR	

[4] First FORD 70 value is second FORD 70 combined with FORD 67.

[5] SMITH 73 value of $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ rate difference is derived from SMITH 73 value of $K^\pm \rightarrow \pi^\pm 2\pi^0$ rate difference.

$K^+ \rightarrow \pi^+\pi^0\pi^0$ RATE DIFFERENCE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID	TECN	CHG
0.0 ±0.6 OUR AVERAGE				
0.08±0.58		SMITH 73	ASPK	±
−1.1 ±1.8	1802	HERZO 69	OSPK	

$K^+ \rightarrow \pi^+\pi^0$ RATE DIFFERENCE

Test of *CPT* conservation.

VALUE (%)	DOCUMENT ID	TECN
0.8±1.2	HERZO 69	OSPK

$K^+ \rightarrow \pi^+\pi^0\gamma$ RATE DIFFERENCE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.9± 3.3 OUR AVERAGE					
0.8± 5.8	2461	SMITH 76	WIRE	±	E_π 55–90 MeV
1.0± 4.0	4000	ABRAMS 73B	ASPK	±	E_π 51–100 MeV
0.0±24.0	24	EDWARDS 72	OSPK		E_π 58–90 MeV

K^+ BRANCHING RATIOS

$\Gamma(\mu^+\nu_\mu)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
63.51±0.19 OUR FIT	Error includes scale factor of 1.2.				
63.24±0.44	62k	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
56.9 ±2.6		[6] ALEXANDER 57	EMUL	+	
58.5 ±3.0		[6] BIRGE 56	EMUL	+	

[6] Old experiments not included in averaging.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_1/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG
11.36±0.12 OUR FIT	Error includes scale factor of 1.8.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.38±0.82	427	[7] YOUNG 65	EMUL	+

[7] Deleted from overall fit because YOUNG 65 constrains his results to add up to 1. Only YOUNG 65 measured ($\mu\nu$) directly.

$\Gamma(e^+\nu_e)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$2.1^{+1.8}_{-1.3}$		4	BOWEN 67B	OSPK	+
<160.0	95		BORREANI 64	HBC	+

$\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ Γ_2/Γ_1

VALUE (units 10^{-5})	EVTS	DOCUMENT ID	TECN	CHG
2.45±0.11 OUR AVERAGE				
2.51±0.15	404	HEINTZE 76	SPEC	+
2.37±0.17	534	HEARD 75B	SPEC	+
2.42±0.42	112	CLARK 72	OSPK	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.8\ ^{+0.8}_{-0.6}$	8	MACEK 69	ASPK	+
$1.9\ ^{+0.7}_{-0.5}$	10	BOTTERILL 67	ASPK	+

$\Gamma(\pi^+\pi^0)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
21.17±0.16 OUR FIT Error includes scale factor of 1.1.					
21.18±0.28	16k	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
21.0 ±0.6		CALLAHAN 65	HLBC		See $\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$
21.6 ±0.6		TRILLING 65B	RVUE		
23.2 ±2.2		[8] ALEXANDER 57	EMUL	+	
27.7 ±2.7		[8] BIRGE 56	EMUL	+	

[8] Earlier experiments not averaged.

$\Gamma(\pi^+\pi^0)/\Gamma(\mu^+\nu_\mu)$ Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG
0.3333±0.0032 OUR FIT Error includes scale factor of 1.1.				
0.331 ±0.005 OUR AVERAGE Error includes scale factor of 1.2.				
0.3355±0.0057		[9] WEISSENBE... 76	SPEC	+
0.305 ±0.018	1600	ZELLER 69	ASPK	+
0.3277±0.0065	4517	[10] AUERBACH 67	OSPK	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.328 ±0.005	25k	[9] WEISSENBE... 74	STRC	+

[9] WEISSENBERG 76 revises WEISSENBERG 74.

[10] AUERBACH 67 changed from 0.3253 ± 0.0065. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$.

$\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_3/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG
3.79±0.05 OUR FIT Error includes scale factor of 1.5.				
3.84±0.27 OUR AVERAGE Error includes scale factor of 1.9.				
3.96±0.15	1045	CALLAHAN 66	FBC	+
3.24±0.34	134	YOUNG 65	EMUL	+

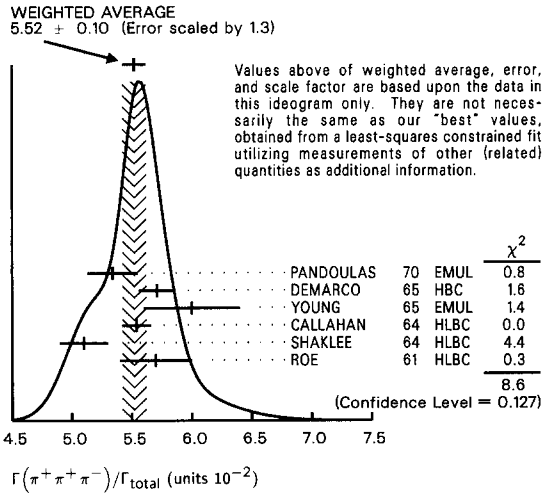
$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_4/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
5.59±0.05 OUR FIT Error includes scale factor of 2.0.					
5.52±0.10 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
5.34±0.21	693	[11] PANDOULAS 70	EMUL	+	
5.71±0.15		DEMARCO 65	HBC		
6.0 ±0.4	44	YOUNG 65	EMUL	+	
5.54±0.12	2332	CALLAHAN 64	HLBC	+	
5.1 ±0.2	540	SHAKLEE 64	HLBC	+	
5.7 ±0.3		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.56±0.20	2330	[12] CHIANG 72	OSPK	+	1.84 GeV/c K^+
5.2 ±0.3		[13] TAYLOR 59	EMUL	+	
6.8 ±0.4		[13] ALEXANDER 57	EMUL	+	
5.6 ±0.4		[13] BIRGE 56	EMUL	+	

[11] Includes events of TAYLOR 59.

[12] Value is not independent of CHIANG 72 $\Gamma(\mu^+\nu_\mu)/\Gamma_{\rm total}$, $\Gamma(\pi^+\pi^0)/\Gamma_{\rm total}$, $\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$, $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{\rm total}$, and $\Gamma(\pi^0 e^+\nu_e)/\Gamma_{\rm total}$.

[13] Earlier experiments not averaged.



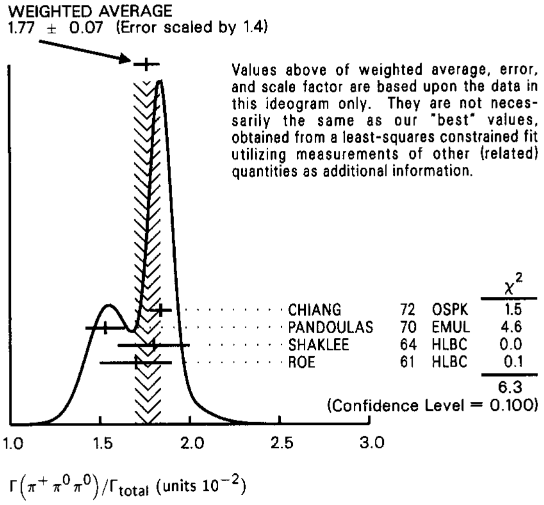
Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$ Γ_5/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.73±0.04 OUR FIT Error includes scale factor of 1.2.					
1.77±0.07 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
1.84±0.06	1307	CHIANG 72	OSPK	+	1.84 GeV/c K^+
1.53±0.11	198	[14] PANDOULAS 70	EMUL	+	
1.8 ±0.2	108	SHAKLEE 64	HLBC	+	
1.7 ±0.2		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5 ±0.2		[15] TAYLOR 59	EMUL	+	
2.2 ±0.4		[15] ALEXANDER 57	EMUL	+	
2.1 ±0.5		[15] BIRGE 56	EMUL	+	

[14] Includes events of TAYLOR 59.

[15] Earlier experiments not averaged.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^0)$ Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.0819±0.0020 OUR FIT Error includes scale factor of 1.2.					
0.081 ±0.005	574	[16] LUCAS 73B	HBC	−	Dalitz pairs only

[16] LUCAS 73B gives N($\pi 2\pi^0$) = 574 ± 5.9%, N(2π) = 3564 ± 3.1%. We quote 0.5N($\pi 2\pi^0$)/N(2π) where 0.5 is because only Dalitz pair π^0's were used.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_5/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.310±0.007 OUR FIT Error includes scale factor of 1.2.					
0.304±0.009 OUR AVERAGE					
0.303±0.009	2027	BISI 65	BC	+	HBC+HLBC
0.393±0.099	17	YOUNG 65	EMUL	+	

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{\rm total}$ Γ_6/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
3.18±0.08 OUR FIT Error includes scale factor of 1.6.					
3.33±0.16	2345	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.8 ±0.4		[17] TAYLOR 59	EMUL	+	
5.9 ±1.3		[17] ALEXANDER 57	EMUL	+	
2.8 ±1.0		[17] BIRGE 56	EMUL	+	

[17] Earlier experiments not averaged.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$ Γ_6/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG
0.0501±0.0014 OUR FIT Error includes scale factor of 1.6.				
0.0488±0.0026 OUR AVERAGE				
0.054 ±0.009	240	ZELLER 69	ASPK	+
0.0480±0.0037	424	[18] GARLAND 68	OSPK	+
0.0486±0.0040	307	[19] AUERBACH 67	OSPK	+

[18] GARLAND 68 changed from 0.055 ± 0.004 in agreement with μ-spectrum calculation of GAILLARD 70 appendix B. L.G.Pondrom, (private communication 73).

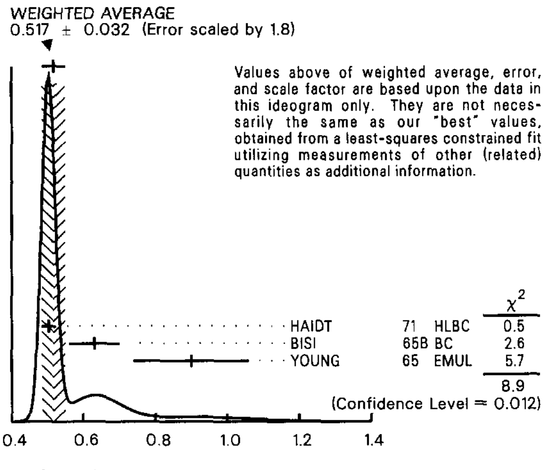
[19] AUERBACH 67 changed from 0.0602 ± 0.0046 by erratum which brings the μ-spectrum calculation into agreement with GAILLARD 70 appendix B.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_6/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.569±0.015 OUR FIT Error includes scale factor of 1.6.					
0.517±0.032 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
0.503±0.019	1505	[20] HAIDT 71	HLBC	+	
0.63 ±0.07	2845	[21] BISI 65B	BC	+	HBC+HLBC
0.90 ±0.16	38	YOUNG 65	EMUL	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.510±0.017	1505	[20] EICHTEN 68	HLBC	+	

[20] HAIDT 71 is a reanalysis of EICHTEN 68.

[21] Error enlarged for background problems. See GAILLARD 70.



$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0e^+\nu_e)$ Γ_6/Γ_7

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.660±0.016 OUR FIT	Error includes scale factor of 1.5.				
0.680±0.013 OUR AVERAGE					
0.705±0.063	554	[22] LUCAS 73B	HBC	−	Dalitz pairs only
0.698±0.025	3480	[23] CHIANG 72	OSPK	+	1.84 GeV/c K^+
0.667±0.017	5601	BOTTERILL 68B	ASPK	+	
0.703±0.056	1509	[24] CALLAHAN 66B	HLBC		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.670±0.014		[25] HEINTZE 77	SPEC	+	
0.67 ±0.12		WEISSENBE... 76	SPEC	+	
0.608±0.014	1585	[26] BRAUN 75	HLBC	+	
0.596±0.025		[27] HAIDT 71	HLBC	+	
0.604±0.022	1398	[27] EICHTEN 68	HLBC		

[22] LUCAS 73B gives N($K_{\mu3}$) = 554 ± 7.6%, N(K_{e3}) = 786 ± 3.1%. We divide.

[23] CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0e^+\nu_e)$ is statistically independent of CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$ and $\Gamma(\pi^0e^+\nu_e)/\Gamma_{total}$.

[24] From CALLAHAN 66B we use only the $K_{\mu3}/K_{e3}$ ratio and do not include in the fit the ratios $K_{\mu3}/(\pi\pi^+\pi^0)$ and $K_{e3}/(\pi\pi^+\pi^0)$, since they show large disagreements with the rest of the data.

[25] HEINTZE 77 value from fit to λ_0. Assumes μ-e universality.

[26] BRAUN 75 value is from form factor fit. Assumes μ-e universality.

[27] HAIDT 71 is a reanalysis of EICHTEN 68. Only individual ratios included in fit (see $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ and $\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$).

$\left[\Gamma(\pi^+\pi^0) + \Gamma(\pi^0\mu^+\nu_\mu)\right]/\Gamma_{total}$ $(\Gamma_3+\Gamma_6)/\Gamma$

We combine these two modes for experiments measuring them in xenon bubble chamber because of difficulties of separating them there.

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
24.35±0.16 OUR FIT	Error includes scale factor of 1.1.			
24.6 ±1.0 OUR AVERAGE	Error includes scale factor of 1.4.			
25.4 ±0.9	886	SHAKLEE 64	HLBC	+
23.4 ±1.1		ROE 61	HLBC	+

$\Gamma(\pi^0e^+\nu_e)/\Gamma_{total}$ Γ_7/Γ

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
4.82±0.06 OUR FIT	Error includes scale factor of 1.3.				
4.85±0.09 OUR AVERAGE					
4.86±0.10	3516	CHIANG 72	OSPK	+	1.84 GeV/c K^+
4.7 ±0.3	429	SHAKLEE 64	HLBC	+	
5.0 ±0.5		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.1 ±1.3		[28] ALEXANDER 57	EMUL	+	
3.2 ±1.3		[28] BIRGE 56	EMUL	+	

[28] Earlier experiments not averaged.

$\Gamma(\pi^0e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ Γ_7/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.0759±0.0011 OUR FIT	Error includes scale factor of 1.4.			
0.0752±0.0024 OUR AVERAGE				
0.069 ±0.006	350	ZELLER 69	ASPK	+
0.0775±0.0033	960	BOTTERILL 68C	ASPK	+
0.069 ±0.006	561	GARLAND 68	OSPK	+
0.0791±0.0054	295	[29] AUERBACH 67	OSPK	+

[29] AUERBACH 67 changed from 0.0797 ± 0.0054. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$. The value 0.0785 ± 0.0025 given in AUERBACH 67 is an average of AUERBACH 67 $\Gamma(\pi^0e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ and CESTER 66 $\Gamma(\pi^0e^+\nu_e)/\left[\Gamma(\mu^+\nu_\mu) + \Gamma(\pi^+\pi^0)\right]$.

$\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^0)$ Γ_7/Γ_3

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.228±0.004 OUR FIT	Error includes scale factor of 1.3.				
0.221±0.012	786	[30] LUCAS 73B	HBC	−	Dalitz pairs only

[30] LUCAS 73B gives N(K_{e3}) = 786 ± 3.1%, N(2π) = 3564 ± 3.1%. We divide.

$\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_7/Γ_4

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.863±0.011 OUR FIT	Error includes scale factor of 1.3.			
0.860±0.014 OUR AVERAGE				
0.867±0.027	2768	BARMIN 87	XEBC	+
0.856±0.040	2827	BRAUN 75	HLBC	+
0.850±0.019	4385	[31] HAIDT 71	HLBC	+
0.94 ±0.09	854	BELLOTTI 67B	HLBC	
0.90 ±0.06	230	BORREANI 64	HBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.846±0.021	4385	[31] EICHTEN 68	HLBC	+
0.90 ±0.16	37	YOUNG 65	EMUL	+

[31] HAIDT 71 is a reanalysis of EICHTEN 68.

$\Gamma(\pi^0e^+\nu_e)/\left[\Gamma(\mu^+\nu_\mu) + \Gamma(\pi^+\pi^0)\right]$ $\Gamma_7/(\Gamma_1+\Gamma_3)$

VALUE (units 10^{-2})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
5.69±0.08 OUR FIT	Error includes scale factor of 1.4.			
6.01±0.15 OUR AVERAGE				
5.92±0.65		[32] WEISSENBE... 76	SPEC	+
6.16±0.22	5110	ESCHSTRUTH 68	OSPK	+
5.89±0.21	1679	CESTER 66	OSPK	+

[32] Value calculated from WEISSENBERG 76 ($\pi^0e\nu$), ($\mu\nu$), and ($\pi\pi^0$) values to eliminate dependence on our 1974 ($\pi2\pi^0$) and ($\pi\pi^+\pi^-$) fractions.

$\Gamma(\pi^0\pi^0e^+\nu_e)/\Gamma(\pi^0e^+\nu_e)$ Γ_8/Γ_7

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
$4.3^{+0.9}_{-0.7}$ OUR FIT					
$4.1^{+1.0}_{-0.7}$ OUR AVERAGE					
$4.2^{+1.0}_{-0.9}$		25	BOLOTOV 86B	CALO	−
$3.8^{+5.0}_{-1.2}$		2	LJUNG 73	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<37.0	90	0	ROMANO 71	HLBC	+

$\Gamma(\pi^0\pi^0e^+\nu_e)/\Gamma_{total}$ Γ_8/Γ

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
2.1 ±0.4 OUR FIT				
2.54±0.89	10	BARMIN 88B	HLBC	+

$\Gamma(\pi^+\pi^-e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_9/Γ_4

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
6.99±0.30 OUR AVERAGE	Error includes scale factor of 1.2.			
7.21±0.32	30k	ROSSELET 77	SPEC	+
7.36±0.68	500	BOURQUIN 71	ASPK	
7.0 ±0.9	106	SCHWEINB... 71	HLBC	+
5.83±0.63	269	ELY 69	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
6.7 ±1.5	69	BIRGE 65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma_{total}$ Γ_{10}/Γ

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.77^{+0.54}_{-0.50}$	1	CLINE 65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ Γ_{10}/Γ_4

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
2.57±1.55	7	BISI 67	DBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~2.5	1	GREINER 64	EMUL	+

$\Gamma(\pi^+\gamma\gamma)/\Gamma_{total}$ Γ_{11}/Γ

All values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
< **0.084**	90	0	ASANO 82	CNTR	+	Tπ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.42 ±0.52		0	ABRAMS 77	SPEC	+	Tπ <92 MeV
< 0.35	90	0	LJUNG 73	HLBC	+	6–102,114–127 MeV
< 0.5	90	0	KLEMS 71	OSPK	+	Tπ <117 MeV
−0.1 ±0.6			CHEN 68	OSPK	+	Tπ 60–90 MeV

$\Gamma(\pi^+3\gamma)/\Gamma_{total}$ Γ_{12}/Γ

Values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<1.0	90	ASANO 82	CNTR	+	$T(\pi)$ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.0	90	KLEMS 71	OSPK	+	$T(\pi)$ >117 MeV

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma(e^+\nu_e)$ Γ_{13}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.8	90	0	HEINTZE	79	SPEC	+

$\Gamma(\mu^+\nu_\mu\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<6.0	90	0	[33] PANG	73	CNTR	+

[33] PANG 73 assumes μ spectrum from ν-ν interaction of BARDIN 70.

$\Gamma(\mu^+\nu_\mu e^+e^-)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{15}/Γ_9

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
27. ±8.	14	[34] DIAMANT-...	76	SPEC	+	Extrapolated BR
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.3±0.9	14	[34] DIAMANT-...	76	SPEC	+	$m(ee)$ >140

[34] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+\pi^-e\nu$ BR ratio. The first DIAMANT-BERGER 76 value is the second value extrapolated to 0 to include low mass e pairs.

$\Gamma(e^+\nu_e e^+e^-)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{16}/Γ_9

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
$0.54^{+0.54}_{-0.27}$	4	DIAMANT-...	76	SPEC	+

$\Gamma(\mu^+\nu_\mu\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	CHG
<4.1	90	ATIYA	89	CNTR	+

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
5.46±0.28 OUR AVERAGE						
6.0 ±0.9		BARMIN	88	HLBC	+	P(μ) <231.5 MeV/c
5.4 ±0.3		[35] AKIBA	85	SPEC		P(μ) <231.5 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.2 ±0.5	57	[36] BARMIN	88	HLBC	+	$E(\gamma)$ >20 MeV
5.8 ±3.5	12	WEISSENBE...	74	STRC	+	$E(\gamma)$ >9 MeV

[35] Assumes μ-e universality and uses constraints from $K \to e\nu\gamma$.

[36] Not independent of above BARMIN 88 value. Cuts differ.

$\Gamma(\mu^+\nu_\mu\gamma\ (\text{SD}^+))/\Gamma_{\text{total}}$ Γ_{19}/Γ

Structure-dependent part with $+\gamma$ helicity (SD$^+$ term). See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN
<3.0	90	AKIBA	85	SPEC

$\Gamma(\mu^+\nu_\mu\gamma\ (\text{SD}^+\text{INT}))/\Gamma_{\text{total}}$ Γ_{20}/Γ

Interference term between internal Bremsstrahlung and SD$^+$ term. See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN
<2.7	90	AKIBA	85	SPEC

$\Gamma(\mu^+\nu_\mu\gamma\ (\text{SD}^- + \text{SD}^-\text{INT}))/\Gamma_{\text{total}}$ Γ_{21}/Γ

Sum of structure-dependent part with $-\gamma$ helicity (SD$^-$ term) and interference term between internal Bremsstrahlung and SD$^-$ term. See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
<2.6	90	[37] AKIBA	85	SPEC

[37] Assumes μ-e universality and uses constraints from $K \to e\nu\gamma$.

$\Gamma(e^+\nu_e\gamma\ (\text{SD}^+))/\Gamma_{\text{total}}$ Γ_{22}/Γ

Structure-dependent part with $+\gamma$ helicity (SD$^+$ term). See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<7.1	90	MACEK	70	OSPK	+	P(e) 234–247

$\Gamma(e^+\nu_e\gamma\ (\text{SD}^+))/\Gamma(\mu^+\nu_\mu)$ Γ_{22}/Γ_1

Structure-dependent part with $+\gamma$ helicity (SD$^+$ term). See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
2.40±0.36	107	[38] HEINTZE	79	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.33±0.42	51	[38] HEINTZE	79	SPEC	+

[38] First HEINTZE 79 result is second combined with HEARD 75 result from section $\Gamma(e^+\nu_e\gamma\ (\text{SD}^+))/\Gamma(e^+\nu_e)$ below.

$\Gamma(e^+\nu_e\gamma\ (\text{SD}^+))/\Gamma(e^+\nu_e)$ Γ_{22}/Γ_2

Structure-dependent part with $+\gamma$ helicity (SD$^+$ term). See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$1.05^{+0.25}_{-0.30}$	56	[39] HEARD	75	SPEC	+	P(e) 236–247

[39] This value is included in the first HEINTZE 79 value in the section on $\Gamma(e^+\nu_e\gamma\ (\text{SD}^+))/\Gamma(\mu^+\nu_\mu)$ above.

$\Gamma(e^+\nu_e\gamma\ (\text{SD}^-))/\Gamma_{\text{total}}$ Γ_{23}/Γ

Structure-dependent part with $-\gamma$ helicity (SD$^-$ term). See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section of the Full Data Listings above.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG
<1.6	90	[40] HEINTZE	79	SPEC	+

[40] Implies (axial vector/vector) amplitude ratio outside range from −1.8 to −0.54.

$\Gamma(\pi^+\pi^0\gamma)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2.75±0.15 OUR AVERAGE							
2.71±0.45		140	BOLOTOV	87	WIRE	−	Tπ^- 55–90 MeV
2.87±0.32		2461	SMITH	76	WIRE	±	T$\pi^\pm$ 55–90 MeV
2.71±0.19		2100	ABRAMS	72	ASPK	±	Tπ^+ 55–90 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$1.5\ ^{+1.1}_{-0.6}$			[41] LJUNG	73	HLBC	+	Tπ^+ 55–80 MeV
$2.6\ ^{+1.5}_{-1.1}$			[41] LJUNG	73	HLBC	+	Tπ^+ 55–90 MeV
$6.8\ ^{+3.7}_{-2.1}$		17	[41] LJUNG	73	HLBC	+	Tπ^+ 55–102 MeV
2.4 ±0.8		24	EDWARDS	72	OSPK		Tπ^+ 58–90 MeV
<1.0		0	[42] MALTSEV	70	HLBC	+	Tπ^+ <55 MeV
<1.9	90	0	EMMERSON	69	OSPK		Tπ^+ 55–80 MeV
2.2 ±0.7		18	CLINE	64	FBC	+	Tπ^+ 55–80 MeV

[41] The LJUNG 73 values are not independent.

[42] MALTSEV 70 selects low π^+ energy to enhance direct emission contribution.

$\Gamma(\pi^+\pi^0\gamma\ (\text{DE}))/\Gamma_{\text{total}}$ Γ_{25}/Γ

Direct emission part of $\Gamma(\pi^+\pi^0\gamma)/\Gamma_{\text{total}}$.

VALUE (units 10^{-5})	DOCUMENT ID		TECN	CHG	COMMENT
1.8 ±0.4 OUR AVERAGE					
$2.05\pm0.46^{+0.39}_{-0.23}$	BOLOTOV	87	WIRE	−	Tπ^- 55–90 MeV
2.3 ±3.2	SMITH	76	WIRE	±	T$\pi^\pm$ 55–90 MeV
1.56±0.35±0.5	ABRAMS	72	ASPK	±	T$\pi^\pm$ 55–90 MeV

$\Gamma(\pi^+\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	CHG	COMMENT
1.0±0.4	STAMER	65	EMUL	+	$E(\gamma)$ >11 MeV

$\Gamma(\pi^+\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^0\pi^0)$ Γ_{27}/Γ_5

VALUE (units 10^{-4})	DOCUMENT ID		TECN	CHG	COMMENT
$4.3^{+3.2}_{-1.7}$	BOLOTOV	85	SPEC	−	$E(\gamma)$ > 10 MeV

$\Gamma(\pi^0\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<6.1	90	0	LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV

$\Gamma(\pi^0e^+\nu_e\gamma)/\Gamma(\pi^0e^+\nu_e)$ Γ_{29}/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.56±0.04 OUR AVERAGE						
0.56±0.04	192	[43] BOLOTOV	86B	CALO	−	$E(\gamma)$ >10 MeV
0.76±0.28	13	[44] ROMANO	71	HLBC		$E(\gamma)$ >10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.48±0.20	16	[45] LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV
$0.22^{+0.15}_{-0.10}$		[45] LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV
0.53±0.22		[44] ROMANO	71	HLBC	+	$E(\gamma)$ >30 MeV
1.2 ±0.8		BELLOTTI	67	HLBC	+	$E(\gamma)$ >30 MeV

[43] $\cos\theta(e\gamma)$ between 0.6 and 0.9.

[44] Both ROMANO 71 values are for $\cos\theta(e\gamma)$ between 0.6 and 0.9. Second value is for comparison with second LJUNG 73 value. We use lowest $E(\gamma)$ cut for Summary Table value. See ROMANO 71 for E_γ dependence.

[45] First LJUNG 73 value is for $\cos\theta(e\gamma)$ <0.9, second value is for $\cos\theta(e\gamma)$ between 0.6 and 0.9 for comparison with ROMANO 71.

$\Gamma(\pi^0e^+\nu_e\gamma\ (\text{SD}))/\Gamma_{\text{total}}$ Γ_{30}/Γ

Structure-dependent part.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	CHG
<5.3	90	BOLOTOV	86B	CALO	−

$\Gamma(\pi^+\pi^+e^-\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_{31}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9.0	95	0	SCHWEINB... 71	HLBC	+
<6.9	95	0	ELY 69	HLBC	+
$<20.$	95		BIRGE 65	FBC	+

$\Gamma(\pi^+\pi^+e^-\overline{\nu}_e)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{31}/Γ_9

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN
<3	90	3	[46] BLOCH 76	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<130.$	95	0	BOURQUIN 71	ASPK

[46] BLOCH 76 quotes 3.6×10^{-4} at CL = 95%, we convert.

$\Gamma(\pi^+\pi^+\mu^-\overline{\nu}_\mu)/\Gamma_{\text{total}}$ Γ_{32}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	CHG
<3.0	95	0	BIRGE 65	FBC	+

$\Gamma(\pi^+e^+e^-)/\Gamma_{\text{total}}$ Γ_{33}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by combined first-order weak and electromagnetic interactions.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.7	90		CENCE 74	ASPK	+	Three track evts
<0.27	90		CENCE 74	ASPK	+	Two track events
<32.0	90		BEIER 72	OSPK	±	
<4.4	90		BISI 67	DBC	+	
<0.88	90		CLINE 67B	FBC	+	
<2.45	90	1	CAMERINI 64	FBC	+	

$\Gamma(\pi^+e^+e^-)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{33}/Γ_9

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	CHG
7.0 ± 1.3	41	[47] BLOCH 75	SPEC	+

[47] BLOCH 75 quotes this result multiplied by our 1974 $\pi^+\pi^-e\nu$ BR fraction.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{34}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-7})	CL%	DOCUMENT ID	TECN	CHG
<2.3	90	ATIYA 89	CNTR	+
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<24	90	BISI 67	DBC	+
<30	90	CAMERINI 65	FBC	+

$\Gamma(\pi^+\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_{35}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<3.4	90		ATIYA 90	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<14	90		ASANO 81B	CNTR	+	$T(\pi)$ 116–127 MeV
<94	90		[48] CABLE 73	CNTR	+	$T(\pi)$ 60–105 MeV
<56	90		[48] CABLE 73	CNTR	+	$T(\pi)$ 60–127 MeV
<5700	90	0	[49] LJUNG 73	HLBC	+	
<140	90		[48] KLEMS 71	OSPK	+	$T(\pi)$ 117–127 MeV

[48] KLEMS 71 and CABLE 73 assume π spectrum same as K_{e3} decay. Second CABLE 73 limit combines CABLE 73 and KLEMS 71 data for vector interaction.

[49] LJUNG 73 assumes vector interaction.

$\Gamma(\mu^-\nu e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{36}/Γ_9

Test of lepton family number conservation.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	CHG
<0.5	90	0	[50] DIAMANT-... 76	SPEC	+

[50] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+\pi^-e\nu$ BR ratio.

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ Γ_{37}/Γ

Forbidden by lepton family number conservation.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<0.004	90	0	LYONS 81	HLBC	0	200 GeV K^+ narrow band ν beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.012	90		COOPER 82	HLBC		Wideband ν beam

$\Gamma(\pi^+\mu^+e^-)/\Gamma_{\text{total}}$ Γ_{38}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
<2.1	90	0	LEE 90	SPEC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<11	90	0	CAMPAGNARI 88	SPEC	+	In LEE 90
<48	90	0	DIAMANT-... 76	SPEC	+	

$\Gamma(\pi^\pm\mu^\mp e^+)/\Gamma_{\text{total}}$ Γ_{39}/Γ

VALUE (units 10^{-8})	CL%	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.8	90	BEIER 72	OSPK	±

$\Gamma(\pi^\pm\mu^\mp e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{39}/Γ_9

Test of lepton family number or total lepton number conservation.
Sum of $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	CHG
<1.9	90	0	[51] DIAMANT-... 76	SPEC	+

[51] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+\pi^-e\nu$ BR ratio.

$\Gamma(\pi^+e^+\mu^-)/\Gamma_{\text{total}}$ Γ_{44}/Γ

VALUE (units 10^{-8})	CL%	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.4	90	BEIER 72	OSPK	±

$\Gamma(\pi^-e^+e^+)/\Gamma_{\text{total}}$ Γ_{40}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-5})	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<1.5	CHANG 68	HBC	−

$\Gamma(\pi^-e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ Γ_{40}/Γ_9

Test of total lepton number conservation.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	CHG
<2.5	90	0	[52] DIAMANT-... 76	SPEC	+

[52] DIAMANT-BERGER 76 quotes this result times our 1975 BR ratio.

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_{41}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<3.3	90	COOPER 82	HLBC	Wideband ν beam

$\Gamma(\pi^0e^+\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_{42}/Γ

Forbidden by total lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.003	90	COOPER 82	HLBC	Wideband ν beam

$\Gamma(\pi^+\gamma)/\Gamma_{\text{total}}$ Γ_{43}/Γ

Violates angular momentum conservation. Not listed in Summary Table.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.4	90	ASANO 82	CNTR	+
<4.0	90	[53] KLEMS 71	OSPK	+

[53] Test of model of Selleri, NC 60A, 291(1969).

K^+ LONGITUDINAL POLARIZATION OF EMITTED μ^+

$K^+ \to \mu^+\nu$

Tests for right-handed currents in strangeness-changing decay.

VALUE	DOCUMENT ID	TECN	CHG
−0.97 ±0.04 OUR AVERAGE			
-0.970 ± 0.047	YAMANAKA 86	SPEC	+
$-1.0\ \ \pm0.1$	CUTTS 69	SPRK	+
$-0.96\ \pm0.12$	COOMBES 57	CNTR	+

NOTE ON DALITZ PLOT PARAMETERS FOR $K \to 3\pi$ DECAYS

The Dalitz plot distribution for $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$, $K^\pm \to \pi^0\pi^0\pi^\pm$, and $K_L^0 \to \pi^+\pi^-\pi^0$ can be parameterized by a series expansion such as that introduced by Weinberg.[1] We use the form

$$\left|M\right|^2 \propto 1 + g\frac{(s_3-s_0)}{m_{\pi^+}^2} + h\left[\frac{s_3-s_0}{m_{\pi^+}^2}\right]^2 + j\,\frac{(s_2-s_1)}{m_{\pi^+}^2} + k\left[\frac{s_2-s_1}{m_{\pi^+}^2}\right]^2 + \cdots\,, \qquad (1)$$

where $m_{\pi^+}^2$ has been introduced to make the coefficients g, h, j, and k dimensionless, and

$$s_i = (P_K - P_i)^2 = (m_K - m_i)^2 - 2m_K T_i\ ,\quad i = 1,2,3,$$

$$s_0 = \frac{1}{3}\sum_i s_i = \frac{1}{3}(m_K^2 + m_1^2 + m_2^2 + m_3^2)\ .$$

Here the P_i are four-vectors, m_i and T_i are the mass and kinetic energy of the i^{th} pion, and the index 3 is used for the odd pion.

The coefficient g is a measure of the slope in the variable s_3 (or T_3) of the Dalitz plot, while h and k measure the quadratic dependence on s_3 and $(s_2 - s_1)$, respectively. The coefficient j is related to the asymmetry of the plot and must be zero if CP invariance holds. Note also that if CP is good, g, h, and k must be the same for $K^+ \to \pi^+\pi^+\pi^-$ as for $K^- \to \pi^-\pi^-\pi^+$.

Since different experiments use different forms for $\left|M\right|^2$, in order to compare the experiments we have converted to g, h, j, and k whatever coefficients have been measured. Where such conversions have been done, the measured coefficient a_y, a_t, a_u, or a_v is given in the comment at the right. For definitions of these coefficients, details of this conversion, and discussion of the data, see the April 1982 version of this note.[2]

See also the review of Devlin and Dickey,[3] which contains an analysis of $K \to 2\pi$ and $K \to 3\pi$ data in terms of transition amplitudes with appropriate energy dependence.

References

1. S. Weinberg, Phys. Rev. Lett. **4**, 87 (1960).
2. Particle Data Group, Phys. Lett. **111B**, 69 (1982).
3. T.J. Devlin and J.O. Dickey, Rev. Mod. Phys. **51**, 237 (1979).

ENERGY DEPENDENCE OF $K^{\pm}$ DALITZ PLOT

$$|\text{matrix element}|^2 = 1 + gu + hu^2 + kv^2$$

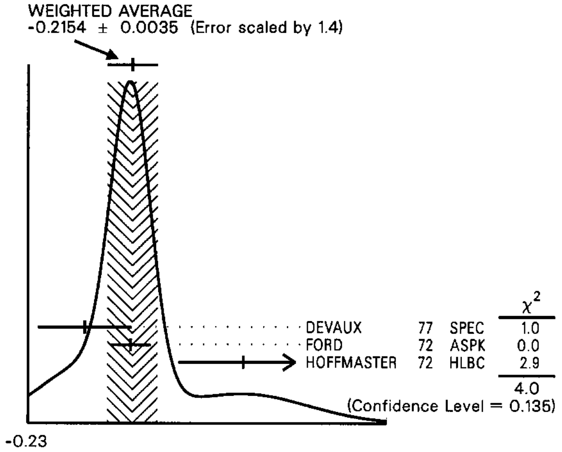
where $u = (s_3 - s_0) / m^2(\pi)$ and $v = (s_1 - s_2) / m^2(\pi)$

LINEAR COEFFICIENT $g_{\tau+}$ FOR $K^+ \to \pi^+\pi^+\pi^-$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \to 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the 1982 edition of this Review published in Physics Letters **111B**, 70 (April 1982).

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.2154±0.0035 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
−0.2221±0.0065	225k	DEVAUX 77	SPEC	+	a_y =.2814 ± .0082
−0.2157±0.0028	750k	FORD 72	ASPK	+	a_y =.2734 ± .0035
−0.200 ±0.009	39819	[54] HOFFMASTER 72	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.196 ±0.012	17898	[55] GRAUMAN 70	HLBC	+	a_y =0.228 ± 0.030
−0.218 ±0.016	9994	[56] BUTLER 68	HBC	+	a_y =0.277 ± 0.020
−0.22 ±0.024	5428	[56,57] ZINCHENKO 67	HBC	+	a_y =0.28 ± 0.03

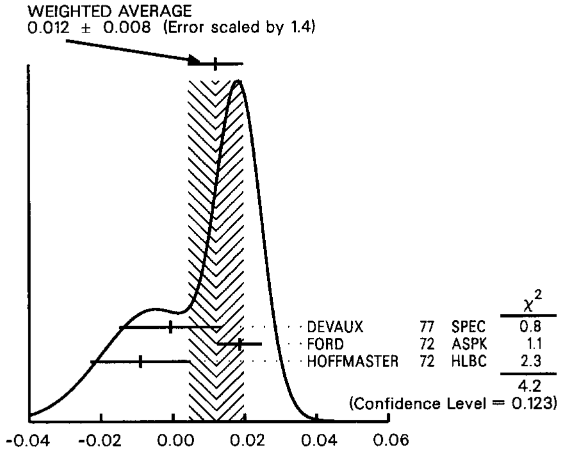
[54] HOFFMASTER 72 includes GRAUMAN 70 data.
[55] Emulsion data added — all events included by HOFFMASTER 72
[56] Experiments with large errors not included in average.
[57] Also includes DBC events.



Linear energy dependence for $K^+ \to \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT h FOR $K^+ \to \pi^+\pi^+\pi^-$

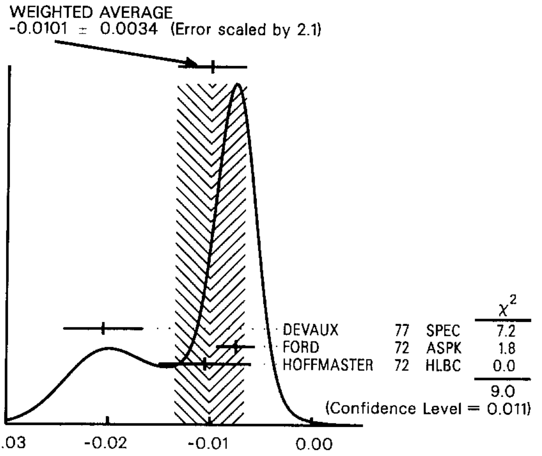
VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.012 ±0.008 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.		
−0.0006±0.0143	225k	DEVAUX 77	SPEC	+
0.0187±0.0062	750k	FORD 72	ASPK	+
−0.009 ±0.014	39819	HOFFMASTER 72	HLBC	+



Quadratic coefficient h for $K^+ \to \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT k FOR $K^+ \to \pi^+\pi^+\pi^-$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
−0.0101±0.0034 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.		
−0.0205±0.0039	225k	DEVAUX 77	SPEC	+
−0.0075±0.0019	750k	FORD 72	ASPK	+
−0.0105±0.0045	39819	HOFFMASTER 72	HLBC	+



Quadratic coefficient k for $K^+ \rightarrow \pi^+\pi^+\pi^-$

LINEAR COEFFICIENT g_{τ^-} FOR $K^- \rightarrow \pi^-\pi^-\pi^+$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \rightarrow 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the 1982 edition of this Review published in Physics Letters **111B**, 70 (April 1982).

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.217 ±0.007 OUR AVERAGE		Error includes scale factor of 2.5.			
−0.2186±0.0028	750k	FORD 72	ASPK	−	a_y=.2770 ± .0035
−0.193 ±0.010	50919	MAST 69	HBC	−	a_y=0.244 ± 0.013
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.199 ±0.008	81k	[58] LUCAS 73	HBC	−	a_y=0.252 ± 0.011
−0.190 ±0.023	5778	[59,60] MOSCOSO 68	HBC	−	a_y=0.242 ± 0.029
−0.220 ±0.035	1347	[61] FERRO-LUZZI 61	HBC	−	a_y=0.28 ± 0.045

[58] Quadratic dependence is required by K_L^0 experiments. For comparison we average only those $K^{\pm}$ experiments which quote quadratic fit values.

[59] Experiments with large errors not included in average.

[60] Also includes DBC events.

[61] No radiative corrections included.

QUADRATIC COEFFICIENT h FOR $K^- \rightarrow \pi^-\pi^-\pi^+$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.010 ±0.006 OUR AVERAGE				
0.0125±0.0062	750k	FORD 72	ASPK	−
−0.001 ±0.012	50919	MAST 69	HBC	−

QUADRATIC COEFFICIENT k FOR $K^- \rightarrow \pi^-\pi^-\pi^+$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
−0.0084±0.0019 OUR AVERAGE				
−0.0083±0.0019	750k	FORD 72	ASPK	−
−0.014 ±0.012	50919	MAST 69	HBC	−

$(g_{\tau^+} - g_{\tau^-}) \,/\, (g_{\tau^+} + g_{\tau^-})$

A nonzero value for this quantity indicates *CP* violation.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*
−0.70±0.53	3.2M	FORD 70	ASPK

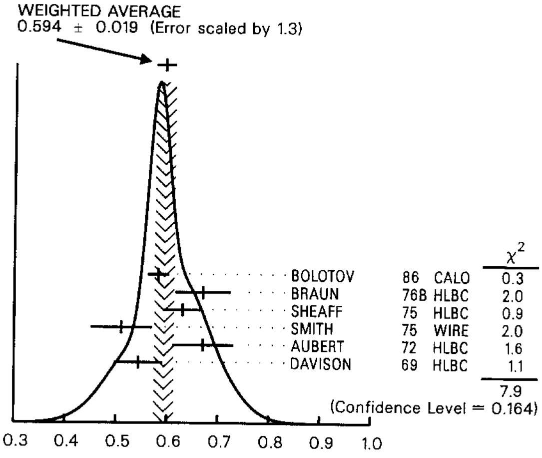
LINEAR COEFFICIENT g FOR $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

Unless otherwise stated, all experiments include terms quadratic in $(s_3 - s_0) \,/\, m^2(\pi^+)$. See mini-review above.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.594±0.019 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
0.582±0.021	43k	BOLOTOV 86	CALO	−	
0.670±0.054	3263	BRAUN 76B	HLBC	+	
0.630±0.038	5635	SHEAFF 75	HLBC	+	
0.510±0.060	27k	SMITH 75	WIRE	+	
0.67 ±0.06	1365	AUBERT 72	HLBC	+	
0.544±0.048	4048	DAVISON 69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.806±0.220	4639	[62] BERTRAND 76	EMUL	+	
0.484±0.084	574	[63] LUCAS 73B	HBC	−	Dalitz pairs only
0.527±0.102	198	[62] PANDOULAS 70	EMUL	+	
0.586±0.098	1874	[63] BISI 65	HLBC	+	Also HBC
0.48 ±0.04	1792	[63] KALMUS 64	HLBC	+	

[62] Experiments with large errors not included in average.

[63] Authors give linear fit only.



Linear energy dependence for $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

QUADRATIC COEFFICIENT h FOR $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

See mini-review above.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.035±0.015 OUR AVERAGE					
0.037±0.024	43k	BOLOTOV 86	CALO	−	
0.152±0.082	3263	BRAUN 76B	HLBC	+	
0.041±0.030	5635	SHEAFF 75	HLBC	+	
0.009±0.040	27k	SMITH 75	WIRE	+	
−0.01 ±0.08	1365	AUBERT 72	HLBC	+	
0.026±0.050	4048	DAVISON 69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.164±0.121	4639	[64] BERTRAND 76	EMUL	+	
0.018±0.124	198	[64] PANDOULAS 70	EMUL	+	

[64] Experiments with large errors not included in average.

NOTE ON $K^{\pm}_{\ell 3}$ AND $K^0_{\ell 3}$ FORM FACTORS

Assuming that only the vector current contributes to $K \rightarrow \pi\ell\nu$ decays, we write the matrix element as

$$M \propto f_+(t)\left[(P_K + P_\pi)_\mu \bar{\ell}\gamma_\mu(1+\gamma_5)\nu\right]$$

$$+ f_-(t)\left[m_\ell \bar{\ell}(1+\gamma_5)\nu\right] \;, \qquad (1)$$

where P_K and P_π are the four-momenta of the K and π mesons, m_ℓ is the lepton mass, and f_+ and f_- are dimensionless form factors which can depend only on $t = (P_K - P_\pi)^2$, the square of the four-momentum transfer to the leptons. If time-reversal invariance holds, f_+ and f_- are relatively real. $K_{\mu 3}$ experiments measure f_+ and f_-, while K_{e3} experiments are sensitive only to f_+ because the small electron mass makes the f_- term negligible.

(a) $K_{\mu 3}$ experiments. Analyses of $K_{\mu 3}$ data frequently assume a linear dependence of f_+ and f_- on t, i.e.,

$$f_\pm(t) = f_\pm(0)\left[1 + \lambda_\pm(t/m_\pi^2)\right] \;. \qquad (2)$$

Most $K_{\mu 3}$ data are adequately described by Eq. (2) for f_+ and a constant f_- (i.e., $\lambda_- = 0$). There are two equivalent parametrizations commonly used in these analyses:

(1) $\lambda_+, \xi(0)$ parametrization. Analyses of $K_{\mu 3}$ data often introduce the ratio of the two form factors

$$\xi(t) = f_-(t)/f_+(t) \;.$$

The $K_{\mu 3}$ decay distribution is then described by the two parameters λ_+ and $\xi(0)$ (assuming time reversal invariance and $\lambda_- = 0$). These parameters can be determined by three different methods:

Method A. By studying the Dalitz plot or the pion spectrum of $K_{\mu 3}$ decay. The Dalitz plot density is (see, e.g., Chounet et al.[1]):

$$\rho(E_\pi, E_\mu) \propto f_+^2(t)\left[A + B\xi(t) + C\xi(t)^2\right] \ ,$$

where

$$A = m_K\left(2E_\mu E_\nu - m_K E'_\pi\right) + m_\mu^2\left(\frac{1}{4}E'_\pi - E_\nu\right) \ ,$$

$$B = m_\mu^2\left(E_\nu - \frac{1}{2}E'_\pi\right) \ ,$$

$$C = \frac{1}{4}m_\mu^2 E'_\pi \ ,$$

$$E'_\pi = E_\pi^{\max} - E_\pi = \left(m_K^2 + m_\pi^2 - m_\mu^2\right)/2m_K - E_\pi \ .$$

Here E_π, E_μ, and E_ν are, respectively, the pion, muon, and neutrino energies in the kaon center of mass. The density ρ is fit to the data to determine the values of $\lambda_+, \xi(0)$, and their correlation.

Method B. By measuring the $K_{\mu 3}/K_{e3}$ branching ratio and comparing it with the theoretical ratio (see, e.g., Fearing et al.[2]) as given in terms of λ_+ and $\xi(0)$, assuming μ-e universality:

$$\Gamma(K_{\mu 3}^{\pm})/\Gamma(K_{e3}^{\pm}) = 0.6457 + 1.4115\lambda_+ + 0.1264\xi(0)$$
$$+0.0192\xi(0)^2 + 0.0080\lambda_+\xi(0) \ ,$$

$$\Gamma(K_{\mu 3}^{0})/\Gamma(K_{e3}^{0}) = 0.6452 + 1.3162\lambda_+ + 0.1264\xi(0)$$
$$+0.0186\xi(0)^2 + 0.0064\lambda_+\xi(0) \ .$$

This cannot determine λ_+ and $\xi(0)$ simultaneously but simply fixes a relationship between them.

Method C. By measuring the muon polarization in $K_{\mu 3}$ decay. In the rest frame of the K, the μ is expected to be polarized in the direction $\mathbf{A}$ with $\mathbf{P} = \mathbf{A}/\left|\mathbf{A}\right|$, where $\mathbf{A}$ is given (Cabibbo and Maksymowicz[3]) by

$$\mathbf{A} = a_1(\xi)\mathbf{p}_\mu$$
$$-a_2(\xi)\left[\frac{\mathbf{p}_\mu}{m_\mu}\left(m_K - E_\pi + \frac{\mathbf{p}_\pi\cdot\mathbf{p}_\mu}{\left|\mathbf{p}_\mu\right|^2}(E_\mu - m_\mu)\right) + \mathbf{p}_\pi\right]$$
$$+m_K \mathrm{Im}\xi(t)(\mathbf{p}_\pi \times \mathbf{p}_\mu) \ .$$

If time-reversal invariance holds, ξ is real, and thus there is no polarization perpendicular to the K-decay plane. Polarization experiments measure the weighted average of $\xi(t)$ over the t range of the experiment, where the weighting accounts for the variation with t of the sensitivity to $\xi(t)$.

(2) λ_+, λ_0 parametrization. Most of the more recent $K_{\mu 3}$ analyses have parameterized in terms of the form factors f_+ and f_0 which are associated with vector and scalar exchange, respectively, to the lepton pair. f_0 is related to f_+ and f_- by

$$f_0(t) = f_+(t) + \left[t/(m_K^2 - m_\pi^2)\right]f_-(t) \ .$$

Here $f_0(0)$ must equal $f_+(0)$ unless $f_-(t)$ diverges at $t = 0$. The earlier assumption that f_+ is linear in t and f_- is constant leads to f_0 linear in t:

$$f_0(t) = f_0(0)\left[1 + \lambda_0(t/m_\pi^2)\right] \ .$$

With the assumption that $f_0(0) = f_+(0)$, the two parametrizations, $(\lambda_+, \xi(0))$ and (λ_+, λ_0) are equivalent as long as correlation information is retained. (λ_+, λ_0) correlations tend to be less strong than $(\lambda_+, \xi(0))$ correlations.

The experimental results for $\xi(0)$ and its correlation with λ_+ are listed in the $K^{\pm}$ and K_L^0 sections of the Full Listings in section ξ_{A}, ξ_{B}, or ξ_{C} depending on whether method A, B, or C discussed above was used. The corresponding values of λ_+ are also listed.

Because recent experiments tend to use the (λ_+, λ_0) parametrization, we include a subsection for λ_0 results. Wherever possible we have converted $\xi(0)$ results into λ_0 results and vice versa.

See the 1982 version of this note[4] for additional discussion of the $K_{\mu 3}^0$ parameters, correlations, and conversion between parametrizations, and also for a comparison of the experimental results.

(b) K_{e3} experiments. Analysis of K_{e3} data is simpler than that of $K_{\mu 3}$ because the second term of the matrix element assuming a pure vector current [Eq. (1) above] can be neglected. Here f_+ is usually assumed to be linear in t, and the linear coefficient λ_+ of Eq. (2) is determined.

If we remove the assumption of a pure vector current, then the matrix element for the decay, in addition to the terms in Eq. (2), would contain

$$+2m_K\, f_S\,\bar{\ell}(1 + \gamma_5)\nu$$
$$+(2f_T/m_K)(P_K)_\lambda(P_\pi)_\mu\,\bar{\ell}\,\sigma_{\lambda\mu}(1 + \gamma_5)\nu \ ,$$

where f_S is the scalar form factor, and f_T is the tensor form factor. In the case of the K_{e3} decays where the f_- term can be neglected, experiments have yielded limits on $|f_S/f_+|$ and $|f_T/f_+|$.

References

1. L.M. Chounet, J.M. Gaillard, and M.K. Gaillard, Phys. Rep. **4C**, 199 (1972).
2. H.W. Fearing, E. Fischbach, and J. Smith, Phys. Rev. **D2**, 542 (1970).
3. N. Cabibbo and A. Maksymowicz, Phys. Lett. **9**, 352 (1964).
4. Particle Data Group, Phys. Lett. **111B**, 73 (1982).

$K^{\pm}$ FORM FACTORS

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.
f_S and f_T refer to the scalar and tensor term.
$f_0 = f_+ + f_- t/(m^2(K) - m^2(\pi))$.
λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.
λ_+ refers to the $K_{\mu 3}$ value except in the K_{e3} sections.
$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K_{\mu 3}$.
$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K_{\mu 3}$.
t = momentum transfer to the π in units of $m^2(\pi)$.
DP = Dalitz plot analysis.

PI = π spectrum analysis.
MU = μ spectrum analysis.
POL= μ polarization analysis.
BR = $K_{\mu3}/K_{e3}$ branching ratio analysis.
E = positron or electron spectrum analysis.
RC = radiative corrections.

$\xi_A = f_-/f_+$ (determined from spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.35±0.15 OUR EVALUATION			From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.27±0.25	−17	3973	WHITMAN 80	SPEC	+	DP
−0.8 ±0.8	−20	490	[65] ARNOLD 74	HLBC	+	DP
−0.57±0.24	−9	6527	[66] MERLAN 74	ASPK	+	DP
−0.36±0.40	−19	1897	[67] BRAUN 73C	HLBC	+	DP
−0.62±0.28	−12	4025	[68] ANKENBRA... 72	ASPK	+	PI
+0.45±0.28	−15	3480	[69] CHIANG 72	OSPK	+	DP
−1.1 ±0.56	−29	3240	[70] HAIDT 71	HLBC	+	DP
−0.5 ±0.8	−26	2041	[71] KIJEWSKI 69	OSPK	+	PI
+0.72±0.93	−17	444	CALLAHAN 66B	FBC	+	PI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.5 ±0.9	none	78	EISLER 68	HLBC	+	PI, $\lambda_+=0$
$0.0^{+1.1}_{-0.9}$		2648	[72] CALLAHAN 66B	FBC	+	μ, $\lambda_+=0$
+0.7 ±0.5		87	GIACOMELLI 64	EMUL	+	MU+BR,$\lambda_+=0$
−0.08±0.7			[73] JENSEN 64	XEBC	+	DP+BR
+1.8 ±0.6		76	BROWN 62B	XEBC	+	DP+BR, $\lambda_+=0$

[65] ARNOLD 74 figure 4 was used to obtain ξ_A and $d\xi(0)/d\lambda_+$.

[66] MERLAN 74 figure 5 was used to obtain $d\xi(0)/d\lambda_+$.

[67] BRAUN 73C gives $\xi(t) = -0.34 \pm 0.20$, $d\xi(t)/d\lambda_+ = -14$ for $\lambda_+ = 0.027$, $t = 6.6$. We calculate above $\xi(0)$ and $d\xi(0)/d\lambda_+$ for their $\lambda_+ = 0.025 \pm 0.017$.

[68] ANKENBRANDT 72 figure 3 was used to obtain $d\xi(0)/d\lambda_+$.

[69] CHIANG 72 figure 10 was used to obtain $d\xi(0)/d\lambda_+$. Fit had $\lambda_- = \lambda_+$ but would not change for $\lambda_- = 0$. L.Pondrom, (private communication 74).

[70] HAIDT 71 table 8 (Dalitz plot analysis) gives $d\xi(0)/d\lambda_+ = (-1.1+0.5)/(0.050-0.029) = -29$, error raised from 0.50 to agree with $d\xi(0) = 0.20$ for fixed λ_+.

[71] KIJEWSKI 69 figure 17 was used to obtain $d\xi(0)/d\lambda_+$ and errors.

[72] CALLAHAN 66 table 1 (π analysis) gives $d\xi(0)/d\lambda_+ = (0.72-0.05)/(0-0.04) = -17$, error raised from 0.80 to agree with $d\xi(0) = 0.37$ for fixed λ_+. t unknown.

[73] JENSEN 64 gives $\lambda_+^\mu = \lambda_+^e = -0.020 \pm 0.027$. $d\xi(0)/d\lambda_+$ unknown. Includes SHAKLEE 64 $\xi_B(K_{\mu3}/K_{e3})$.

$\xi_B = f_-/f_+$ (determined from $K_{\mu3}/K_{e3}$)

The $K_{\mu3}/K_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_B values. Instead they are obtained directly from the fitted $K_{\mu3}/K_{e3}$ ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0e^+\nu_e)$, with the exception of HEINTZE 77. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.35±0.15 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.12±0.12	55k	[74] HEINTZE 77	CNTR	+	$\lambda_+=0.029$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0 ±0.15	5825	CHIANG 72	OSPK	+	$\lambda_+=0.03$, fig.10
−0.81±0.27	1505	[75] HAIDT 71	HLBC	+	$\lambda_+=0.028$, fig.8
−0.35±0.22		[76] BOTTERILL 70	OSPK	+	$\lambda_+=0.045\pm0.015$
+0.91±0.82		ZELLER 69	ASPK	+	$\lambda_+=0.023$
−0.08±0.15	5601	[76] BOTTERILL 68B	ASPK	+	$\lambda_+=0.023\pm0.008$
−0.60±0.20	1398	[75] EICHTEN 68	HLBC	+	See note
+1.0 ±0.6	986	GARLAND 68	OSPK	+	$\lambda_+=0$
+0.75±0.50	306	AUERBACH 67	OSPK	+	$\lambda_+=0$
+0.4 ±0.4	636	CALLAHAN 66B	FBC	+	$\lambda_+=0$
+0.6 ±0.5		BISI 65B	HBC	+	$\lambda_+=0$
+0.8 ±0.6	500	CUTTS 65	OSPK	+	$\lambda_+=0$
$-0.17^{+0.75}_{-0.99}$		SHAKLEE 64	XEBC	+	$\lambda_+=0$

[74] Calculated by us from λ_0 and λ_+ given below.

[75] EICHTEN 68 has $\lambda_+ = 0.023 \pm 0.008$, $t = 4$, independent of λ_-. Replaced by HAIDT 71.

[76] BOTTERILL 70 is re-evaluation of BOTTERILL 68B with different λ_+.

$\xi_C = f_-/f_+$ (determined from μ polarization in $K_{\mu3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+=0$. $d\xi/d\lambda = \xi t$. For radiative correction to muon polarization in $K_{\mu3}$, see GINSBERG 71. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.35±0.15 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
−0.25±1.20	1585	[77] BRAUN 75	HLBC	+	POL, t=4.2
−0.95±0.3	3133	[78] CUTTS 69	OSPK	+	Total pol. t=4.0
−1.0 ±0.3	6000	[79] BETTELS 68	HLBC	+	Total pol. t=4.9
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.64±0.27	40k	[80] MERLAN 74	ASPK	+	POL, $d\xi(0)/d\lambda_+ = +1.7$
−1.4 ±1.8	397	[81] CALLAHAN 66B	FBC	+	Total pol.
$-0.7^{+0.9}_{-3.3}$	2950	[81] CALLAHAN 66B	FBC	+	Long. pol.
$+1.2^{+2.4}_{-1.8}$	2100	[81] BORREANI 65	HLBC	+	Polarization
−4.0 to +1.7	500	[81] CUTTS 65	OSPK	+	Long. pol.

[77] BRAUN 75 $d\xi(0)/d\lambda_+ = \xi t = -0.25\times4.2 = -1.0$.

[78] CUTTS 69 $t = 4.0$ was calculated from figure 8. $d\xi(0)/d\lambda_+ = \xi t = -0.95\times4 = -3.8$.

[79] BETTELS 68 $d\xi(0)/d\lambda_+ = \xi t = -1.0\times4.9 = -4.9$.

[80] MERLAN 74 polarization result (figure 5) not possible. See discussion of polarization experiments in note on "$K_{\ell3}$ Form Factors" in the 1982 edition of this Review [Physics Letters **111B** (April 1982)].

[81] t value not given.

IMAGINARY PART OF ξ

Test of T reversal invariance.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
−0.017±0.025 OUR AVERAGE					
−0.016±0.025	20M	CAMPBELL 81	CNTR	+	Pol.
$-0.3^{+0.3}_{-0.4}$	3133	CUTTS 69	OSPK	+	Total pol. fig.7
−0.1 ±0.3	6000	BETTELS 68	HLBC	+	Total pol.
0.0 ±1.0	2648	CALLAHAN 66B	FBC	+	MU
+1.6 ±1.3	397	CALLAHAN 66B	FBC	+	Total pol.
$0.5^{+1.4}_{-0.5}$	2950	CALLAHAN 66B	FBC	+	Long. pol.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.010±0.019	32M	[82] BLATT 83	CNTR		Polarization

[82] Combined result of MORSE 80 ($K^0_{\mu3}$) and CAMPBELL 81 ($K^+_{\mu3}$).

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K_{\mu3}$ DECAY)

See also the corresponding entries and footnotes in sections ξ_A, ξ_C, and λ_0. For radiative correction of $K_{\mu3}$ Dalitz plot, see GINSBERG 70 and BECHERRAWY 70.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.033±0.008 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
+0.050±0.013	3973	WHITMAN 80	SPEC	+	DP
0.025±0.030	490	ARNOLD 74	HLBC	+	DP
0.027±0.019	6527	MERLAN 74	ASPK	+	DP
0.025±0.017	1897	BRAUN 73C	HLBC	+	DP
0.024±0.019	4025	[83] ANKENBRA... 72	ASPK	+	PI
−0.006±0.015	3480	CHIANG 72	OSPK	+	DP
0.050±0.018	3240	HAIDT 71	HLBC	+	DP
0.009±0.026	2041	KIJEWSKI 69	OSPK	+	PI
0.0 ±0.05	444	CALLAHAN 66B	FBC	+	PI

[83] ANKENBRANDT 72 λ_+ from figure 3 to match $d\xi(0)/d\lambda_+$. Text gives 0.024 ± 0.022.

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K_{\mu3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ_+^μ and $d\xi/d\lambda$.

VALUE	$d\lambda_0/d\lambda_+$	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.004±0.007 OUR EVALUATION			From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
+0.029±0.011	−0.37	3973	WHITMAN 80	SPEC	+	DP
+0.019±0.010	+0.03	55k	[84] HEINTZE 77	SPEC	+	BR
+0.008±0.097	+0.92	1585	[85] BRAUN 75	HLBC	+	POL
−0.040±0.040	−0.62	490	ARNOLD 74	HLBC	+	DP
−0.019±0.015	+0.27	6527	[86] MERLAN 74	ASPK	+	DP
−0.008±0.020	−0.53	1897	[87] BRAUN 73C	HLBC	+	DP
−0.026±0.013	+0.03	4025	[88] ANKENBRA... 72	ASPK	+	PI
+0.030±0.014	−0.21	3480	[88] CHIANG 72	OSPK	+	DP
−0.039±0.029	−1.34	3240	[88] HAIDT 71	HLBC	+	DP
−0.056±0.024	+0.69	3133	[85] CUTTS 69	OSPK	+	POL
−0.031±0.045	−1.10	2041	[88] KIJEWSKI 69	OSPK	+	PI
−0.063±0.024	+0.60	6000	[85] BETTELS 68	HLBC	+	POL
+0.058±0.036	−0.37	444	[88] CALLAHAN 66B	FBC	+	PI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.017±0.011			[89] BRAUN 74	HLBC	+	$K_{\mu3}/K_{e3}$ vs. t

[84] HEINTZE 77 uses $\lambda_+ = 0.029 \pm 0.003$. $d\lambda_0/d\lambda_+$ estimated by us.

[85] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[86] MERLAN 74 λ_0 and $d\lambda_0/d\lambda_+$ were calculated by us from ξ_A, λ_+^μ, and $d\xi(0)/d\lambda_+$. Their figure 6 gives $\lambda_0 = -0.025 \pm 0.012$ and no $d\lambda_0/d\lambda_+$.

[87] This value and error are taken from BRAUN 75 but correspond to the BRAUN 73C λ_+^μ result. $d\lambda_0/d\lambda_+$ is from BRAUN 73C $d\xi(0)/d\lambda_+$ in ξ_A above.

[88] λ_0 calculated by us from $\xi(0)$, λ_+^μ, and $d\xi(0)/d\lambda_+$.

[89] BRAUN 74 is a combined $K_{\mu3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu3}$) and BRAUN 73B (K_{e3}) form factor results.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K_{e3} DECAY)

For radiative correction of K_{e3} Dalitz plot, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.028±0.004 OUR AVERAGE						
0.027±0.008		[90] BRAUN	73B	HLBC	+	DP, no RC
0.029±0.011	4017	CHIANG	72	OSPK	+	DP, RC negligible
0.027±0.010	2707	STEINER	71	HLBC	+	DP, uses RC
0.045±0.015	1458	BOTTERILL	70	OSPK		PI, uses RC
0.08 ±0.04	960	BOTTERILL	68C	ASPK	+	e^+, uses RC
$-0.02\,^{+0.08}_{-0.12}$	90	EISLER	68	HLBC	+	PI, uses RC
$0.045\,^{+0.017}_{-0.018}$	854	BELLOTTI	67B	FBC	+	DP, uses RC
+0.016±0.016	1393	IMLAY	67	OSPK	+	DP, no RC
$+0.028\,^{+0.013}_{-0.014}$	515	KALMUS	67	FBC	+	e^+, PI, no RC
−0.04 ±0.05	230	BORREANI	64	HBC	+	e^+, no RC
−0.010±0.029	407	JENSEN	64	XEBC	+	PI, no RC
+0.036±0.045	217	BROWN	62B	XEBC	+	PI, no RC

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.025±0.007		[91] BRAUN	74	HLBC	+	$K_{\mu3}/K_{e3}$ vs. t

[90] BRAUN 73B states that radiative corrections of GINSBERG 67 would lower λ_+^e by 0.002 but that radiative corrections of BECHERRAWY 70 disagrees and would raise λ_+^e by 0.005.

[91] BRAUN 74 is a combined $K_{\mu3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu3}$) and BRAUN 73B (K_{e3}) form factor results.

$|f_S/f_+|$ FOR K_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$0.12\,^{+0.04}_{-0.05}$ **OUR AVERAGE**			Error includes scale factor of 1.3.				
0.00±0.10		2827	BRAUN	75	HLBC	+	
$0.14\,^{+0.03}_{-0.04}$		2707	STEINER	71	HLBC	+	λ_+, f_S, f_T, ϕ fit

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.13	90	4017	CHIANG	72	OSPK	+	
<0.23	90		BOTTERILL	68C	ASPK		
<0.18	90		BELLOTTI	67B	HLBC		
<0.30	95		KALMUS	67	HLBC	+	

$|f_T/f_+|$ FOR K_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$0.22\,^{+0.15}_{-0.13}$ **OUR AVERAGE**							
0.07±0.37		2827	BRAUN	75	HLBC	+	
$0.24\,^{+0.16}_{-0.14}$		2707	STEINER	71	HLBC	+	λ_+, f_S, f_T, ϕ fit

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.75	90	4017	CHIANG	72	OSPK	+	
<0.58	90		BOTTERILL	68C	ASPK		
<0.58	90		BELLOTTI	67B	HLBC		
<1.1	95		KALMUS	67	HLBC	+	

f_T/f_+ FOR $K_{\mu3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	EVTS	DOCUMENT ID		TECN
0.02±0.12	1585	BRAUN	75	HLBC

DECAY FORM FACTORS FOR $K^{\pm} \rightarrow \pi^+\pi^- e^{\pm}\nu$

Given in ROSSELET 77, BEIER 73, and BASILE 71C.

DECAY FORM FACTOR FOR $K^{\pm} \rightarrow \pi^0\pi^0 e^{\pm}\nu$

Given in BOLOTOV 86B and BARMIN 88B.

REFERENCES FOR $K^{\pm}$

ATIYA	90	PRL 64 21	+Chiang, Frank, Haggerty+	(BNL, LANL, PRIN, TRIU)
LEE	90	PRL 64 165	+Alliegro, Campagnari+	(BNL, FNAL, PSI, WASH, YALE)
ATIYA	89	PRL 63 2177	+Chiang, Frank, Haggerty+	(BNL, LANL, PRIN, TRIU)
BARMIN	88	SJNP 47 643 Translated from YAF 47 1011.	+Barylov, Davidenko, Demidov, Dolgolenko+	(ITEP)
BARMIN	88B	SJNP 48 1032 Translated from YAF 48 1719.	+Barylov, Davidenko, Demidov, Dolgolenko+	(ITEP)
CAMPAGNARI	88	PRL 61 2062	+Alliegro, Chaloupka+	(BNL, FNAL, PSI, WASH, YALE)
GALL	88	PRL 60 186	+Austin+	(BOST, MIT, WILL, CIT, CMU, WYOM)
BARMIN	87	SJNP 45 62 Translated from YAF 45 97.	+Barylov, Davidenko, Demidov+	(ITEP)
BOLOTOV	87	SJNP 45 1023 Translated from YAF 45 1652.	+Gninenko, Dzhilkibaev, Isakov, Klubakov+	(INRM)
BOLOTOV	86	SJNP 44 73 Translated from YAF 44 117.	+Gninenko, Dzhilkibaev, Isakov+	(INRM)
BOLOTOV	86B	SJNP 44 68 Translated from YAF 44 108.	+Gninenko, Dzhilkibaev, Isakov+	(INRM)
YAMANAKA	86	PR D34 85	+Hayano, Taniguchi, Ishikawa+	(KEK, TOKY)
Also	84	PRL 52 329	Hayano, Yamanaka, Taniguchi+	(TOKY, KEK)
AKIBA	85	PR D32 2911	+Ishikawa, Iwasaki+	(TOKY, TINT, TSUK, KEK)
BOLOTOV	85	JETPL 42 481 Translated from ZETFP 42 390.	+Gninenko, Dzhilkibaev, Isakov+	(INRM)
BLATT	83	PR D27 1056	+Adair, Black, Campbell+	(YALE, BNL)
ASANO	82	PL 113B 195	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, OSAK)
COOPER	82	PL 112B 97	+Guy, Michette, Tyndel, Venus	(RL)
ASANO	81B	PL 107B 159	+Kikutani, Kurokawa, Miyachi+	(KEK, TOKY, OSAK)
CAMPBELL	81	PRL 47 1032	+Black, Blatt, Kasha, Schmidt+	(YALE, BNL)
Also	83	PR D27 1056	Blatt, Adair, Black, Campbell+	(YALE, BNL)
LUM	81	PR D23 2522	+Wiegand, Kessler, Deslattes, Seki+	(LBL, NBS+)
LYONS	81	ZPHY C10 215	+Albajar, Myatt	(OXF)
MORSE	80	PR D21 1750	+Leipuner, Larsen, Schmidt, Blatt+	(BNL, YALE)
WHITMAN	80	PR D21 652	+Abrams, Carroll, Kycia, Li+	(ILLC, BNL, ILL)
BARKOV	79	NP B148 53	+Vasserman, Zolotorev, Krupin+	(NOVO, KIAE)
HEINTZE	79	NP B149 365	+Heinzelmann, Igo-Kemenes+	(HEID, CERN)
ABRAMS	77	PR D15 22	+Carroll, Kycia, Li, Michael, Mockett+	(BNL)
DEVAUX	77	NP B126 11	+Bloch, Diamant-Berger, Maillard+	(SACL, GEVA)
HEINTZE	77	PL 70B 482	+Heinzelmann, Igo-Kemenes+	(HEID, CERN)
ROSSELET	77	PR D15 574	+Extermann, Fischer, Guisan+	(GEVA, SACL)
BERTRAND	76	NP B114 387	+Sacton+	(BRUX, UBEL, DUUC, LOUC, WARS)
BLOCH	76	PL 60B 393	+Bunce, Devaux, Diamant-Berger+	(GEVA, SACL)
BRAUN	76B	LNC 17 521	+Martyn, Erriquez+	(AACH, BARI, BELG, CERN)
DIAMANT-...	76	PL 62B 485	Diamant-Berger, Bloch, Devaux+	(SACL, GEVA)
HEINTZE	76	PL 60B 302	+Heinzelmann, Igo-Kemenes, Mundhenke+	(HEID)
SMITH	76	NP B109 173	+Booth, Renshall, Jones+	(GLAS, LIVP, OXF, RHEL)
WEISSENBE...	76	NP B115 55	Weissenberg, Egorov, Minervina+	(ITEP, LEBD)
BLOCH	75	PL 56B 201	+Brehin, Bunce, Devaux+	(SACL, GEVA)
BRAUN	75	NP B89 210	+Cornelssen+	(AACH, BARI, BRUX, CERN)
CHENG	75	NP A254 381	+Asano, Chen, Dugan, Hu, Wu+	(COLU, YALE)
HEARD	75	PL 55B 324	+Heintze, Heinzelmann+	(CERN, HEID)
HEARD	75B	PL 55B 327	+Heintze, Heinzelmann+	(CERN, HEID)
SHEAFF	75	PR D12 2570		(WISC)
SMITH	75	NP B91 45	+Booth, Renshall, Jones+	(GLAS, LIVP, OXF, RHEL)
ARNOLD	74	PR D9 1221	+Roe, Sinclair	(MICH)
BRAUN	74	PL 51B 393	+Cornelssen, Martyn+	(AACH, BARI, BRUX, CERN)
CENCE	74	PR D10 776	+Harris, Jones, Morgado+	(HAWA, LBL, WISC)
Also	73	Thesis unpub.	Clarke	(WISC)
KUNSELMAN	74	PR C9 2469		(WYOM)
MERLAN	74	PR D9 107	+Kasha, Wanderer, Adair+	(YALE, BNL, LASL)
WEISSENBE...	74	PL 48B 474	Weissenberg, Egorov, Minervina+	(ITEP, LEBD)
ABRAMS	73B	PRL 30 500	+Carroll, Kycia, Li, Menes, Michael+	(BNL)
BACKENSTO...	73	PL 43B 431	Backenstoss+	(CERN, KARL, HEID, STOH)
BEIER	73	PRL 30 399	+Buchholz, Mann, Parker, Roberts	(PENN)
BRAUN	73B	PL 47B 185	+Cornelssen	(AACH, BARI, BRUX, CERN)
Also	75	NP B89 210	Braun, Cornelssen+	(AACH, BARI, BRUX, CERN)
BRAUN	73C	PL 47B 182	+Cornelssen	(AACH, BARI, BRUX, CERN)
Also	75	NP B89 210	Braun, Cornelssen+	(AACH, BARI, BRUX, CERN)
CABLE	73	PR D8 3807	+Hildebrand, Pang, Stiening	(EFI, LBL)
LJUNG	73	PR D8 1307	+Cline	(WISC)
Also	72	PRL 28 523	Ljung	(WISC)
Also	72	PRL 28 1287	Cline, Ljung	(WISC)
Also	69	PRL 23 326	Camerini, Ljung, Sheaff, Cline	(WISC)
LUCAS	73	PR D8 719	+Taft, Willis	(YALE)
LUCAS	73B	PR D8 727	+Taft, Willis	(YALE)
PANG	73	PR D8 1989	+Hildebrand, Cable, Stiening	(EFI, ARIZ, LBL)
Also	72	PL 40B 699	Cable, Hildebrand, Pang, Stiening	(EFI, LBL)
SMITH	73	NP B60 411	+Booth, Renshall, Jones+	(GLAS, LIVP, OXF, RHEL)
ABRAMS	72	PRL 29 1118	+Carroll, Kycia, Li, Menes, Michael+	(BNL)
ANKENBRA...	72	PRL 28 1472	Ankenbrandt, Larsen+	(BNL, LASL, FNAL, YALE)
AUBERT	72	NC 12A 509	+Heusse, Pascaud, Vialle+	(ORSA, BRUX, EPOL)
BEIER	72	PRL 29 678	+Buchholz, Mann, Parker	(PENN)
CHIANG	72	PR D6 1254	+Rosen, Shapiro, Handler, Olsen+	(ROCH, WISC)
CLARK	72	PRL 29 1274	+Cork, Elioff, Kerth, McReynolds, Newton+	(LBL)
EDWARDS	72	PR D5 2720	+Beier, Bertram, Herzo, Koester+	(ILL)
FORD	72	PL 38B 335	+Piroue, Remmel, Smith, Souder	(PRIN)
HOFFMASTER	72	NP B36 1	+Koller, Taylor+	(STEV, SETO, LEHI)
BASILE	71C	PL 36B 619	+Brehin, Diamant-Berger, Kunz+	(SACL, GEVA)
BOURQUIN	71	PL 36B 615	+Boymond, Extermann, Marasco+	(GEVA, SACL)
GINSBERG	71	PR D4 2893		(MIT)
HAIDT	71	PR D3 10		(AACH, BARI, CERN, EPOL, NIJM+)
Also	69	PL 29B 691	Haidt+	(AACH, BARI, CERN, EPOL, NIJM, ORSA+)
KLEMS	71	PR D4 66	+Hildebrand, Stiening	(CHIC, LRL)
Also	70	PRL 24 1086	Klems, Hildebrand, Stiening	(LRL, CHIC)
Also	70B	PRL 25 473	Klems, Hildebrand, Stiening	(LRL, CHIC)
OTT	71	PR D3 52	+Pritchard	(LOQM)
ROMANO	71	PL 36B 525	+Renton, Aubert, Burban-Lutz	(BARI, CERN, ORSA)
SCHWEINB...	71	PL 36B 246	Schweinberger	(AACH, BELG, CERN, NIJM+)
STEINER	71	PL 36B 521		(AACH, BARI, CERN, EPOL, ORSA, NIJM, PADO+)
BARDIN	70	PL 32B 121	+Bilenky, Pontecorvo	(JINR)
BECHERRAWY	70	PR D1 1452		(ROCH)
BOTTERILL	70	PL 31B 325	+Brown, Clegg, Corbett, Culligan+	(OXF)
FORD	70	PRL 25 1370	+Piroue, Remmel, Smith, Souder	(PRIN)
GAILLARD	70	CERN 70-14	+Chounet	(CERN, ORSA)
GINSBERG	70	PR D1 229		(HAIF)
GRAUMAN	70	PR D1 1277	+Koller, Taylor, Pandoulas+	(STEV, SETO, LEHI)
Also	69	PRL 23 737	Grauman, Koller, Taylor+	(STEV, SETO, LEHI)
MACEK	70	PR D1 1249	+Mann, McFarlane, Roberts	(PENN)
MALTSEV	70	SJNP 10 678 Translated from YAF 10 1195.	+Pestova, Solodovnikova, Fadeev+	(JINR)
PANDOULAS	70	PR D2 1205	+Taylor, Koller, Grauman+	(STEV, SETO)
CUTTS	69	PR 184 1380	+Stiening, Wiegand, Deutsch	(LRL, MIT)
Also	68	PRL 20 955	Cutts, Stiening, Wiegand, Deutsch	(LRL, MIT)
DAVISON	69	PR 180 1333	+Bacastow, Barkas, Evans, Fung, Porter+	(UCR)
ELY	69	PR 180 1319	+Gidal, Hagopian, Kalmus+	(LOUC, WISC, LRL)
EMMERSON	69	PRL 23 393	+Quirk	(OXF)
HERZO	69	PR 186 1403	+Banner, Beier, Bertram, Edwards+	(ILL)
KIJEWSKI	69	UCRL 18433 Thesis		(LBL)
LOBKOWICZ	69	PR 185 1676	+Melissinos, Nagashima, Tewksbury+	(ROCH, BNL)
Also	66	PRL 17 548	Lobkowicz, Melissinos, Nagashima+	(ROCH, BNL)
MACEK	69	PRL 22 32	+Mann, McFarlane, Roberts+	(PENN, TEMP)
MAST	69	PR 183 1200	+Gershwin, Alston-Garnjost, Bangerter+	(LRL)
ZELLER	69	PR 182 1420	+Haddock, Helland, Pahl+	(UCLA, LRL)
BETTELS	68	NC 56A 1106		(AACH, BARI, BERG, CERN, EPOL, NIJM, ORSA+)
Also	71	PR D3 10	Haidt	(AACH, BARI, CERN, EPOL, NIJM+)
BOTTERILL	68B	PRL 21 766	+Brown, Clegg, Corbett+	(OXF)
BOTTERILL	68C	PR 174 1661	+Brown, Clegg, Corbett+	(OXF)
BUTLER	68	UCRL 18420	+Bland, Goldhaber, Goldhaber, Hirata+	(LRL)
CHANG	68	PRL 20 510	+Yodh, Ehrlich, Plano+	(UMD, RUTG)
CHEN	68	PRL 20 73	+Cutts, Kijewski, Stiening+	(LRL, MIT)
EICHTEN	68	PL 27B 586		(AACH, BARI, CERN, EPOL, ORSA, PADO, VALE)
EISLER	68	PR 169 1090	+Fung, Marateck, Meyer, Plano	(RUTG)
ESCHSTRUTH	68	PR 165 1487	+Franklin, Hughes+	(PRIN, PENN)
GARLAND	68	PR 167 1225	+Tsipis, Devons, Rosen+	(COLU, RUTG, WISC)
MOSCOSO	68	Thesis		(ORSA)
AUERBACH	67	PR 155 1505	+Dobbs, Mann+	(PENN, PRIN)
Also Erratum.	74	PR D9 3216	Auerbach	
BELLOTTI	67	Heidelberg Conf.	+Pullia	(MILA)
BELLOTTI	67B	NC 52A 1287	+Fiorini, Pullia	(MILA)
Also	66B	PL 20 690	Bellotti, Fiorini, Pullia+	(MILA)
BISI	67	PL 25B 572	+Cester, Chiesa, Vigone	(TORI)
BOTTERILL	67	PRL 19 982	+Brown, Corbett, Culligan+	(OXF)
Also	68	PR 171 1402	Botterill, Brown, Clegg, Corbett+	(OXF)

BOWEN 67B PR 154 1314 +Mann, McFarlane, Hughes+ (PPA)
CLINE 67B Herceg Novi Tbl. 4
Proc. International School on Elementary Particle Physics.
FLETCHER 67 PRL 19 98 +Beier, Edwards+ (ILL)
FORD 67 PRL 18 1214 +Lemonick, Nauenberg, Piroue (PRIN)
GINSBERG 67 PR 162 1570 (MASB)
IMLAY 67 PR 160 1203 +Eschstruth, Franklin+ (PRIN)
KALMUS 67 PR 159 1187 +Kernan (LRL)
ZINCHENKO 67 Rutgers Thesis (RUTG)
CALLAHAN 66 NC 44A 90 (WISC)
CALLAHAN 66B PR 150 1153 +Camerini+ (WISC, LRL, UCR, BARI)
CESTER 66 PL 21 343 +Eschstruth, Oneill+ (PPA)
See footnote 1 in AUERBACH 67.
Also 67 PR 155 1505 Auerbach, Dobbs, Mann+ (PENN, PRIN)
BIRGE 65 PR 139B 1600 +Ely, Gidal, Camerini, Cline+ (LRL, WISC)
BISI 65 NC 35 768 +Borreani, Cester, Ferraro+ (TORI)
BISI 65B PR 139B 1068 +Borreani, Marzari-Chiesa, Rinaudo+ (TORI)
BORREANI 65 PR 140B 1686 +Gidal, Rinaudo, Caforio+ (BARI, TORI)
CALLAHAN 65 PRL 15 129 +Cline (WISC)
CAMERINI 65 NC 37 1795 +Cline, Gidal, Kalmus, Kernan (WISC, LRL)
CLINE 65 PL 15 293 +Fry (WISC)
CUTTS 65 PR 138B 969 +Elioff, Stiening (LRL)
DEMARCO 65 PR 140B 1430 +Grosso, Rinaudo (TORI, CERN)
FITCH 65B PR 140B 1088 +Quarles, Wilkins (PRIN, MTHO)
GREINER 65 ARNS 15 67 (LRL)
STAMER 65 PR 138B 440 +Huetter, Koller, Taylor, Grauman (STEV)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 5.
YOUNG 65 UCRL 16362 Thesis (LRL)
Also 67 PR 156 1464 Young, Osborne, Barkas (LRL)
BORREANI 64 PL 12 123 +Rinaudo, Werbrouck (TORI)
CALLAHAN 64 PR 136B 1463 +March, Stark (WISC)
CAMERINI 64 PRL 13 318 +Cline, Fry, Powell (WISC, LRL)
CLINE 64 PRL 13 101 +Fry (WISC)
GIACOMELLI 64 NC 34 1134 +Monti, Quareni+ (BGNA, MUNI)
GREINER 64 PRL 13 284 +Osborne, Barkas (LRL)
JENSEN 64 PR 136B 1431 +Shaklee, Roe, Sinclair (MICH)
KALMUS 64 PRL 13 99 +Kernan, Pu, Powell, Dowd (LRL, WISC)
SHAKLEE 64 PR 136B 1423 +Jensen, Roe, Sinclair (MICH)
BARKAS 63 PRL 11 26 +Dyer, Heckman (LRL)
BOYARSKI 62 PR 128 2398 +Loh, Niemela, Ritson (MIT)
BROWN 62B PRL 8 450 +Kadyk, Trilling, Roe+ (LRL, MICH)
BARKAS 61 PR 124 1209 +Dyer, Mason, Norris, Nickols, Smit (LRL)
BHOWMIK 61 NC 20 857 +Jain, Mathur (DELH)
FERRO-LUZZI 61 NC 22 1087 +Miller, Murray, Rosenfeld+ (LRL)
NORDIN 61 PR 123 2166 (LRL)
ROE 61 PRL 7 346 +Sinclair, Brown, Glaser+ (MICH, LRL)
FREDEN 60B PR 118 564 +Gilbert, White (LRL)
BURROWES 59 PRL 2 117 +Caldwell, Frisch, Hill+ (MIT)
TAYLOR 59 PR 114 359 +Harris, Orear, Lee, Baumel (COLU)
EISENBERG 58 NC 8 663 +Koch, Lohrmann, Nikolic+ (BERN)
ALEXANDER 57 NC 6 478 +Johnston, Oceallaigh (DUUC)
COHEN 57 Fund. Cons. Phys. +Crowe, Dumond (NAAS, LRL, CIT)
COOMBES 57 PR 108 1348 +Cork, Galbraith, Lambertson, Wenzel (LBL)
BIRGE 56 NC 4 834 +Perkins, Peterson, Stork, Whitehead (LRL)
ILOFF 56 PR 102 927 +Goldhaber, Lannutti, Gilbert+ (LRL)

OTHER RELATED PAPERS

CHOUNET 72 PRPL 4C 199 +Gaillard, Gaillard (ORSA, CERN)
FEARING 70 PR D2 542 +Fischbach, Smith (STON, BOHR)
HAIDT 69B PL 29B 696 + (AACH, BARI, CERN, EPOL, NIJM, ORSA+)
CRONIN 68B Vienna Conf. 241 (PRIN)
Rapporteur talk.
WILLIS 67 Heidelberg Conf. 273 (YALE)
Rapporteur talk.
CABIBBO 66 Berkeley Conf. 33 (CERN)
ADAIR 64 PL 12 67 +Leipuner (YALE, BNL)
CABIBBO 64 PL 9 352 +Maksymowicz (CERN)
Also 64B PL 11 360 Cabibbo, Maksymowicz (CERN)
Also 65 PL 14 72 Cabibbo, Maksymowicz (CERN)
BIRGE 63 PRL 11 35 +Ely, Gidal, Camerini+ (LRL, WISC, BARI)
BLOCK 62B CERN Conf. 371 +Lendinara, Monari (NWES, BGNA)
BRENE 61 NP 22 553 +Egardt, Qvist (NORD)

K^0

$I(J^P) = \frac{1}{2}(0^-)$

K^0 MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
497.671±0.031 OUR FIT					
497.676±0.030 OUR AVERAGE					
497.661±0.033	3713	BARKOV	87B	CMD	$e^+ e^- \rightarrow K^0_L K^0_S$
497.742±0.085	780	BARKOV	85B	CMD	$e^+ e^- \rightarrow K^0_L K^0_S$
497.44 ±0.50		FITCH	67	OSPK	
498.9 ±0.5	4500	BALTAY	66	HBC	K^0 from $\overline{p} p$
497.44 ±0.33	2223	KIM	65B	HBC	K^0 from $\overline{p} p$
498.1 ±0.4		CHRISTENSON	64	OSPK	

K^0 – $K^{\pm}$ MASS DIFFERENCE

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
4.024±0.032 OUR FIT						
3.92 ±0.14 OUR AVERAGE						
3.95 ±0.21	417	HILL	68B	DBC	+	$K^+ d \rightarrow K^0 p p$
3.90 ±0.25	9	BURNSTEIN	65	HBC	−	
3.71 ±0.35	7	KIM	65B	HBC	−	$K^- p \rightarrow n \overline{K}^0$
5.4 ±1.1		CRAWFORD	59	HBC	+	
3.9 ±0.6		ROSENFELD	59	HBC	−	

REFERENCES FOR K^0

BARKOV 87B SJNP 46 630 +Vasserman, Vorobev, Ivanov+ (NOVO)
Translated from YAF 46 1088.
BARKOV 85B JETPL 42 138 +Blinov, Vasserman+ (NOVO)
Translated from ZETFP 42 113.
HILL 68B PR 168 1534 +Robinson, Sakitt, Canter (BNL, CMU)
FITCH 67 PR 164 1711 +Roth, Russ, Vernon (PRIN)
BALTAY 66 PR 142 932 +Sandweiss, Stonehill+ (YALE, BNL)
BURNSTEIN 65 PR 138B 895 +Rubin (UMD)
KIM 65B PR 140B 1334 +Kirsch, Miller (COLU)
CHRISTENSON 64 PRL 13 138 +Cronin, Fitch, Turlay (PRIN)
CRAWFORD 59 PRL 2 112 +Cresti, Good, Stevenson, Ticho (LRL)
ROSENFELD 59 PRL 2 110 +Solmitz, Tripp (LRL)

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

K^0_S MEAN LIFE

For earlier measurements, beginning with BOLDT 58B, see our our 1986 edition, Physics Letters **170B**, 130 (1986).

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.8922±0.0020 OUR AVERAGE					
0.8920±0.0044	214k	GROSSMAN	87	SPEC	E=100–350 GeV
0.881 ±0.009	26k	ARONSON	76	SPEC	
0.8913±0.0032		[1] CARITHERS	75	SPEC	
0.8937±0.0048	6M	GEWENIGER	74B	ASPK	
0.8958±0.0045	50k	[2] SKJEGGEST...	72	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.905 ±0.007		[3] ARONSON	82B	SPEC	E=30–110 GeV
0.867 ±0.024	2173	[4] FACKLER	73	OSPK	
0.856 ±0.008	19994	[5] DONALD	68B	HBC	
0.872 ±0.009	20000	[5,6] HILL	68	DBC	
0.866 ±0.016		[5] ALFF-...	66B	OSPK	
0.843 ±0.013	5000	[5] KIRSCH	66	HBC	

[1] CARITHERS 75 value is for K^0_L – K^0_S mass difference $\Delta(m) = 0.5348 \pm 0.0021$. The $\Delta(m)$ dependence of the total decay rate (inverse mean life) is $\Gamma(K^0_S) = [(1.122 \pm 0.004) + 0.16(\Delta(m) - 0.5348)/\Delta(m)]\, 10^{10}$/s. Value would not change with our current $\Delta(m) = 0.5349 \pm 0.0022$.

[2] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

[3] ARONSON 82 find that K^0_S mean life may depend on the kaon energy.

[4] FACKLER 73 does not include systematic errors.

[5] Pre-1971 experiments are excluded from the average because of disagreement with later more precise experiments.

[6] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

K^0_S DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-$		(68.61±0.28) %	S=1.2
Γ_2	$\pi^0\pi^0$		(31.39±0.28) %	S=1.2
Γ_3	$\pi^+\pi^-\gamma$	[a,b]	(1.85±0.10) × 10^{-3}	
Γ_4	$\gamma\gamma$		(2.4 ±1.2) × 10^{-6}	
Γ_5	$\pi^+\pi^-\pi^0$		< 4.9 × 10^{-5}	CL=90%
Γ_6	$3\pi^0$		< 3.7 × 10^{-5}	CL=90%
	Flavor-Changing neutral current (*FC*) modes			
Γ_7	$\mu^+\mu^-$	*FC*	< 3.2 × 10^{-7}	CL=90%
Γ_8	e^+e^-	*FC*	< 1.0 × 10^{-5}	CL=90%
Γ_9	$\pi^0 e^+ e^-$	*FC*	< 4.5 × 10^{-5}	CL=90%

[a] See the Listings below for the energy limits used in this measurement.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 17 measurements and one constraint to determine 2 parameters. The overall fit has a χ^2 = 16.5 for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{cc} x_2 & -100 \\ & x_1 \end{array}$$

K_S^0 BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.6861±0.0028 OUR FIT	Error includes scale factor of 1.2.			
0.671 ±0.010 OUR AVERAGE				
0.670 ±0.010	3447	[7] DOYLE 69	HBC	$\pi^- p \to \Lambda K^0$
0.70 ±0.08		COLUMBIA 60B	HBC	
0.68 ±0.04		CRAWFORD 59B	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.740 ±0.024		[7] ANDERSON 62B	HBC	

[7] Anderson result not published, events added to Doyle sample.

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^0\pi^0)$ Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.186±0.028 OUR FIT	Error includes scale factor of 1.2.			
2.197±0.026 OUR AVERAGE				
2.11 ±0.09	1315	EVERHART 76	WIRE	$\pi^- p \to \Lambda K^0$
2.169±0.094	16k	COWELL 74	OSPK	$\pi^- p \to \Lambda K^0$
2.16 ±0.08	4799	HILL 73	DBC	$K^+ d \to K^0 pp$
2.22 ±0.10	3068	[8] ALITTI 72	HBC	$K^+ p \to \pi^+ p K^0$
2.22 ±0.08	6380	MORSE 72B	DBC	$K^+ n \to K^0 p$
2.10 ±0.11	701	[9] NAGY 72	HLBC	$K^+ n \to K^0 p$
2.22 ±0.095	6150	[10] BALTAY 71	HBC	$K p \to K^0$ neutrals
2.282±0.043	7944	[11] MOFFETT 70	OSPK	$K^+ n \to K^0 p$
2.10 ±0.06	3700	MORFIN 69	HLBC	$K^+ n \to K^0 p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.12 ±0.17	267	[9] BOZOKI 69	HLBC	
2.285±0.055	3016	[11] GOBBI 69	OSPK	$K^+ n \to K^0 p$

[8] The directly measured quantity is $K_S^0 \to \pi^+\pi^-/\text{all } K^0 = 0.345 \pm 0.005$.

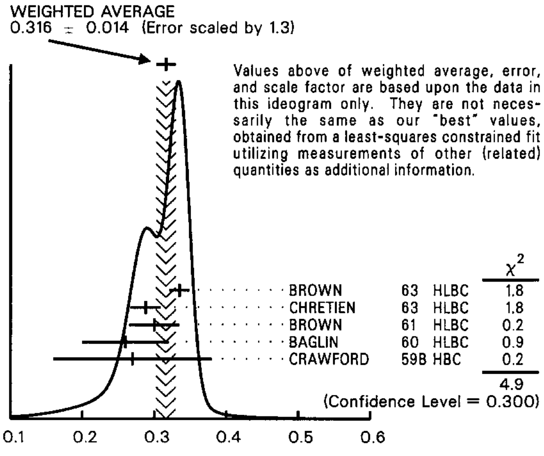
[9] NAGY 72 is a final result which includes BOZOKI 69.

[10] The directly measured quantity is $K_S^0 \to \pi^+\pi^-/\text{all } \overline{K}^0 = 0.345 \pm 0.005$.

[11] MOFFETT 70 is a final result which includes GOBBI 69.

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN
0.3139±0.0028 OUR FIT	Error includes scale factor of 1.2.		
0.316 ±0.014 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.		
0.335 ±0.014	1066	BROWN 63	HLBC
0.288 ±0.021	198	CHRETIEN 63	HLBC
0.30 ±0.035		BROWN 61	HLBC
0.26 ±0.06		BAGLIN 60	HLBC
0.27 ±0.11		CRAWFORD 59B	HBC



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-)$ Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.70±0.14 OUR AVERAGE				
2.68±0.15		[12] TAUREG 76	SPEC	p_γ >50 MeV/c
2.8 ±0.6		[13] BURGUN 73	HBC	p_γ >50 MeV/c
3.3 ±1.2	10	WEBBER 70	HBC	p_γ >50 MeV/c
no ratio given	27	BELLOTTI 66	HBC	p_γ >50 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.0 ±0.6	29	[14] BOBISUT 74	HLBC	p_γ >40 MeV/c

[12] TAUREG 76 find direct emission contribution <0.06, CL = 90%.

[13] BURGUN 73 estimates that direct emission contribution is 0.3 ± 0.6.

[14] BOBISUT 74 not included in average because p_γ cut differs. Estimates direct emission contribution to be 0.5 or less, CL = 95%.

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0024±0.0012		19	BURKHARDT 87	CALO	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.013	90		BALATS 89	SPEC	
< 0.133	90		BARMIN 86B	XEBC	
< 0.2	90		VASSERMAN 86	CALO	$\phi \to K_S^0 K_L^0$
< 0.4	90	0	BARMIN 73B	HLBC	
< 0.71	90	0	[15] BANNER 72B	OSPK	
< 2.0	90	0	MORSE 72B	DBC	
< 2.2	90	0	[15] REPELLIN 71	OSPK	
<21.0	90	0	[15] BANNER 69	OSPK	

[15] These limits are for maximum interference in K_S^0-K_L^0 to 2γ's

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.49	90	BARMIN 85	HLBC	K^+ 850 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.85	90	METCALF 72	ASPK	

$\Gamma(3\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
<0.37	90	BARMIN 83	HLBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<4.3	90	BARMIN 73	HLBC

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ Γ_7/Γ_1

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN
< 0.047	90	GJESDAL 73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<20.0	90	BOHM 69	OSPK
< 1.07	90	HYAMS 69B	OSPK
<32.6	90	[16] STUTZKE 69	OSPK
<10.0	90	BOTT-... 67	OSPK

[16] Value calculated by us, using 2.3 instead of 1 event, 90% CL.

$\Gamma(e^+e^-)/\Gamma(\pi^+\pi^-)$ Γ_8/Γ_1

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN
< 1.5	90	BARMIN 86	XEBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<16.0	90	[17] BITSADZE 86	CALO
<50.0	90	BOHM 69	OSPK

[17] Use $B(\pi^+\pi^-) = 0.6861$.

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ Γ_9/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN
<4.5	90	GIBBONS 88	SPEC

NOTE ON *CP* VIOLATION IN $K_S^0 \to 3\pi$

For $K_S^0 \to 3\pi$, the quantities which measure CP violation are the ratios of amplitudes

$$\eta_{+-0} = \frac{A_S(K_S \to \pi^+\pi^-\pi^0)}{A_L(K_L \to \pi^+\pi^-\pi^0)} ,$$

$$\eta_{000} = \frac{A_S(K_S \to \pi^0\pi^0\pi^0)}{A_L(K_L \to \pi^0\pi^0\pi^0)} .$$

If one assumes that CPT invariance holds and that there are no transitions to $I = 3$ states, then $\text{Re}(\eta_{+-0})$ and $\text{Re}(\eta_{000})$ can be neglected, and CP violation would be observed as nonzero values of $\text{Im}(\eta_{+-0})$ and $\text{Im}(\eta_{000})$. We list the relative rates

$$(\text{Im}\eta_{+-0})^2 = \frac{\Gamma(K_S \to \pi^+\pi^-\pi^0)}{\Gamma(K_L \to \pi^+\pi^-\pi^0)}$$

$$(\text{Im}\eta_{000})^2 = \frac{\Gamma(K_S \to \pi^0\pi^0\pi^0)}{\Gamma(K_L \to \pi^0\pi^0\pi^0)}$$

obtained under the above assumptions.

In the above expressions the three pions are restricted to the dominant symmetric $I = 1$ state, a $CP = -1$ state which couples to K_S only if CP is violated. The decay $K_S \to \pi^+\pi^-\pi^0$ also has CP-allowed amplitudes to $I = 0$ and $I = 2$ states of the three pions. The angular momenta in these states cannot be S wave so they are strongly suppressed by centrifugal barrier effects, and, for the $I = 2$ state, by the $\Delta I = 1/2$ rule as well.

CP-VIOLATION PARAMETERS IN K_S^0 DECAY

$\text{Im}(\eta_{+-0})^2$

where η_{+-0} = A($K_S^0 \to \pi^+\pi^-\pi^0$, CP-violating) / A($K_L^0 \to \pi^+\pi^-\pi^0$). CPT assumed valid (i.e. $\text{Re}(\eta_{+-0}) = 0$).

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.12	90	384	METCALF	72	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.23	90	601	[18] BARMIN	85	HLBC	K^+ 850 MeV
<1.2	90	192	BALDO-...	75	HLBC	
<0.71	90	148	MALLARY	73	OSPK	Re(A)=−0.05 ± 0.17
<0.66	90	180	JAMES	72	HBC	
<1.2	90	99	JONES	72	OSPK	
<1.2	90	99	CHO	71	DBC	
<1.0	90	98	JAMES	71	HBC	Incl. in JAMES 72
<1.2	95	50	[19] MEISNER	71	HBC	CL=90% not avail.
<0.8	90	71	WEBBER	70	HBC	
<0.45	90		BEHR	66	HLBC	
<3.8	90	18	ANDERSON	65	HBC	Incl. in WEBBER 70

[18] BARMIN 85 find $\text{Re}(\eta_{+-0}) = (0.05 \pm 0.17)$ and $\text{Im}(\eta_{+-0}) = (0.15 \pm 0.33)$. Includes events of BALDO-CEOLIN 75.

[19] These authors find Re(A) = 2.75 ± 0.65, above value at Re(A) = 0.

$\text{Im}(\eta_{000})^2$

where η_{000} = A($K_S^0 \to 3\pi^0$) / A($K_L^0 \to 3\pi^0$). See text header for section "$\text{Im}(\eta_{+-0})^2$" above. This limit determines branching ratio $\Gamma(3\pi^0)/\Gamma_{\text{total}}$ above.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.1	90	632	[20] BARMIN	83	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.28	90		[21] GJESDAL	74B	SPEC	Indirect meas.
<1.2	90	22	BARMIN	73	HLBC	

[20] BARMIN 83 find $\text{Re}(\eta_{000}) = (-0.08 \pm 0.18)$ and $\text{Im}(\eta_{000}) = (-0.05 \pm 0.27)$. Assuming CPT invariance they obtain the limit quoted above.

[21] GJESDAL 74B uses $K2\pi$, $K_{\mu 3}$, and K_{e3} decay results, unitarity, and CPT. Calculates $|(\eta_{000})| = 0.26 \pm 0.20$. We convert to upper limit.

REFERENCES FOR K_S^0

BALATS 89 SJNP 49 828 +Berezin, Bogdanov, Vishnevskii, Vishnyakov+ (ITEP)
Translated from YAF 49 1332.
GIBBONS 88 PRL 61 2661 +Papadimitriou+ (EFI, ELMT, FNAL, PRIN, SACL)
BURKHARDT 87 PL B199 139 + (CERN, DORT, EDIN, MANZ, ORSA, PISA, SIEG)
GROSSMAN 87 PRL 59 18 +Heller, James, Shupe+ (MINN, MICH, RUTG)
BARMIN 86 SJNP 44 622 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 44 965.
BARMIN 86B NC 96A 159 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
BITSADZE 86 PL 167B 138 +Budagov (BRAT, SOFI, SERP, TBLI, JINR, BAKU+)
VASSERMAN 86 JETPL 43 588 +Golubev, Gluskin, Druzhinin+ (NOVO)
Translated from ZETFP 43 457.
BARMIN 85 NC 85A 67 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
Also 85B SJNP 41 759 Barmin, Barylov, Volkov+ (ITEP)
Translated from YAF 41 1187.
BARMIN 83 PL 128B 129 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
Also 84 SJNP 39 269 Barmin, Barylov, Golubchikov+ (ITEP, PADO)
Translated from YAF 39 428.
ARONSON 82 PRL 48 1078 +Bernstein+ (BNL, CHIC, STAN, WISC)
ARONSON 82B PRL 48 1306 +Bock, Cheng, Fischbach (BNL, CHIC, PURD)
Also 82B PL 116B 73 Fischbach, Cheng+ (PURD, BNL, CHIC)
Also 83 PR D28 476 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
Also 83B PR D28 495 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
ARONSON 76 NC 32A 236 +McIntyre, Roehrig+ (WISC, EFI, UCSD, ILLC)
EVERHART 76 PR D14 661 +Kraus, Lande, Long, Lowenstein+ (PENN)
TAUREG 76 PL 65B 92 +Zech, Dydak, Navarria+ (HEID, CERN, DORT)
BALDO-... 75 NC 25A 688 Baldo-Ceolin, Bobisut, Calimani+ (PADO, WISC)
CARITHERS 75 PRL 34 1244 +Modis, Nygren, Pun+ (COLU, NYU)
BOBISUT 74 LNC 11 646 +Huzita, Mattioli, Puglierin (PADO)
COWELL 74 PR D10 2083 +Lee-Franzini, Orcutt, Franzini+ (STON, COLU)
GEWENIGER 74B PL 48B 487 +Gjesdal, Presser+ (CERN, HEID)
GJESDAL 74B PL 52B 119 +Presser, Steffen+ (CERN, HEID)
BARMIN 73 PL 46B 465 +Barylov, Davidenko, Demidov+ (ITEP)
BARMIN 73B PL 47B 463 +Barylov, Davidenko, Demidov+ (ITEP)
BURGUN 73 PL 46B 481 +Bertranet, Lesquoy, Muller, Pauli+ (SACL, CERN)
FACKLER 73 PRL 31 847 +Frisch, Martin, Smoot, Sompayrac (MIT)
GJESDAL 73 PL 44B 217 +Presser, Steffen, Steinberger+ (CERN, HEID)
HILL 73 PR D8 1290 +Sakitt, Samios, Burris, Engler+ (BNL, CMU)
MALLARY 73 PR D7 1953 +Binnie, Gallivan, Gomez, Peck, Sciulli+ (CIT)
ALITTI 72 PL 39B 568 +Lesquoy, Muller (SACL)
BANNER 72B PRL 29 237 +Cronin, Hoffman, Knapp, Shochet (PRIN)
JAMES 72 NP B49 1 +Montanet, Paul, Saetre+ (CERN, SACL, OSLO)
JONES 72 NC 9A 151 +Abashian, Graham, Mantsch, Orr, Smith+ (ILL)
METCALF 72 PL 40B 703 +Neuhofer, Niebergall+ (CERN, IPN, WIEN)
MORSE 72B PRL 28 388 +Nauenberg, Bierman, Sager+ (COLO, PRIN, UMD)
NAGY 72 NP B47 94 +Telbisz, Vestergombi (BUDA)
Also 69 PL 30B 498 Bozoki, Fenyves, Gombosi, Nagy+ (BUDA)
SKJEGGEST... 72 NP B48 343 Skjeggestad, James+ (OSLO, CERN, SACL)
BALTAY 71 PRL 27 1678 +Bridgewater, Cooper, Gershwin, Habibi+ (COLU)
Also 71 Nevis 187 Thesis Cooper (COLU)
CHO 71 PR D3 1557 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
JAMES 71 PL 35B 265 +Montanet, Paul, Pauli+ (CERN, SACL, OSLO)
MEISNER 71 PR D3 59 +Mann, Hertzbach, Kofler+ (MASA, BNL, YALE)
REPELLIN 71 PL 36B 603 +Wolff, Chollet, Gaillard, Jane+ (ORSA, CERN)
MOFFETT 70 BAPS 15 512 +Gobbi, Green, Hakel, Rosen (ROCH)
WEBBER 70 PR D1 1967 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 UCRL 19226 Thesis Webber (LRL)
BANNER 69 PR 188 2033 +Cronin, Liu, Pilcher (PRIN)
BOHM 69 Thesis (AACH)
BOZOKI 69 PL 30B 498 +Fenyves, Gombosi, Nagy+ (BUDA)
DOYLE 69 UCRL 18139 Thesis (LRL)
GOBBI 69 PRL 22 682 +Green, Hakel, Moffett, Rosen+ (ROCH)
HYAMS 69B PL 29B 521 +Koch, Potter, VonLindern, Lorenz+ (CERN, MPIM)
MORFIN 69 PRL 23 660 +Sinclair (MICH)
STUTZKE 69 PR 177 2009 +Abashian, Jones, Mantsch, Orr, Smith (ILL)
DONALD 68B PL 27B 58 +Edwards, Nisar+ (LIVP, CERN, IPNP, CDEF)
HILL 68 PR 171 1418 +Robinson, Sakitt+ (BNL, CMU)
BOTT-... 67 PL 24B 194 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
ALFF-... 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
BEHR 66 PL 22 540 +Brisson, Petiau+ (EPOL, MILA, PADO, ORSA)
BELLOTTI 66 NC 45A 737 +Pullia, Baldo-Ceolin+ (MILA, PADO)
KIRSCH 66 PR 147 939 +Schmidt (COLU)
ANDERSON 65 PRL 14 475 +Crawford, Golden, Stern, Binford+ (LRL, WISC)
BROWN 63 PR 130 769 +Kadyk, Trilling, Roe+ (LRL, MICH)
CHRETIEN 63 PR 131 2208 + (BRAN, BROW, HARV, MIT)
ANDERSON 62B CERN Conf. 836 +Crawford+ (LRL)
BROWN 61 NC 19 1155 +Bryant, Burnstein, Glaser, Kadyk+ (MICH)
BAGLIN 60 NC 18 1043 +Bloch, Brisson, Hennessy+ (EPOL)
COLUMBIA 60B Rochester Conf. 727 Schwartz+ (COLU)
CRAWFORD 59B PRL 2 266 +Cresti, Douglass, Good, Ticho+ (LRL)
BOLDT 58B PRL 1 150 +Caldwell, Pal (MIT)

OTHER RELATED PAPERS

TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
CRAWFORD 62 CERN Conf. 827 (LRL)
FITCH 61 NC 22 1160 +Piroue, Perkins (PRIN, LASL)
GOOD 61 PR 124 1223 +Matsen, Muller, Piccioni+ (LRL)
BIRGE 60 Rochester Conf. 601 +Ely+ (LRL, WISC)
MULLER 60 PRL 4 418 +Birge, Fowler, Good, Piccioni+ (LRL, BNL)

K_L^0

$I(J^P) = \frac{1}{2}(0^-)$

$m(K_L^0) - m(K_S^0)$

For earlier measurements, beginning with GOOD 61 and FITCH 61, see our our 1986 edition, Physics Letters **170B**, 132 (1986).

VALUE (10^{10} $\hbar$ s^{-1})	DOCUMENT ID		TECN	COMMENT
0.5351±0.0024 OUR AVERAGE				
0.5340±0.00255±0.0015	[1] GEWENIGER	74C	SPEC	Gap method
0.5334±0.0040 ±0.0015	[1] GJESDAL	74	SPEC	Charge asymmetry
0.542 ±0.006	CULLEN	70	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.482 ±0.014	[2] ARONSON	82B	SPEC	E=30–110 GeV
0.534 ±0.007	[3] CARNEGIE	71	ASPK	Gap method
0.542 ±0.006	[3] ARONSON	70	ASPK	Gap method

[1] These two experiments have a common systematic error due to the uncertainty in the momentum scale, as pointed out in WAHL 89.

[2] ARONSON 82 find that $\Delta(m)$ may depend on the kaon energy.

[3] ARONSON 70 and CARNEGIE 71 use K_S^0 mean life = $(0.862 \pm 0.006) \times 10^{-10}$ s. We have not attempted to adjust these values for the subsequent change in the K_S^0 mean life or in η_{+-}.

K_L^0 MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN
5.17 ±0.04 OUR FIT				
5.15 ±0.04 OUR AVERAGE				
5.154±0.044	0.4M	VOSBURGH	72	CNTR
5.15 ±0.14		DEVLIN	67	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.0 ±0.5		[4] LOWYS	67	HLBC
$6.1\ {}^{+1.5}_{-1.2}$	1700	ASTBURY	65C	CNTR
5.3 ±0.6		FUJII	64	OSPK
$5.1\ {}^{+2.4}_{-1.3}$	15	DARMON	62	FBC
$8.1\ {}^{+3.2}_{-2.4}$	34	BARDON	58	CNTR

[4] Sum of partial decay rates.

K^0_L DECAY MODES

	Mode			Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$3\pi^0$			(21.6 ± 0.8) %	S=1.5
Γ_2	$\pi^+\pi^-\pi^0$			(12.38 ± 0.21) %	S=1.5
Γ_3	$\pi^\pm\mu^\mp\nu$		[a]	(27.0 ± 0.4) %	S=1.3
	Called $K_{\mu3}$.				
Γ_4	$\pi^-\mu^+\nu_\mu$				
Γ_5	$\pi^+\mu^-\overline{\nu}_\mu$				
Γ_6	$\pi^\pm e^\mp\nu$		[a]	(38.7 ± 0.5) %	S=1.4
	Called K_{e3}.				
Γ_7	$\pi^-e^+\nu_e$				
Γ_8	$\pi^+e^-\overline{\nu}_e$				
Γ_9	2γ			$(5.70 \pm 0.27) \times 10^{-4}$	S=1.9
Γ_{10}	$\pi^0 2\gamma$			$< 2.7 \times 10^{-6}$	CL=90%
Γ_{11}	$\pi^0\pi^\pm e^\mp\nu$		[a]	$(6.2 \pm 2.0) \times 10^{-5}$	
Γ_{12}	$(\pi\mu$ atom$)\,\nu$			$(1.05 \pm 0.11) \times 10^{-7}$	
Γ_{13}	$\pi^\pm e^\mp\nu_e\gamma$		[b,c]	(1.3 ± 0.8) %	
Γ_{14}	$\pi^+\pi^-\gamma$		[b,c]	$(4.41 \pm 0.32) \times 10^{-5}$	

Charge conjugation × Parity (*CP*) or Lepton Family number (*LF*) violating modes, or Flavor-Changing neutral current (*FC*) modes

	Mode			Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{15}	$\pi^+\pi^-$	*CP*		$(2.03 \pm 0.04) \times 10^{-3}$	S=1.2
Γ_{16}	$\pi^0\pi^0$	*CP*		$(9.09 \pm 0.35) \times 10^{-4}$	S=1.8
Γ_{17}	$e^\pm\mu^\mp$	*LF*	[a]	$< 2.2 \times 10^{-10}$	CL=90%
Γ_{18}	$\mu^+\mu^-$	*FC*		$(6.3 \pm 1.1) \times 10^{-9}$	
Γ_{19}	$\mu^+\mu^-\gamma$	*FC*		$(2.8 \pm 2.8) \times 10^{-7}$	
Γ_{20}	$\pi^0\mu^+\mu^-$	*FC*		$< 1.2 \times 10^{-6}$	CL=90%
Γ_{21}	e^+e^-	*FC*		$< 3.2 \times 10^{-10}$	CL=90%
Γ_{22}	$e^+e^-\gamma$	*FC*		$(1.7 \pm 0.9) \times 10^{-5}$	
Γ_{23}	$\pi^0e^+e^-$	*FC*		$< 4 \times 10^{-8}$	CL=90%
Γ_{24}	$\pi^+\pi^-e^+e^-$	*FC*		$< 2.5 \times 10^{-6}$	CL=90%
Γ_{25}	$\mu^+\mu^-e^+e^-$	*FC*		$< 4.9 \times 10^{-6}$	CL=90%
Γ_{26}	$e^+e^-e^+e^-$	*FC*		$< 2.6 \times 10^{-6}$	CL=90%

[a] Value is for the sum of the charge states indicated.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] See the Listings below for the energy limits used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 4 partial widths, and 12 branching ratios uses 53 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 54.8$ for 46 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−35						
x_3	−78	6					
x_6	−86	7	46				
x_9	−1	12	−3	−3			
x_{15}	−28	44	13	15	33		
x_{16}	−7	19	1	1	76	45	
Γ	2	−4	0	0	−1	−2	−1
	x_1	x_2	x_3	x_6	x_9	x_{15}	x_{16}

	Mode		Rate (10^8 s^{-1})	Scale factor
Γ_1	$3\pi^0$		0.0419 ± 0.0016	1.4
Γ_2	$\pi^+\pi^-\pi^0$		0.0239 ± 0.0004	1.4
Γ_3	$\pi^\pm\mu^\mp\nu$	[a]	0.0522 ± 0.0008	1.2
	Called $K_{\mu3}$.			
Γ_6	$\pi^\pm e^\mp\nu$	[a]	0.0749 ± 0.0011	1.3
	Called K_{e3}.			
Γ_9	2γ		$(1.10 \pm 0.05) \times 10^{-4}$	1.9
Γ_{15}	$\pi^+\pi^-$		$(3.92 \pm 0.08) \times 10^{-4}$	1.2
Γ_{16}	$\pi^0\pi^0$		$(1.76 \pm 0.07) \times 10^{-4}$	1.7

K^0_L DECAY RATES

$\Gamma(3\pi^0)$ Γ_1

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.19±0.16 OUR FIT Error includes scale factor of 1.4.					
$5.22^{+1.03}_{-0.84}$	54	BEHR	66	HLBC	Assumes *CP*

$\Gamma(\pi^+\pi^-\pi^0)$ Γ_2

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.39±0.04 OUR FIT Error includes scale factor of 1.4.					
2.38±0.09 OUR AVERAGE					
$2.32^{+0.13}_{-0.15}$	192	BALDO-...	75	HLBC	Assumes *CP*
2.35±0.20	180	[5] JAMES	72	HBC	Assumes *CP*
2.71±0.28	99	CHO	71	DBC	Assumes *CP*
2.12±0.33	50	MEISNER	71	HBC	Assumes *CP*
2.20±0.35	53	WEBBER	70	HBC	Assumes *CP*
$2.62^{+0.28}_{-0.27}$	136	BEHR	66	HLBC	Assumes *CP*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.5 ±0.3	98	[5] JAMES	71	HBC	Assumes *CP*
3.26±0.77	18	ANDERSON	65	HBC	
1.4 ±0.4	14	FRANZINI	65	HBC	

In the fit this rate is well determined by the mean life and the branching ratio $\Gamma(\pi^+\pi^-\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)\right]$. For this reason the discrepancy between the $\Gamma(\pi^+\pi^-\pi^0)$ measurements does not affect the scale factor of the overall fit.

[5] JAMES 72 is a final measurement and includes JAMES 71.

$\Gamma(\pi^\pm\mu^\mp\nu)$ Γ_3

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*
5.22±0.08 OUR FIT Error includes scale factor of 1.2.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$4.54^{+1.24}_{-1.08}$	19	LOWYS	67	HLBC

$\Gamma(\pi^\pm e^\mp\nu)$ Γ_6

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
7.49±0.11 OUR FIT Error includes scale factor of 1.3.					
7.7 ±0.5 OUR AVERAGE					
7.81±0.56	620	CHAN	71	HBC	
$7.52^{+0.85}_{-0.72}$		AUBERT	65	HLBC	$\Delta S{=}\Delta Q$,*CP* assumed

$\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)$ $(\Gamma_2{+}\Gamma_3{+}\Gamma_6)$

$K^0_L \to$ charged.

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*
15.10±0.19 OUR FIT Error includes scale factor of 1.3.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15.1 ±1.9	98	AUERBACH	66B	OSPK

$\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)$ $(\Gamma_3{+}\Gamma_6)$

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
12.70±0.18 OUR FIT Error includes scale factor of 1.3.					
11.9 ±0.6 OUR AVERAGE Error includes scale factor of 1.2.					
12.4 ±0.7	410	[6] BURGUN	72	HBC	$K^+p \to K^0p\pi^+$
13.1 ±1.3	252	[6] WEBBER	71	HBC	$K^-p \to n\overline{K}^0$
11.6 ±0.9	393	[6,7] CHO	70	DBC	$K^+n \to K^0p$
$9.85^{+1.15}_{-1.05}$	109	[6] FRANZINI	65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.47±1.69	126	[6] MANN	72	HBC	$K^-p \to n\overline{K}^0$
10.3 ±0.8	335	[7] HILL	67	DBC	$K^+n \to K^0p$

[6] Assumes $\Delta S = \Delta Q$ rule.

[7] CHO 70 includes events of HILL 67.

K^0_L BRANCHING RATIOS

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_1/Γ_2

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.75±0.08 OUR FIT Error includes scale factor of 1.4.					
1.81±0.13 OUR AVERAGE					
1.80±0.13	1010	BUDAGOV	68	HLBC	
2.0 ±0.6	188	ALEKSANYAN	64B	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.65±0.07	883	BARMIN	72B	HLBC	Error statistical only

$\Gamma(3\pi^0)/\left[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)\right]$ $\Gamma_1/(\Gamma_2{+}\Gamma_3{+}\Gamma_6)$

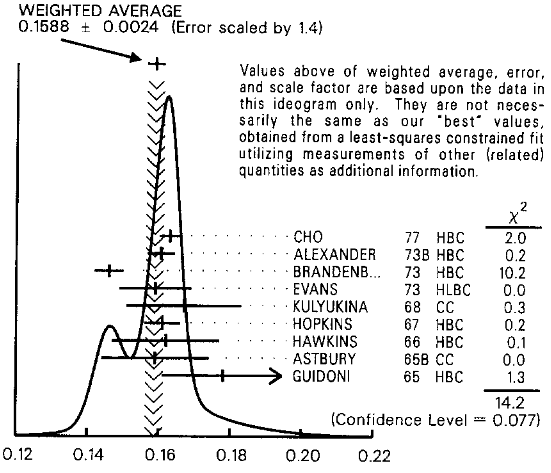
VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.277±0.013 OUR FIT Error includes scale factor of 1.5.					
0.260±0.011 OUR AVERAGE					
0.251±0.014	549	BUDAGOV	68	HLBC	ORSAY measur.
0.277±0.021	444	BUDAGOV	68	HLBC	Ecole polytec.meas
$0.31^{+0.07}_{-0.06}$	29	KULYUKINA	68	CC	
0.24 ±0.08	24	ANIKINA	64	CC	

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	DOCUMENT ID
0.1238±0.0021 OUR FIT Error includes scale factor of 1.5.	

$\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.1586±0.0026 OUR FIT Error includes scale factor of 1.6.					
0.1588±0.0024 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
0.163 ±0.003	6499	CHO	77	HBC	
0.1605±0.0038	1590	ALEXANDER	73B	HBC	
0.146 ±0.004	3200	BRANDENB...	73	HBC	
0.159 ±0.010	558	EVANS	73	HLBC	
0.167 ±0.016	1402	KULYUKINA	68	CC	
0.161 ±0.005		HOPKINS	67	HBC	
0.162 ±0.015	126	HAWKINS	66	HBC	
0.159 ±0.015	326	ASTBURY	65B	CC	
0.178 ±0.017	566	GUIDONI	65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.15 $^{+0.03}_{-0.04}$	66	ASTBURY	65	CC	
0.144 ±0.004	1729	HOPKINS	65	HBC	See HOPKINS 67
0.151 ±0.020	79	ADAIR	64	HBC	
0.157 $^{+0.03}_{-0.04}$	75	LUERS	64	HBC	
0.185 ±0.038	59	ASTIER	61	CC	



$\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$

$\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu)$ Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.697±0.010 OUR FIT					
0.697±0.010 OUR AVERAGE					
0.702±0.011	33k	CHO	80	HBC	
0.662±0.037	10k	WILLIAMS	74	ASPK	
0.741±0.044	6700	BRANDENB...	73	HBC	
0.662±0.030	1309	EVANS	73	HLBC	
0.71 ±0.05	770	BUDAGOV	68	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.68 ±0.08	3548	BASILE	70	OSPK	
0.71 ±0.04	569	[8] BEILLIERE	69	HLBC	
0.648±0.030	1309	EVANS	69	HLBC	Repl. by EVANS 73
0.67 ±0.13		[9] KULYUKINA	68	CC	
0.82 ±0.10		DEBOUARD	67	OSPK	
0.7 ±0.2	273	HAWKINS	67	HBC	
0.81 ±0.08		HOPKINS	67	HBC	
0.81 ±0.19		ADAIR	64	HBC	

[8] BEILLIERE 69 is a scanning experiment using same exposure as BUDAGOV 68.

[9] KULYUKINA 68 $\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu)$ is not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ and $\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$.

$\Gamma(\pi^\pm\mu^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.3456±0.0030 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.335 ±0.055	330	[10] KULYUKINA	68	CC
0.39 $^{+0.08}_{-0.10}$	172	[10] ASTBURY	65	CC
0.356 ±0.07	251	[10] LUERS	64	HBC

[10] This mode not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ and $\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$.

$\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_6/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.4958±0.0032 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.498 ±0.052	500	KULYUKINA	68	CC
0.46 $^{+0.08}_{-0.10}$	202	ASTBURY	65	CC
0.487 ±0.05	153	LUERS	64	HBC
0.46 ±0.11	24	NYAGU	61	CC

$\Gamma(\pi^\pm e^\mp\nu)/[\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_6/(\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.5893±0.0033 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.415 ±0.120	320	ASTIER	61	CC

$[\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]/\Gamma_{\rm total}$ $(\Gamma_3+\Gamma_6)/\Gamma$

VALUE	DOCUMENT ID
0.656±0.007 OUR FIT Error includes scale factor of 1.5.	

$\Gamma(2\gamma)/\Gamma_{\rm total}$ Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
5.70±0.27 OUR FIT Error includes scale factor of 1.9.					
4.9 ±0.5 OUR AVERAGE					
4.54±0.84		[11] BANNER	72B	OSPK	
4.5 ±1.0	23	ENSTROM	71	OSPK	K_L^0 1.5–9 GeV/c
5.5 ±1.1	90	KUNZ	68	OSPK	Norm.to 3 π(C+N)
6.7 ±2.2	32	TODOROFF	67	OSPK	Repl. CRIEGEE 66
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.0 ±1.0		[12] REPELLIN	71	OSPK	
7.4 ±1.6	33	[13] CRONIN	67	OSPK	
1.3 ±0.6		[14] CRIEGEE	66	OSPK	

[11] This value uses $(\eta_{00}/\eta_{+-})^2 = 1.05\pm0.14$. In general, $\Gamma(2\gamma)/\Gamma_{\rm total} = [(4.32\pm0.55)\times10^{-4}][(\eta_{00}/\eta_{+-})^2]$.

[12] Assumes regeneration amplitude in copper at 2 GeV is 22 mb. To evaluate for a given regeneration amplitude and error, multiply by (regeneration amplitude/22mb)^2.

[13] CRONIN 67 replaced by KUNZ 68.

[14] CRIEGEE 66 replaced by TODOROFF 67.

$\Gamma(2\gamma)/\Gamma(3\pi^0)$ Γ_9/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.64±0.16 OUR FIT Error includes scale factor of 1.7.					
2.24±0.22 OUR AVERAGE					
2.13±0.43	28	BARMIN	71	HLBC	
2.24±0.28	115	BANNER	69	OSPK	
2.5 ±0.7	16	ARNOLD	68B	HLBC	Vacuum decay

$\Gamma(2\gamma)/\Gamma(\pi^0\pi^0)$ Γ_9/Γ_{16}

VALUE	EVTS	DOCUMENT ID		TECN
0.627±0.019 OUR FIT Error includes scale factor of 2.2.				
0.632±0.004±0.008	110k	BURKHARDT	87	CALO

$\Gamma(\pi^0 2\gamma)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
< 2.7	90		PAPADIMITR...	89	CALO
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<230	90	0	BANNER	69	OSPK

$\Gamma(\pi^0\pi^\pm e^\mp\nu)/\Gamma_{\rm total}$ Γ_{11}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN
0.062±0.020		16	CARROLL	80C	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.2	90		[15] DONALDSON	74	SPEC

[15] DONALDSON 74 uses $K_L^0 \to \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.126.

$\Gamma((\pi\mu\ \text{atom})\,\nu)/\Gamma(\pi^\pm\mu^\mp\nu)$ Γ_{12}/Γ_3

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN
3.90±0.39	155	[16] ARONSON	86	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	18	COOMBES	76	WIRE

[16] ARONSON 86 quote theoretical value of $(4.31 \pm 0.08) \times 10^{-7}$.

$\Gamma(\pi^\pm e^\mp\nu_e\gamma)/\Gamma(\pi^\pm e^\mp\nu)$ Γ_{13}/Γ_6

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
3.3±2.0	10	PEACH	71	HLBC	γ KE >15 MeV

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0441±0.0032		1062	[17] CARROLL 80B	SPEC	E_γ >20 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0152±0.0016		516	[18] CARROLL 80B	SPEC	E_γ >20 MeV
0.0289±0.0028		546	[19] CARROLL 80B	SPEC	
< 3.2	90		BOBISUT 74	HLBC	E_γ >40 MeV
0.062 ±0.021		24	[20] DONALDSON 74C	SPEC	
< 0.46	90		WOO 74	SPEC	
< 0.4	90		THATCHER 68	OSPK	E_γ 20–170 MeV
< 5.0		0	BELLOTTI 66	HLBC	E_γ 40–130 MeV
< 3.0		1	NEFKENS 66	OSPK	E_γ 120 MeV
<15.0			ANIKINA 65	CC	

[17] Both components. Uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.1239.

[18] Internal Bremsstrahlung component only.

[19] Direct γ emission component only.

[20] Uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.126.

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{15}/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	DOCUMENT ID	
2.03 ±0.04 OUR FIT	Error includes scale factor of 1.2.	
2.101±0.065	[21] ETAFIT	90

[21] This ETAFIT value is computed from fitted values of $|\eta_{+-}|$, the K^0_L and K^0_S lifetimes, and the $K^0_S \to \pi^+\pi^-$ branching fraction. See the discussion in the "Note on *CP* violation in K^0_L decay."

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ Γ_{15}/Γ_2

Violates *CP* conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
1.639±0.032 OUR FIT	Error includes scale factor of 1.1.			
1.64 ±0.04	4200	MESSNER 73	ASPK	η_{+-} = 2.23

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_{15}/(\Gamma_3+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.09±0.06 OUR FIT	Error includes scale factor of 1.2.			
3.09±0.10 OUR AVERAGE				
3.13±0.14	1687	COUPAL 85	SPEC	η_{+-}=2.28 ± 0.06
3.04±0.14	2703	DEVOE 77	SPEC	η_{+-}=2.25 ± 0.05
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.51±0.23	309	[22] DEBOUARD 67	OSPK	η_{+-}=2.00 ± 0.09
2.35±0.19	525	[22] FITCH 67	OSPK	η_{+-}=1.94 ± 0.08

[22] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \to 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_{15}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.60 ±0.05 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.60 ±0.07	4200	[23] MESSNER 73	ASPK	η_{+-} = 2.23 ± 0.05
1.93 ±0.26		[24] BASILE 66	OSPK	η_{+-} = 1.92 ± 0.13
1.993±0.080		[24] BOTT-... 66	OSPK	η_{+-} = 1.95 ± 0.04
2.08 ±0.35	54	[24] GALBRAITH 65	OSPK	η_{+-} = 1.99 ± 0.16
2.0 ±0.4	45	[24] CHRISTENSON 64	OSPK	η_{+-} = 1.95 ± 0.20

[23] From same data as $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ MESSNER 73, but with different normalization.

[24] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \to 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^0\pi^0)/\Gamma_{\rm total}$ Γ_{16}/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.909±0.035 OUR FIT	Error includes scale factor of 1.8.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.5 ±0.8	189	[25] GAILLARD 69	OSPK	η_{00}=3.6 ± 0.6
$1.2^{+1.5}_{-1.2}$	7	[26] CRIEGEE 66	OSPK	

[25] Latest result of this experiment given by FAISSNER 70 $\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$.

[26] CRIEGEE 66 experiment not designed to measure $2\pi^0$ decay mode.

$\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$ Γ_{16}/Γ_1

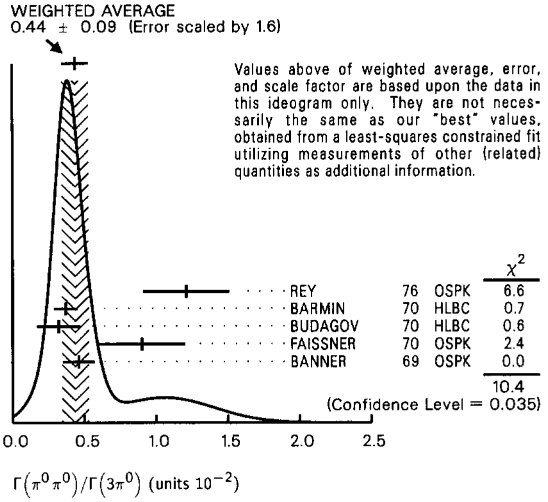
Violates *CP* conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
0.420±0.023 OUR FIT	Error includes scale factor of 1.6.			
0.44 ±0.09 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			
1.21 ±0.30	150	[27] REY 76	OSPK	η_{00}=3.8 ± 0.5
0.37 ±0.08	29	BARMIN 70	HLBC	η_{00}=2.02 ± 0.23
0.32 ±0.15	30	BUDAGOV 70	HLBC	η_{00}=1.9 ± 0.5
0.90 ±0.30	172	[28] FAISSNER 70	OSPK	η_{00}=3.2 ± 0.5
0.46 ±0.11	57	BANNER 69	OSPK	η_{00}=2.2 ± 0.3
not seen		BARTLETT 68	OSPK	See η_{00} below
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.31 ±0.31	133	[27] CENCE 69	OSPK	η_{00}=3.7 ± 0.5
1.89 ±0.31	109	[29] CRONIN 67	OSPK	η_{00}=4.9 ± 0.5
1.36 ±0.18		[29] CRONIN 67B	OSPK	η_{00}=3.92 ± 0.3

[27] CENCE 69 events are included in REY 76.

[28] FAISSNER 70 contains same $2\pi^0$ events as GAILLARD 69 $\Gamma(\pi^0\pi^0)/\Gamma_{\rm total}$.

[29] CRONIN 67B is further analysis of CRONIN 67, now both withdrawn.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^+\pi^-)$ Γ_{16}/Γ_{15}

Violates *CP* conservation.

VALUE	DOCUMENT ID	
0.448 ±0.015 OUR FIT	Error includes scale factor of 2.4.	
0.4518±0.0066	[30] ETAFIT	90

[30] This ETAFIT value is computed from fitted values of $|\eta_{00}/\eta_{+-}|$ and the $\Gamma(K^0_S \to \pi^+\pi^-)/\Gamma(K^0_S \to \pi^0\pi^0)$ branching fraction. See the discussion in the "Note on *CP* violation in K^0_L decay."

$\Gamma(e^\pm\mu^\mp)/\Gamma_{\rm total}$ Γ_{17}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	CL%	DOCUMENT ID	TECN	COMMENT
< 2.2	90	MATHIAZHA...89	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.3	90	INAGAKI 89	SPEC	
< 19	90	SCHAFFNER 89	SPEC	
<110	90	COUSINS 88	SPEC	
< 67	90	GREENLEE 88	SPEC	Repl. by SCHAFFNER 89
< 15.7	90	[31] CLARK 71	ASPK	

[31] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^\pm\mu^\mp)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_{17}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test of lepton family number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 0.1	90	BOTT-... 67	OSPK
< 0.08	90	FITCH 67	OSPK
< 1.0	90	CARPENTER 66	OSPK
<10.0		ANIKINA 65	CC

$\Gamma(\mu^+\mu^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_{18}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 2.0	90	BOTT-... 67	OSPK
< 35.0	90	FITCH 67	OSPK
<250.0	90	ALFF-... 66B	OSPK
<100.0		ANIKINA 65	CC

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ Γ_{18}/Γ_{15}

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

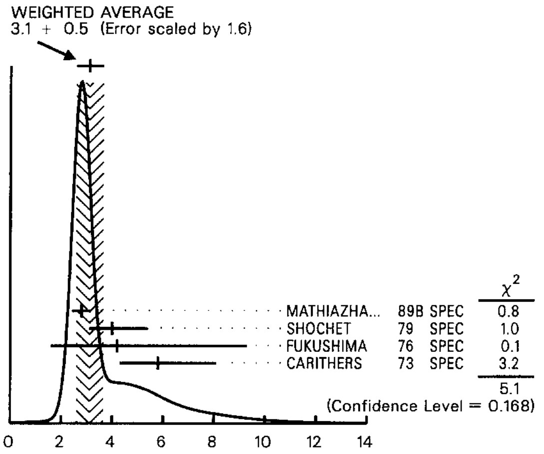
VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
3.1 ±0.5 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
2.8 ±0.3 ±0.2		87	MATHIAZHA...89B	SPEC	
$4.0^{+1.4}_{-0.9}$		15	SHOCHET 79	SPEC	
$4.2^{+5.1}_{-2.6}$		3	[32] FUKUSHIMA 76	SPEC	
$5.8^{+2.3}_{-1.5}$		9	[33] CARITHERS 73	SPEC	

• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.12±0.54	90	54	INAGAKI	89 SPEC	Stat. error only
< 1.53	90	0	[34] CLARK	71 SPEC	
< 18.	90	0	DARRIULAT	70 SPEC	
<140.	90	0	FOETH	69 SPEC	

[32] FUKUSHIMA 76 errors are at CL = 90%.

[33] CARITHERS 73 errors are at CL = 68%, W.Carithers, (private communication 79).

[34] CLARK 71 limit raised from 1.2×10^{-6} by FIELD 74 reanalysis. Not in agreement with subsequent experiments. So not averaged.



$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ (units 10^{-6})

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{\rm total}$ Γ_{19}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	CHG
0.28±0.28		1	[35] CARROLL 80D	SPEC	±0
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.81	90		[36] DONALDSON 74	SPEC	

[35] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.1239.

[36] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.126.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\rm total}$ Γ_{20}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN
<0.12	90	0	[37] CARROLL 80D	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.66	90		[38] DONALDSON 74	SPEC

[37] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.1239.

[38] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.126.

$\Gamma(e^+e^-)/\Gamma_{\rm total}$ Γ_{21}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 3.2	90		MATHIAZHA... 89	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.6	90		INAGAKI 89	SPEC	
< 110	90		COUSINS 88	SPEC	
< 45	90		GREENLEE 88	SPEC	Repl. by JASTRZEMBSKI 88
< 12	90		JASTRZEM... 88	SPEC	
< 15.7	90		[39] CLARK 71	ASPK	
<1500	90	0	FOETH 69	ASPK	

[39] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^+e^-)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu)]$ $\Gamma_{21}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 23.0	90	BOTT-... 67	OSPK
< 200.0	90	ALFF-... 66B	OSPK
<1000.0		ANIKINA 65	CC

$\Gamma(e^+e^-\gamma)/\Gamma_{\rm total}$ Γ_{22}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	CHG
1.74±0.87		4	[40] CARROLL 80D	SPEC	±0
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.7	90	0	[41] BARMIN 72	HLBC	

[40] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.1239.

[41] Uses $K_L^0 \rightarrow 3\pi^0/\text{total} = 0.214$.

$\Gamma(\pi^0e^+e^-)/\Gamma_{\rm total}$ Γ_{23}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN
<0.04	90		BARR 88	SPEC
<0.04	90		GIBBONS 88	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.32	90		JASTRZEM... 88	SPEC
<2.3	90	0	[42] CARROLL 80D	SPEC

[42] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.1239.

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\rm total}$ Γ_{24}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN
< 2.5	90	0	BALATS 83	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 8.81	90		[43] DONALDSON 76	SPEC
<30			ANIKINA 73	STRC

[43] Uses $K_L^0 \rightarrow \pi^+\pi^-\pi^0/(\text{all } K_L^0)$ decays = 0.126.

$\Gamma(\mu^+\mu^-e^+e^-)/\Gamma_{\rm total}$ Γ_{25}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN
<4.9	90	BALATS 83	SPEC

$\Gamma(e^+e^-e^+e^-)/\Gamma_{\rm total}$ Γ_{26}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN
<2.6	90	BALATS 83	SPEC

ENERGY DEPENDENCE OF K_L^0 DALITZ PLOT

For discussion, see note on Dalitz plot parameters in the $K^\pm$ section of the Full Listings above. For definitions of a_v, a_t, a_u, and a_y, see the earlier version of the same note in the 1982 edition of this Review published in Physics Letters 111B, 70 (April 1982).

$$|\text{matrix element}|^2 = 1 + gu + hu^2 + jv + kv^2$$

where $u = (s_3 - s_0)\ /\ m^2(\pi)$ and $v = (s_1 - s_2)\ /\ m^2(\pi)$

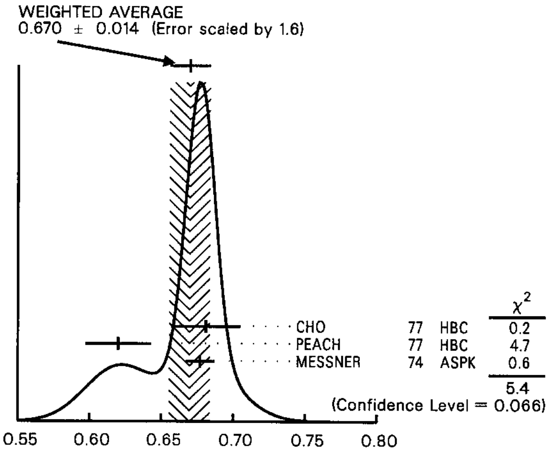
LINEAR COEFFICIENT g FOR $K_L^0 \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.670±0.014 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			
0.681±0.024	6499	CHO 77	HBC	
0.620±0.023	4709	PEACH 77	HBC	
0.677±0.010	509k	MESSNER 74	ASPK	$a_y = -0.917 \pm 0.013$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.69 ±0.07	192	[44] BALDO-... 75	HLBC	
0.590±0.022	56k	[44] BUCHANAN 75	SPEC	$a_u = -0.277 \pm 0.010$
0.619±0.027	20k	[44,45] BISI 74	ASPK	$a_t = -0.282 \pm 0.011$
0.612±0.032		[44] ALEXANDER 73B	HBC	
0.73 ±0.04	3200	[44] BRANDENB... 73	HBC	
0.50 ±0.11	180	[44] JAMES 72	HBC	
0.608±0.043	1486	[44] KRENZ 72	HLBC	$a_t = -0.277 \pm 0.018$
0.688±0.074	384	[44] METCALF 72	ASPK	$a_t = -0.31 \pm 0.03$
0.650±0.012	29k	[44] ALBROW 70	ASPK	$a_y = -0.858 \pm 0.015$
0.593±0.022	36k	[44,46] BUCHANAN 70	SPEC	$a_u = -0.278 \pm 0.010$
0.664±0.056	4400	[44] SMITH 70	OSPK	$a_t = -0.306 \pm 0.024$
0.400±0.045	2446	[44] BASILE 68B	OSPK	$a_t = -0.188 \pm 0.020$
0.649±0.044	1350	[44] HOPKINS 67	HBC	$a_t = -0.294 \pm 0.018$
0.428±0.055	1198	[44] NEFKENS 67	OSPK	$a_u = -0.204 \pm 0.025$
0.64 ±0.17	280	[44] ANIKINA 66	CC	$a_v = -8.2^{+0.9}_{-1.3}$
0.70 ±0.12	126	[44] HAWKINS 66	HBC	$a_v = -8.6 \pm 0.7$
0.32 ±0.13	66	[44] ASTBURY 65	CC	$a_v = -5.5 \pm 1.5$
0.51 ±0.09	310	[44] ASTBURY 65B	CC	$a_v = -7.3^{+0.6}_{-0.8}$
0.55 ±0.23	79	[44] ADAIR 64	HBC	$a_v = -7.6 \pm 1.7$
0.51 ±0.20	77	[44] LUERS 64	HBC	$a_v = -7.3 \pm 1.6$

[44] Quadratic dependence required by some experiments. (See sections on "QUADRATIC COEFFICIENT h" and "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

[45] BISI 74 value comes from quadratic fit with quad. term consistent with zero. g error is thus larger than if linear fit were used.

[46] BUCHANAN 70 result revised by BUCHANAN 75 to include radiative correlations and to use more reliable K_L^0 momentum spectrum of second experiment (had same beam).



Linear coeff. g for $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ matrix element squared

QUADRATIC COEFFICIENT h FOR $K_L^0 \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.079±0.007 OUR AVERAGE				
0.095±0.032	6499	CHO	77	HBC
0.048±0.036	4709	PEACH	77	HBC
0.079±0.007	509k	MESSNER	74	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.011±0.018	29k	[47] ALBROW	70	ASPK
0.043±0.052	4400	[47] SMITH	70	OSPK

See notes in section "LINEAR COEFFICIENT g FOR $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ |MATRIX ELEMENT|^2" above.

[47] Quadratic coefficients h and k required by some experiments. (See section on "QUADRATIC COEFFICIENT k" below.) Correlations prevent us from averaging results of fits not including g, h, and k terms.

QUADRATIC COEFFICIENT k FOR $K_L^0 \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.0098±0.0018 OUR AVERAGE				
0.024 ±0.010	6499	CHO	77	HBC
−0.008 ±0.012	4709	PEACH	77	HBC
0.0097±0.0018	509k	MESSNER	74	ASPK

LINEAR COEFFICIENT j FOR $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ (CP-VIOLATING TERM)

Listed in CP-violation section below.

K_L^0 FORM FACTORS

For discussion, see note on form factors in the $K^\pm$ section of the Full Listings above.

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.

f_S and f_T refer to the scalar and tensor term.

$f_0 = f_+ + f_- t/(m^2(K) - m^2(\pi))$.

λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.

λ_+ refers to the $K_{\mu 3}$ value except in the K_{e3} sections.

$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K_{\mu 3}$.

$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K_{\mu 3}$.

t = momentum transfer to the π in units of $m^2(\pi)$.

DP = Dalitz plot analysis.

PI = π spectrum analysis.

MU = μ spectrum analysis.

POL= μ polarization analysis.

BR = $K_{\mu 3}/K_{e3}$ branching ratio analysis.

E = positron or electron spectrum analysis.

RC = radiative corrections.

$\xi_a = f_-/f_+$ (determinded from spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	EVTS	DOCUMENT ID		TECN	COMMENT
−0.11±0.09 OUR EVALUATION			From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL 111B (April 1982).			
−0.10±0.09	−12	150k	[48] BIRULEV	81	SPEC	DP
+0.26±0.16	−13	14k	[49] CHO	80	HBC	DP
+0.13±0.23	−20	16k	[49] HILL	79	STRC	DP
−0.25±0.22	−5.9	32k	[50] BUCHANAN	75	SPEC	DP
−0.11±0.07	−17	1.6M	[51] DONALDSON	74B	SPEC	DP
−1.00±0.45	−20	1385	[52] PEACH	73	HLBC	DP
−1.5 ±0.7	−28	9086	[53] ALBROW	72	ASPK	DP
+1.2 ±0.8	−18	1341	[54] CARPENTER	66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •						
+0.50±0.61	unknown	16k	[55] DALLY	72	ASPK	DP
−3.9 ±0.4		3140	[56] BASILE	70	OSPK	DP, indep of λ_+
$-0.68^{+0.12}_{-0.20}$	−26	16k	[55] CHIEN	70	ASPK	DP

[48] BIRULEV 81 error, $d\xi(0)/d\lambda_+$ calculated by us from λ_0, λ_+. $d\lambda_0/d\lambda_+ = 0$ used.

[49] HILL 79 and CHO 80 calculated by us from λ_0, λ_+, and $d\lambda_0/d\lambda_+$.

[50] BUCHANAN 75 is calculated by us from λ_0, λ_+ and $d\lambda_0/d\lambda_+$ because their appendix A value -0.20 ± 22 assumes $\xi(t)$ constant, i.e. $\lambda_- = \lambda_+$.

[51] DONALDSON 74B gives $\xi = -0.11 \pm 0.02$ not including systematics. Above error and $d\xi(0)/d\lambda_+$ were calculated by us from λ_0 and λ_+ errors (which include systematics) and $d\lambda_0/d\lambda_+$.

[52] PEACH 73 gives $\xi(0) = -0.95 \pm 0.45$ for $\lambda_+ = \lambda_- = 0.025$. The above value is for $\lambda_- = 0$. K.Peach, private communication (1974).

[53] ALBROW 72 fit has λ_- free, gets $\lambda_- = -0.030 \pm 0.060$ or $\Lambda = +0.15^{+0.17}_{-0.11}$.

[54] CARPENTER 66 $\xi(0)$ is for $\lambda_+ = 0$. $d\xi(0)/d\lambda_+$ is from figure 9.

[55] CHIEN 70 errors are statistical only. $d\xi(0)/d\lambda_+$ from figure 4. DALLY 72 is a reanalysis of CHIEN 70. The DALLY 72 result is not compatible with assumption $\lambda_- = 0$ so not included in our fit. The nonzero λ_- value and the relatively large λ_+ value found by DALLY 72 come mainly from a single low t bin (figures 1,2). The (f_+,ξ) correlation was ignored. We estimate from figure 2 that fixing $\lambda_- = 0$ would give $\xi(0) = -1.4 \pm 0.3$ and would add 10 to χ^2. $d\xi(0)/d\lambda_+$ is not given.

[56] BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$\xi_b = f_-/f_+$ (determined from $K_{\mu 3}/K_{e3}$)

The $K_{\mu 3}/K_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_b values. Instead they are obtained directly from the authors $K_{\mu 3}/K_{e3}$ branching ratio via the fitted $K_{\mu 3}/K_{e3}$ ratio ($\Gamma(\pi^\pm \mu^\mp \nu)/\Gamma(\pi^\pm e^\mp \nu)$). The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.11±0.09 OUR EVALUATION		From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL 111B (April 1982).			
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.5 ±0.4	6700	BRANDENB...	73	HBC	BR, λ_+=0.019 ± 0.013
−0.08±0.25	1309	[57] EVANS	73	HLBC	BR, λ_+=0.02
−0.5 ±0.5	3548	BASILE	70	OSPK	BR, λ_+=0.02
+0.45±0.28	569	BEILLIERE	69	HLBC	BR, λ_+=0
−0.22±0.30	1309	[57] EVANS	69	HLBC	
$+0.2\ ^{+0.8}_{-1.2}$		KULYUKINA	68	CC	BR, λ_+=0
+1.1 ±1.1	389	ADAIR	64	HBC	BR, λ_+=0
$+0.66^{+0.9}_{-1.3}$		LUERS	64	HBC	BR, λ_+=0

[57] EVANS 73 replaces EVANS 69.

$\xi_c = f_-/f_+$ (determined from μ polarization in $K_{\mu 3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+ = 0$. $d\xi/d\lambda = \xi t$. For radiative correction to μ polarization in $K_{\mu 3}$, see GINSBERG 73. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.11 ±0.09 OUR EVALUATION		From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL 111B (April 1982).			
+0.178±0.105	207k	[58] CLARK	77	SPEC	POL, $d\xi(0)/d\lambda_+$=+0.68
−0.385±0.105	2.2M	[59] SANDWEISS	73	CNTR	POL, $d\xi(0)/d\lambda_+$=−6
$-1.81\ ^{+0.50}_{-0.26}$		[60] LONGO	69	CNTR	POL, t=3.3
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−1.6 ±0.5	638	[61] ABRAMS	68B	OSPK	Polarization
−1.2 ±0.5	2608	[61] AUERBACH	66B	OSPK	Polarization

[58] CLARK 77 $t = +3.80$, $d\xi(0)/d\lambda_+ = \xi(t)t = 0.178 \times 3.80 = +0.68$.

[59] SANDWEISS 73 is for $\lambda_+ = 0$ and $t = 0$.

[60] LONGO 69 $t = 3.3$ calculated from $d\xi(0)/d\lambda_+ = -6.0$ (table 1) divided by $\xi = -1.81$.

[61] t value not given.

IMAGINARY PART OF ξ

Test of T reversal invariance.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.007±0.026 OUR AVERAGE					
0.009±0.030	12M	MORSE	80	CNTR	Polarization
0.35 ±0.30	207k	[62] CLARK	77	SPEC	POL, t=0
−0.085±0.064	2.2M	[63] SANDWEISS	73	CNTR	POL, t=0
−0.02 ±0.08		LONGO	69	CNTR	POL, t=3.3
−0.2 ±0.6		ABRAMS	68B	OSPK	Polarization
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.012±0.026		SCHMIDT	79	CNTR	Repl. by MORSE 80

[62] CLARK 77 value has additional $\xi(0)$ dependence $+0.21\mathrm{Re}[\xi(0)]$.

[63] SANDWEISS 73 value corrected from value quoted in their paper due to new value of Re(ξ). See footnote 4 of SCHMIDT 79.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K_{\mu 3}$ DECAY)

See also the corresponding entries and notes in section "$\xi_A = f_-/f_+$" above and section "λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K_{\mu 3}$ DECAY)" below. For radiative correction of $K_{\mu 3}$ Dalitz plot see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.034 ± 0.005	**OUR EVALUATION**	From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
0.0427 ± 0.0044	150k	BIRULEV 81	SPEC	DP
0.028 ± 0.010	14k	CHO 80	HBC	DP
0.028 ± 0.011	16k	HILL 79	STRC	DP
0.046 ± 0.030	32k	BUCHANAN 75	SPEC	DP
0.030 ± 0.003	1.6M	DONALDSON 74B	SPEC	DP
0.085 ± 0.015	9086	ALBROW 72	ASPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0337 ± 0.0033	129k	DZHORD... 77	SPEC	Repl. by BIRULEV 81
0.046 ± 0.008	82k	ALBRECHT 74	WIRE	Repl. by BIRULEV 81
0.11 ± 0.04	16k	DALLY 72	ASPK	DP
0.07 ± 0.02	16k	CHIEN 70	ASPK	Repl. by DALLY 72

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K_{\mu 3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ_+^{μ} and $d\xi(0)/d\lambda_+$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID	TECN	COMMENT
0.025 ± 0.006	**OUR EVALUATION**		From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).		
0.0341 ± 0.0067	unknown	150k	[64] BIRULEV 81	SPEC	DP
+0.050 ± 0.008	−0.11	14k	CHO 80	HBC	DP
+0.039 ± 0.010	−0.67	16k	HILL 79	STRC	DP
+0.047 ± 0.009	1.06	207k	[65] CLARK 77	SPEC	POL
+0.025 ± 0.019	+0.5	32k	[66] BUCHANAN 75	SPEC	DP
+0.019 ± 0.004	−0.47	1.6M	[67] DONALDSON 74B	SPEC	DP
−0.060 ± 0.038	−0.71	1385	[68] PEACH 73	HLBC	DP
−0.018 ± 0.009	+0.49	2.2M	[65] SANDWEISS 73	CNTR	POL
−0.043 ± 0.052	−1.39	9086	[69] ALBROW 72	ASPK	DP
$-0.140^{+0.043}_{-0.022}$	+0.49		[65] LONGO 69	CNTR	POL
+0.08 ± 0.07	−0.54	1371	[65] CARPENTER 66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.041 ± 0.008		14k	[70] CHO 80	HBC	BR, λ_+=0.028
+0.0485 ± 0.0076		47k	DZHORD... 77	SPEC	In BIRULEV 81
+0.024 ± 0.011		82k	ALBRECHT 74	WIRE	In BIRULEV 81
+0.06 ± 0.03		6700	[71] BRANDENB... 73	HBC	BR, λ_+=0.019 ± 0.013
−0.067 ± 0.227	unknown	16k	[72] DALLY 72	ASPK	DP
−0.333 ± 0.034	+1.	3140	[73] BASILE 70	OSPK	DP

[64] BIRULEV 81 gives $d\lambda_0/d\lambda_+ = -1.5$, giving an unreasonably narrow error ellipse which dominates all other results. We use $d\lambda_0/d\lambda_+ = 0$.

[65] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[66] BUCHANAN 75 value is from their appendix A and uses only $K_{\mu 3}$ data. $d\lambda_0/d\lambda_+$ was obtained by private communication, C.Buchanan, 1976.

[67] DONALDSON 74B $d\lambda_0/d\lambda_+$ obtained from figure 18.

[68] PEACH 73 assumes $\lambda_+ = 0.025$. Calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[69] ALBROW 72 λ_0 is calculated by us from ξ_A, λ_+ and $d\xi(0)/d\lambda_+$. They give $\lambda_0 = -0.043 \pm 0.039$ for $\lambda_- = 0$. We use our larger calculated error.

[70] CHO 80 BR result not independent of their Dalitz plot result.

[71] Fit for λ_0 does not include this value but instead includes the $K_{\mu 3}/K_{e3}$ result from this experiment.

[72] DALLY 72 gives $f_0 = 1.20 \pm 0.35$, $\lambda_0 = -0.080 \pm 0.272$, $\lambda_0{}' = -0.006 \pm 0.045$, but with a different definition of λ_0. Our quoted λ_0 is his λ_0/f_0. We cannot calculate true λ_0 error without his (λ_0,f_0) correlations. See also note on DALLY 72 in section ξ_A.

[73] BASILE 70 λ_0 is for $\lambda_+ = 0$. Calculated by us from ξ_A with $d\xi(0)/d\lambda_+ = 0$. BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K_{e3} DECAY)

For radiative correction of K_{e3} DP, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0300 ± 0.0016	**OUR AVERAGE**	Error includes scale factor of 1.2.		
0.0306 ± 0.0034	74k	BIRULEV 81	SPEC	DP
0.025 ± 0.005	12k	[74] ENGLER 78B	HBC	DP
0.0348 ± 0.0044	18k	HILL 78	STRC	DP
0.0312 ± 0.0025	500k	GJESDAL 76	SPEC	DP
0.0270 ± 0.0028	25k	BLUMENTHAL 75	SPEC	DP
0.044 ± 0.006	24k	BUCHANAN 75	SPEC	DP
0.040 ± 0.012	2171	WANG 74	OSPK	DP
0.045 ± 0.014	5600	ALBROW 73	ASPK	DP
0.019 ± 0.013	1871	BRANDENB... 73	HBC	PI transv.
0.022 ± 0.014	1910	NEUHOFER 72	ASPK	PI
0.023 ± 0.005	42k	BISI 71	ASPK	DP
0.05 ± 0.01	16k	CHIEN 71	ASPK	DP, no RC
0.02 ± 0.013	1000	ARONSON 68	OSPK	PI
+0.023 ± 0.012	4800	BASILE 68	OSPK	DP, no RC
−0.01 ± 0.02	762	FIRESTONE 67	HBC	DP, no RC
+0.01 ± 0.015	531	KADYK 67	HBC	e,PI, no RC
$+0.08^{+0.10}_{-0.08}$	240	LOWYS 67	FBC	PI
+0.15 ± 0.08	577	FISHER 65	OSPK	DP, no RC
+0.07 ± 0.06	153	LUERS 64	HBC	DP, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.029 ± 0.005	19k	[74] CHO 80	HBC	DP
0.0286 ± 0.0049	26k	BIRULEV 79	SPEC	Repl. by BIRULEV 81
0.032 ± 0.0042	48k	BIRULEV 76	SPEC	Repl. by BIRULEV 81

[74] ENGLER 78B uses an unique K_{e3} subset of CHO 80 events and is less subject to systematic effects.

$|f_S/f_+|$ FOR K_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.04	68	25k	BLUMENTHAL 75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.095	95	18k	HILL 78	STRC	
<0.07	68	48k	BIRULEV 76	SPEC	See also BIRULEV 81
<0.19	95	5600	ALBROW 73	ASPK	
<0.15	68		KULYUKINA 67	CC	

$|f_T/f_+|$ FOR K_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.23	68	25k	BLUMENTHAL 75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.40	95	18k	HILL 78	STRC	
<0.34	68	48k	BIRULEV 76	SPEC	See also BIRULEV 81
<1.0	95	5600	ALBROW 73	ASPK	
<1.0	68		KULYUKINA 67	CC	

$|f_T/f_+|$ FOR $K_{\mu 3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	DOCUMENT ID	TECN
0.12 ± 0.12	BIRULEV 81	SPEC

NOTE ON *CP* VIOLATION IN K_L^0 DECAY

(by L. Wolfenstein, Carnegie-Mellon University and T. Trippe, LBL)

Experimentally Measured Parameters

CP violation has been observed in the semi-leptonic decays $K_L^0 \to \pi^{\mp}\ell^{\pm}\nu$ and in the nonleptonic decay $K_L^0 \to 2\pi$. The experimental numbers that have been measured are[1]

$$\delta = \frac{\Gamma(K_L^0 \to \pi^-\ell^+\nu) - \Gamma(K_L^0 \to \pi^+\ell^-\nu)}{\Gamma(K_L^0 \to \pi^-\ell^+\nu) + \Gamma(K_L^0 \to \pi^+\ell^-\nu)} \tag{1}$$

$$\begin{aligned} \eta_{+-} &= A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-) \\ &= |\eta_{+-}|\, e^{i\phi_{+-}} \end{aligned} \tag{1b}$$

$$\begin{aligned} \eta_{00} &= A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0) \\ &= |\eta_{00}|\, e^{i\phi_{00}} \end{aligned} \tag{1c}$$

Thus there are five real numbers, three magnitudes and two phases. We list $\delta(\mu)$ for $K_L^0 \to \pi\mu\nu$ and $\delta(e)$ for $K_L^0 \to \pi e\nu$ separately and a weighted average δ. Experimentally for the $K_L^0 \to \pi^0\pi^0$ decay the quantities directly measured (and also of greatest theoretical interest) are $|\eta_{00}/\eta_{+-}|$ and $\phi_{00} - \phi_{+-}$.

Analysis Based on *CPT* Invariance[2]

CP violation can occur either in the $K^0 - \overline{K}^0$ mixing or in the decay amplitudes. The mixing is described by:

$$|\,K_L^0\rangle = \Big[(1+\epsilon)\,|\,K^0\,\rangle - (1-\epsilon)\,|\,\overline{K}^0\,\rangle\Big] \Big/ \Big[2(1+|\,\epsilon\,|^2)\Big]^{1/2} \tag{2a}$$

$$|\,K_S^0\rangle = \Big[(1+\epsilon)\,|\,K^0\,\rangle + (1-\epsilon)\,|\,\overline{K}^0\,\rangle\Big] \Big/ \Big[2(1+|\,\epsilon\,|^2)\Big]^{1/2} \tag{2b}$$

where ϵ measures the CP violation. The decay amplitudes are written

$$\langle\, I=0 \mid T \mid K^0 \rangle = e^{i\delta_0} A_0 \qquad (3a)$$

$$\langle\, I=2 \mid T \mid K^0 \rangle = e^{i\delta_2} A_2 \qquad (3b)$$

where δ_I are the $\pi\pi$ scattering phase shifts at the K^0 mass and I is the isospin of the final state. CP violation is measured by $(\mathrm{Im}A_I/\mathrm{Re}A_I)$. Only two of the three quantities ϵ, $(\mathrm{Im}A_I/\mathrm{Re}A_I)$ are meaningful because of the ambiguity in defining the phase of K^0. The standard phase convention due to Wu and Yang[3] sets $\mathrm{Im}A_0 = 0$. One can then write

$$\eta_{+-} = \epsilon + \epsilon' \qquad (4a)$$

$$\eta_{00} = \epsilon - 2\epsilon' \qquad (4b)$$

where

$$\epsilon' = \frac{i}{\sqrt{2}}\, e^{i(\delta_2-\delta_0)}\, \mathrm{Im}(A_2/A_0)$$

neglecting small corrections of order ϵ' times $\mathrm{Re}(A_2/A_0)$. A nonzero value of ϵ' provides definite evidence for CP violation in the decay amplitudes independent of phase convention.

By applying CPT invariance and unitarity it is possible to relate δ to ϵ and to determine the phases of ϵ and ϵ'. If one assumes the $\Delta S = \Delta Q$ rule (see below "Note on the $\Delta S = \Delta Q$ rule in K^0 Decay") the expression for δ becomes

$$\delta = 2\mathrm{Re}\,\epsilon/(1+\mid\epsilon\mid^2) \approx 2\mathrm{Re}\,\epsilon \qquad (5)$$

This quantity is independent of phase convention and is seen from Eq. (2) to equal $\langle K^0_L \mid K^0_S\rangle$. The phases of ϵ and ϵ' are given by

$$\phi(\epsilon) \approx \tan^{-1}\frac{(2\Delta m \tau_s)}{\hbar} = 43.67 \pm 0.13^\circ \qquad (6a)$$

$$\phi(\epsilon') = \delta_2 - \delta_0 + \frac{\pi}{2} \approx 47 \pm 5^\circ \qquad (6b)$$

The approximation in Eq. (6a) depends on the neglect of CP violation in decays other than $K^0 \to 2\pi$ and is known to be good to a few tenths of a degree. Eq. (6a) is evaluated using the values of the $K^0_L - K^0_S$ mass difference $\Delta m = (0.5349 \pm 0.0022) \times 10^{10}\hbar\mathrm{s}^{-1}$ and the K^0_S mean life $\tau_s = (0.8922 \pm 0.0020) \times 10^{-10}\mathrm{s}$ from the current edition. The value of the $\pi\pi$ phase shifts used in Eq. (6b) is taken from the fit given by Devlin and Dickey[4]. However, Kleinknecht[1] uses $\phi(\epsilon') = 37 \pm 5^\circ$ and Wahl[5] uses $\phi(\epsilon') = 45^\circ \pm 15^\circ$. The most important point for the analysis is that $\cos[\phi(\epsilon') - \phi(\epsilon)] \simeq 1$. The consequence of this analysis is that only two real quantities need be measured, the magnitude of ϵ and the value of (ϵ'/ϵ) including its sign. The measured quantity $|\eta_{00}/\eta_{+-}|^2$ which is very close to unity, is given to a good approximation by

$$\begin{aligned}|\eta_{00}/\eta_{+-}|^2 &\approx 1 - 6\mathrm{Re}\,(\epsilon'/\epsilon)\\ &= 1 - 6(\epsilon'/\epsilon)\cos[\phi(\epsilon') - \phi(\epsilon)] \qquad (7)\end{aligned}$$

Since the cos in Eq. (7) is expected theoretically to be very close to unity it is customary to say that $|\eta_{00}/\eta_{+-}|^2$ determines ϵ'/ϵ.

It is possible to use the values of the ϕ_{+-} and $\phi_{00} - \phi_{+-}$ to set limits on CPT violation. [See Tests of Conservation Laws.]

Models

In the superweak model[6] CP violation is restricted to the mass mixing so that to a high degree of accuracy one expects $\epsilon' = 0$. The phase $\phi(\epsilon)$ is given in this model exactly by Eq. (6a) so that this has sometimes been referred to as the superweak phase; however, as noted above, all CPT invariant models give Eq. (6a) as a very good approximation. In the Standard Model CP violation is entirely due to the phase in the Cabibbo-Kobayashi-Maskawa mixing matrix[7] (q.v.). Since CP violation occurs in first order in decay amplitudes and in second order in mass-matrix mixing, one expects a significant non-zero value of ϵ'. The calculation is uncertain partly because m_t and V_{td} are not well known and primarily because of the difficulty of estimating hadronic matrix elements.[8] The theoretical results for ϵ'/ϵ in the standard model are generally in the range 3×10^{-4} to 5×10^{-3}.

Fitting procedures

We list measurements of $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{00}/\eta_{+-}|$. Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from measurements of the K^0_L and K^0_S lifetimes (τ) and branching ratios (B) to $\pi\pi$, using the relations

$$|\eta_{+-}| = \left[\frac{\mathrm{B}(K^0_L \to \pi^+\pi^-)}{\tau(K^0_L)}\ \frac{\tau(K^0_S)}{\mathrm{B}(K^0_S \to \pi^+\pi^-)}\right]^{1/2} ,$$

$$|\eta_{00}| = \left[\frac{\mathrm{B}(K^0_L \to \pi^0\pi^0)}{\tau(K^0_L)}\ \frac{\tau(K^0_S)}{\mathrm{B}(K^0_S \to \pi^0\pi^0)}\right]^{1/2} .$$

We approximate a global fit to these independent sources by first performing two independent fits: 1) BRFIT, a fit to the K^0_L branching ratios, rates, and mean life, and 2) ETAFIT, a fit to the $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{+-}/\eta_{00}|$ measurements. The results from fit 1,

$$\tau(K^0_L) = (5.17 \pm 0.04) \times 10^{-8}\,\mathrm{s}\ ,$$

$$\mathrm{B}(K^0_L \to \pi^+\pi^-) = (2.04 \pm 0.05) \times 10^{-3}\ (\mathrm{S}^* = 1.2)\ ,$$

$$\mathrm{B}(K^0_L \to \pi^0\pi^0) = (7.9 \pm 0.6) \times 10^{-4}\ (\mathrm{S}^* = 1.2)\ ,$$

along with the K^0_S values from this edition are used to compute the values

$$|\eta_{+-}|_{\mathrm{BRFIT}} = (2.265 \pm 0.030) \times 10^{-3}\ ,$$

$$|\eta_{00}|_{\mathrm{BRFIT}} = (2.084 \pm 0.080) \times 10^{-3}\ .$$

These values are included as measurements in the $|\eta_{00}|$ and $|\eta_{+-}|$ sections with a document ID of BRFIT 90. The fit to $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{+-},/\eta_{00}|$ is then redone to include the BRFIT 90 information. Thus the fit values given in this edition,

$$|\eta_{+-}| = (2.268 \pm 0.023) \times 10^{-3}\ (\mathrm{S}^* = 1.1)\ ,$$

$$|\eta_{00}| = (2.253 \pm 0.024) \times 10^{-3}\ (\mathrm{S}^* = 1.1)\ ,$$

include both the direct measurements and the results from the branching ratio fit.

The process is reversed in order to include the direct $|\eta|$ measurements in the branching ratio fit. The results from fit 2 above (before including BRFIT 90 values),

$$|\eta_{+-}| = (2.299 \pm 0.034) \times 10^{-3} \ ,$$

$$|\eta_{00}/\eta_{+-}| = 0.9938 \pm 0.0035 \ (\mathrm{S}^* = 1.4) \ ,$$

are used along with the K_L^0 and K_S^0 mean lives and the $K_S^0 \to \pi\pi$ branching fractions to compute the K_L^0 branching ratios

$$\mathrm{B}(K_L^0 \to \pi^+\pi^-)_{\mathrm{ETAFIT}} = (2.101 \pm 0.065) \times 10^{-3}$$

$$\left[\frac{\mathrm{B}(K_L^0 \to \pi^0\pi^0)}{\mathrm{B}(K_L^0 \to \pi^+\pi^-)}\right]_{\mathrm{ETAFIT}} = 0.4518 \pm 0.0066 \ .$$

$|\eta_{00}/\eta_{+-}|$ is used because it is precisely determined and almost uncorrelated with $|\eta_{+-}|$ whereas $|\eta_{00}|$ is highly correlated with $|\eta_{+-}|$ because of the precise measurements of $|\eta_{00}/\eta_{+-}|$.

These branching ratio values are included as measurements in the branching ratio sections $\Gamma(K_L^0 \to \pi^+\pi^-)/\Gamma(\mathrm{total})$ and $\Gamma(K_L^0 \to \pi^0\pi^0)/\Gamma(K_L^0 \to \pi^+\pi^-)$ with a document ID of ETAFIT 90. Thus the K_L^0 branching ratio fit results in this edition include the results of direct measurements of $|\eta_{+-}|$, $|\eta_{00}|$, and $|\eta_{00}/\eta_{+-}|$.

Note the large scale factor ($\mathrm{S}^* = 1.4$) on $|\eta_{00}/\eta_{+-}|$. This arises from the discrepancy between the ϵ'/ϵ result from the Chicago experiment (PATTERSON 90) which is consistent with zero and the CERN experiment (BURKARDT 88) which is three sigma above zero. Our fitted value is

$$\frac{\epsilon'}{\epsilon} = (2.1 \pm 1.2) \times 10^{-3} \ (\mathrm{S}^* = 1.4) \ .$$

A separate constrained fit is done to combine measurements of the phases ϕ_{+-} and ϕ_{00}, and their difference $\phi_{00} - \phi_{+-}$. The phase difference is now rather precisely determined by the CERN result (CAROSI 90) so that our evaluation, $\phi_{00} - \phi_{+-} = 2.5 \pm 4.5$ ($S^* = 1.8$), is consistent with zero, i.e., not suggesting *CPT* violation.

Footnotes and References

* The S values in parentheses are scale factors by which the errors have been increased to account for discrepancies in the data.

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CP-VIOLATION PARAMETERS IN K_L^0 DECAYS

CHARGE ASYMMETRY IN LEPTONIC DECAYS

Such asymmetry violates *CP*. It is related to Re(ϵ).

$$\delta(\mu) = \left[\Gamma(\pi^-\mu^+\nu_\mu) - \Gamma(\pi^+\mu^-\overline{\nu}_\mu)\right]/\left[\Gamma(\pi^-\mu^+\nu_\mu) + \Gamma(\pi^+\mu^-\overline{\nu}_\mu)\right] \qquad (\Gamma_4 - \Gamma_5)/(\Gamma_4+\Gamma_5)$$

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	EVTS	DOCUMENT ID		TECN
0.304±0.025 OUR AVERAGE				
0.313±0.029	15M	GEWENIGER	74	ASPK
0.278±0.051	7.7M	PICCIONI	72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.60 ±0.14	4.1M	MCCARTHY	73	CNTR
0.57 ±0.17	1M	[75] PACIOTTI	69	OSPK
0.403±0.134	1M	[75] DORFAN	67	OSPK

[75] PACIOTTI 69 is a reanalysis of DORFAN 67 and is corrected for $\mu^+ \mu^-$ range difference in MCCARTHY 72.

$$\delta(e) = \left[\Gamma(\pi^-e^+\nu_e) - \Gamma(\pi^+e^-\overline{\nu}_e)\right]/\left[\Gamma(\pi^-e^+\nu_e) + \Gamma(\pi^+e^-\overline{\nu}_e)\right] \qquad (\Gamma_7 - \Gamma_8)/(\Gamma_7+\Gamma_8)$$

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	EVTS	DOCUMENT ID		TECN
0.333±0.014 OUR AVERAGE				
0.341±0.018	34M	GEWENIGER	74	ASPK
0.318±0.038	40M	FITCH	73	ASPK
0.346±0.033	10M	MARX	70	CNTR
0.246±0.059	10M	[76] SAAL	69	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.36 ±0.18	600k	ASHFORD	72	ASPK
0.224±0.036	10M	[76] BENNETT	67	CNTR

[76] SAAL 69 is a reanalysis of BENNETT 67.

δ = weighted average of $\delta(\mu)$ and $\delta(e)$

(Combination of the above two sections.)

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.327±0.012 OUR AVERAGE					
0.313±0.029	15M	GEWENIGER	74	ASPK	$K_{\mu 3}$
0.341±0.018	34M	GEWENIGER	74	ASPK	K_{e3}
0.318±0.038	40M	FITCH	73	ASPK	K_{e3}
0.333±0.050	33M	WILLIAMS	73	ASPK	$K_{\mu 3} + K_{e3}$
0.278±0.051	7.7M	PICCIONI	72	ASPK	$K_{\mu 3}$
0.346±0.033	10M	MARX	70	CNTR	K_{e3}
0.246±0.059	10M	SAAL	69	CNTR	K_{e3}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.60 ±0.14	4.1M	MCCARTHY	73	CNTR	$K_{\mu 3}$
0.36 ±0.18	600k	ASHFORD	72	ASPK	K_{e3}
0.57 ±0.17	1M	PACIOTTI	69	OSPK	$K_{\mu 3}$

PARAMETERS FOR $K_L^0 \to 2\pi$ DECAY

$\eta_{+-} = \mathrm{A}(K_L^0 \to \pi^+\pi^-) \,/\, \mathrm{A}(K_S^0 \to \pi^+\pi^-)$
$\eta_{00} = \mathrm{A}(K_L^0 \to \pi^0\pi^0) \,/\, \mathrm{A}(K_S^0 \to \pi^0\pi^0)$

The fitted values of $|\eta_{+-}|$ and $|\eta_{00}|$ given below are the results of a fit to $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and Re(ϵ'/ϵ). Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from the fitted values of the $K_L^0 \to \pi\pi$ and $K_S^0 \to \pi\pi$ branching ratios and the K_L^0 and K_S^0 lifetimes. This information is included as data in the $|\eta_{+-}|$ and $|\eta_{00}|$ sections with a Document ID "BRFIT." See the "Note on *CP* Violation in K_L^0 Decay" above for details.

$|\eta_{00}| = |\mathrm{A}(K_L^0 \to 2\pi^0) \,/\, \mathrm{A}(K_S^0 \to 2\pi^0)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.253±0.024 OUR FIT Error includes scale factor of 1.1.					
2.12 ±0.09 OUR AVERAGE Error includes scale factor of 1.2.					
2.084±0.080		[77] BRFIT	90		
2.33 ±0.18		CHRISTENSON	79	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.71 ±0.37	56	[78] WOLFF	71	OSPK	Cu reg., 4γ's
2.95 ±0.63		[78] CHOLLET	70	OSPK	Cu reg., 4γ's

[77] This BRFIT value is computed from fitted values of the K_L^0 and K_S^0 lifetimes and branching fractions to $\pi\pi$. See the discussion in the "Note on *CP* violation in K_L^0 decay."

[78] CHOLLET 70 gives $|\eta_{00}| = (1.23 \pm 0.24) \times$(regeneration amplitude, 2 GeV/c Cu)/10000mb. WOLFF 71 gives $|\eta_{00}| = (1.13 \pm 0.12) \times$(regeneration amplitude, 2 GeV/c Cu)/10000mb. We compute both $|\eta_{00}|$ values for (regeneration amplitude, 2 GeV/c Cu) = 24 ± 2mb. This regeneration amplitude results from averaging over FAISSNER 69, extrapolated using optical-model calculations of Bohm et al., Phys. Lett. **27B**, 594 (1968) and the data of BALATS 71. (From H. Faissner, private communication).

$|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-)\ /\ A(K^0_S \to \pi^+\pi^-)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.268±0.023 OUR FIT Error includes scale factor of 1.1.				
2.279±0.022 OUR AVERAGE				
2.265±0.030		[79] BRFIT 90		
2.27 ±0.12		CHRISTENSON79B	ASPK	
2.30 ±0.035		GEWENIGER 74B	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.28 ±0.06	1687	[80] COUPAL 85	SPEC	$P(K)$=70 GeV/c
2.09 ±0.02		[81] ARONSON 82B	SPEC	E=30–110 GeV

[79] This BRFIT value is computed from fitted values of the K^0_L and K^0_S lifetimes and branching fractions to $\pi\pi$. See the discussion in the "Note on CP violation in K^0_L decay."

[80] COUPAL 85 concludes: no energy dependence of $|\eta_{+-}|$, because their value is consistent with above values which occur at lower energies. Not independent of COUPAL 85 $\Gamma(\pi^+\pi^-)/\Gamma(\pi\ell\nu)$ measurement. Enters $|\eta_{+-}|$ via BRFIT value. In editions prior to 1990, this measurement was erroneously also included in our $|\eta_{+-}|$ average and fit. We thank H. Wahl (WAHL 89) for informing us.

[81] ARONSON 82B find that $|\eta_{+-}|$ may depend on the kaon energy.

$|\eta_{00}/\eta_{+-}|$

VALUE	EVTS	DOCUMENT ID	TECN
0.9935±0.0032 OUR FIT Error includes scale factor of 1.3.			
0.9907±0.0030 OUR AVERAGE			
0.9899±0.0020±0.0025		[82] BURKHARDT 88	CALO
0.9904±0.0084±0.0036		[83] WOODS 88	SPEC
1.014 ±0.016 ±0.007	3152	BERNSTEIN 85B	SPEC
0.995 ±0.025	1122	BLACK 85	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.00 ±0.09		[84] CHRISTENSON79	ASPK
1.03 ±0.07	124	BANNER 72	OSPK
1.00 ±0.06	167	HOLDER 72	ASPK

[82] This is the square root of the ratio R given by BURKHARDT 88.

[83] We calculate $|\eta_{00}/\eta_{+-}| = 1-3(\epsilon'/\epsilon)$ from WOODS 88 (ϵ'/ϵ) value.

[84] Not independent of $|\eta_{+-}|$ and $|\eta_{00}|$ values which are included in fit.

ϵ'/ϵ

$\epsilon'/\epsilon \approx \mathrm{Re}(\epsilon'/\epsilon) = (1-|\eta_{00}/\eta_{+-}|)/3$. See "Note on CP violation in K^0_L decay."

VALUE (units 10^{-3})	DOCUMENT ID	TECN
2.2±1.1 OUR FIT Error includes scale factor of 1.3.		
−0.4±1.4±0.6	PATTERSON 90	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.3±1.1	[85] BURKHARDT 88	CALO
3.2±2.8±1.2	[85] WOODS 88	SPEC

[85] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements and enter the fit via the $|\eta_{00}/\eta_{+-}|$ section.

ϕ_{+-}, PHASE of η_{+-}

The dependence of the phase on the K^0_L - K^0_S mass difference is given for each experiment in the comments below, where DM is (mass difference/$\hbar$) in units 10^{10} s^{-1}. We have evaluated these mass dependences using our April 1990 value, DM = 0.5351 ± 0.0024 to obtain the values and average quoted below. We also give the regeneration phase ϕ_f in the comments below.

VALUE (°)	DOCUMENT ID	TECN	COMMENT
46.0± 1.2 OUR EVALUATION			
46.0± 1.2 OUR AVERAGE			
46.9± 1.4±1.7	[86] CAROSI 90	CALO	
41.7± 3.5	CHRISTENSON79B	ASPK	
45.6± 2.9	[87] CARITHERS 75	SPEC	C regenerator
46.6± 1.7	[88] GEWENIGER 74B	ASPK	Vacuum regen.
• • • We do not use the following data for averages, fits, limits, etc. • • •			
35.3± 3.9	[89] ARONSON 82B	SPEC	E=30–110 GeV
36.2± 6.1	[90] CARNEGIE 72	ASPK	Cu regenerator
37.2±12.0	[91] BALATS 71	OSPK	Cu regenerator
40.7± 4.2	[92] JENSEN 70	ASPK	Vacuum regen.
34.2±10.0	[93] BENNETT 69	CNTR	Cu regenerator
45.4±12.0	[94] BOHM 69B	OSPK	Vacuum regen.
45.2± 7.4	[95] FAISSNER 69	ASPK	Cu regenerator
51.0±11.0	[96] BENNETT 68B	CNTR	Cu reg. uses
70.0±21.0	[97] BOTT-... 67B	OSPK	C regenerator
25.0±35.0	[97] MISCHKE 67	OSPK	Cu regenerator
30.0±45.0	[97] FIRESTONE 66	HBC	
45.0±50.0	[97] FITCH 65	OSPK	Be regenerator

[86] Systematic error is quadratic sum of experimental systematic errors (±0.7°) and the systematic errors due to the current uncertainties in τ_S (±0.6°) and Δm (±1.4°).

[87] CARITHERS 75 $\phi_{+-} = (45.5 \pm 2.8)+224[\Delta(m)-0.5348]^\circ$. $\phi_f = -40.9 \pm 2.6^\circ$.

[88] GEWENIGER 74B $\phi_{+-} = (49.4 \pm 1.0)+565[\Delta(m)-0.540]^\circ$.

[89] ARONSON 82 find that ϕ_{+-} may depend on the kaon energy.

[90] CARNEGIE 72 ϕ_{+-} is insensitive to $\Delta(m)$. $\phi_f = -56.2 \pm 5.2^\circ$.

[91] BALATS 71 $\phi_{+-} = (39.0 \pm 12.0)+198[\Delta(m)-0.544]^\circ$. $\phi_f = -43.0 \pm 4.0^\circ$.

[92] JENSEN 70 $\phi_{+-} = (42.4 \pm 4.0)+576[\Delta(m)-0.538]^\circ$.

[93] BENNETT 69 uses measurement of $(\phi_{+-})-(\phi_f)$ of ALFF-STEINBERGER 66B. BENNETT 69 $\phi_{+-} = (34.9 \pm 10.0)+69[\Delta(m)-0.545]^\circ$. $\phi_f = -49.9 \pm 5.4^\circ$.

[94] BOHM 69B $\phi_{+-} = (41.0 \pm 12.0)+479(\Delta(m)-0.526)^\circ$.

[95] FAISSNER 69 error enlarged to include error in regenerator phase. FAISSNER 69 $\phi_{+-} = (49.3 \pm 7.4)+205[\Delta(m)-0.555]^\circ$. $\phi_f = -42.7 \pm 5.0^\circ$.

[96] BENNETT 69 is a re-evaluation of BENNETT 68B.

[97] Old experiments with large errors not included in average.

ϕ_{00}, PHASE OF η_{00}

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
48.5± 3.1 OUR EVALUATION Error includes scale factor of 1.3.				
48.7± 3.3 OUR AVERAGE Error includes scale factor of 1.3.				
47.1± 2.1±1.8		[98] CAROSI 90	CALO	
55.7± 5.8		CHRISTENSON79	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
38.0±25.0	56	[99] WOLFF 71	OSPK	Cu reg., 4γ's
51.0±30.0		[100] CHOLLET 70	OSPK	Cu reg., 4γ's
first quadrant preferred		GOBBI 69B	OSPK	

[98] Systematic error is quadratic sum of experimental systematic errors (±1.0°) and the systematic errors due to the current uncertainties in τ_S (±0.5°) and Δm (±1.4°).

[99] WOLFF 71 uses regenerator phase $\phi_f = -48.2 \pm 3.5^\circ$.

[100] CHOLLET 70 uses regenerator phase $\phi_f = -46.5 \pm 4.4^\circ$.

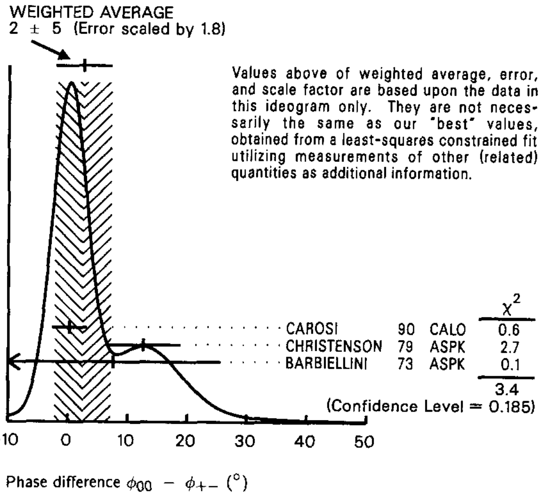
PHASE DIFFERENCE $\phi_{00} - \phi_{+-}$

Test of CPT.

VALUE (°)	DOCUMENT ID	TECN
2.5± 4.5 OUR EVALUATION Error includes scale factor of 1.8.		
2 ± 5 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.		
0.2± 2.6±1.2	[101] CAROSI 90	CALO
12.6± 6.2	[101] CHRISTENSON79	ASPK
7.6±18.0	[102] BARBIELLINI 73	ASPK

[101] Not independent of ϕ_{+-} and ϕ_{00} values. This is taken into account in our evaluation, which consists of a special fit to include correlations, with the errors scaled by the same factors as found for the averages.

[102] Independent of regenerator mechanism, $\Delta(m)$, and lifetimes.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

CHARGE ASYMMETRY IN $\pi^+\pi^-\pi^0$ DECAYS

CP-VIOLATION COEFFICIENT j FOR $K^0_L \to \pi^+\pi^-\pi^0$

Defined at beginning of section "LINEAR COEFFICIENT g FOR $K^0_L \to \pi^+\pi^-\pi^0$ above. See also note on Daltitz plot parameters in $K^\pm$ section and note on CP violation in K^0_L decay above.

VALUE	EVTS	DOCUMENT ID	TECN
0.0011±0.0008 OUR AVERAGE			
0.001 ±0.011	6499	CHO 77	
−0.001 ±0.003	4709	PEACH 77	
0.0013±0.0009	3M	SCRIBANO 70	
0.0 ±0.017	4400	SMITH 70	OSPK
0.001 ±0.004	238k	BLANPIED 68	

NOTE ON $\Delta S = \Delta Q$ IN K^0 DECAYS

The relative amount of $\Delta S \neq \Delta Q$ component present is measured by the parameter x, defined as

$$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu)\ .$$

We list Re$\{x\}$ and Im$\{x\}$ for K_{e3} and $K_{\mu3}$ combined.

$x = (\Delta S = -\Delta Q$ AMPLITUDE) / ($\Delta S = +\Delta Q$ AMPLITUDE)

REAL PART OF x

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.006±0.018 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
$0.10^{+0.18}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \to K^0 \Lambda$
0.04 ± 0.03	4724	NIEBERGALL	74	ASPK	$K^+ p \to K^0 p \pi^+$
-0.008 ± 0.044	1757	FACKLER	73	OSPK	K_{e3} from K^0
-0.03 ± 0.07	1367	HART	73	OSPK	K_{e3} from $K^0 \Lambda$
-0.070 ± 0.036	1079	MALLARY	73	OSPK	K_{e3} from $K^0 \Lambda X$
0.03 ± 0.06	410	[103] BURGUN	72	HBC	$K^+ p \to K^0 p \pi^+$
-0.05 ± 0.09	442	[104] GRAHAM	72	OSPK	$\pi^- p \to K^0 \Lambda$
$0.26^{+0.10}_{-0.14}$	126	MANN	72	HBC	$K^- p \to n \overline{K}^0$
$0.25^{+0.07}_{-0.09}$	252	WEBBER	71	HBC	$K^- p \to n \overline{K}^0$
0.12 ± 0.09	215	[105] CHO	70	DBC	$K^+ d \to K^0 p p$
-0.020 ± 0.025		[106] BENNETT	69	CNTR	Charge asym+ Cu regen.
$0.09^{+0.14}_{-0.16}$	686	LITTENBERG	69	OSPK	$K^+ n \to K^0 p$
$0.09^{+0.07}_{-0.09}$	121	JAMES	68	HBC	$\overline{p} p$
$0.17^{+0.16}_{-0.35}$	116	FELDMAN	67B	OSPK	$\pi^- p \to K^0 \Lambda$
$0.035^{+0.11}_{-0.13}$	196	AUBERT	65	HLBC	K^+ charge exchange
$0.06^{+0.18}_{-0.44}$	152	[107] BALDO-...	65	HLBC	K^- charge exchange
$-0.08^{+0.16}_{-0.28}$	109	[108] FRANZINI	65	HBC	$\overline{p} p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.04^{+0.10}_{-0.13}$	100	[104] GRAHAM	72	OSPK	$K_{\mu 3}$ from $K^0 \Lambda$
-0.13 ± 0.11	342	[104] MANTSCH	72	OSPK	K_{e3} from $K^0 \Lambda$
$0.04^{+0.07}_{-0.08}$	222	[103] BURGUN	71	HBC	$K^+ p \to K^0 p \pi^+$
0.03 ± 0.03		[106] BENNETT	68	CNTR	
0.17 ± 0.10	335	[105] HILL	67	DBC	$K^+ d \to K^0 p p$

[103] BURGUN 72 is a final result which includes BURGUN 71.

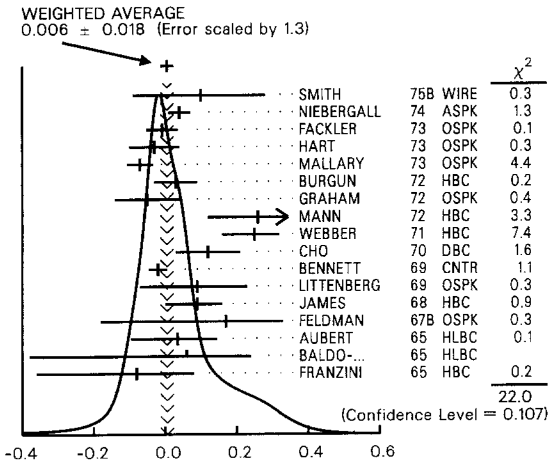
[104] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.

[105] CHO 70 is analysis of unambiguous events in new data and HILL 67.

[106] BENNETT 69 is a reanalysis of BENNETT 68.

[107] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).

[108] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.



Re(x) ($\Delta S = -\Delta Q$ amplitude)

IMAGINARY PART OF x

Assumes $m(K^0_L) - m(K^0_S)$ positive. See Listings above.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.003±0.026 OUR AVERAGE		Error includes scale factor of 1.2.			
$-0.10^{+0.16}_{-0.19}$	79	SMITH	75B	WIRE	$\pi^- p \to K^0 \Lambda$
-0.06 ± 0.05	4724	NIEBERGALL	74	ASPK	$K^+ p \to K^0 p \pi^+$
-0.017 ± 0.060	1757	FACKLER	73	OSPK	K_{e3} from K^0
0.09 ± 0.07	1367	HART	73	OSPK	K_{e3} from $K^0 \Lambda$
$0.107^{+0.092}_{-0.074}$	1079	MALLARY	73	OSPK	K_{e3} from $K^0 \Lambda X$
$0.07^{+0.06}_{-0.07}$	410	[109] BURGUN	72	HBC	$K^+ p \to K^0 p \pi^+$
0.05 ± 0.13	442	[110] GRAHAM	72	OSPK	$\pi^- p \to K^0 \Lambda$
$0.21^{+0.15}_{-0.12}$	126	MANN	72	HBC	$K^- p \to n \overline{K}^0$
0.0 ± 0.08	252	WEBBER	71	HBC	$K^- p \to n \overline{K}^0$
-0.08 ± 0.07	215	[111] CHO	70	DBC	$K^+ d \to K^0 p p$
$-0.11^{+0.10}_{-0.11}$	686	LITTENBERG	69	OSPK	$K^+ n \to K^0 p$
$+0.22^{+0.37}_{-0.29}$	121	JAMES	68	HBC	$\overline{p} p$
0.0 ± 0.25	116	FELDMAN	67B	OSPK	$\pi^- p \to K^0 \Lambda$
$-0.21^{+0.11}_{-0.15}$	196	AUBERT	65	HLBC	K^+ charge exchange
$-0.44^{+0.32}_{-0.19}$	152	[112] BALDO-...	65	HLBC	K^+ charge exchange
$+0.24^{+0.40}_{-0.30}$	109	[113] FRANZINI	65	HBC	$\overline{p} p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.12^{+0.17}_{-0.16}$	100	[110] GRAHAM	72	OSPK	$K_{\mu 3}$ from $K^0 \Lambda$
-0.04 ± 0.16	342	[110] MANTSCH	72	OSPK	K_{e3} from $K^0 \Lambda$
$0.12^{+0.08}_{-0.09}$	222	[109] BURGUN	71	HBC	$K^+ p \to K^0 p \pi^+$
-0.20 ± 0.10	335	[111] HILL	67	DBC	$K^+ d \to K^0 p p$

[109] BURGUN 72 is a final result which includes BURGUN 71.

[110] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.

[111] Footnote 10 of HILL 67 should read +0.58, not −0.58 (private communication) CHO 70 is analysis of unambiguous events in new data and HILL 67.

[112] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).

[113] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.

REFERENCES FOR K^0_L

BRFIT	90			
CAROSI	90	PL B237 303	+Clarke+	(CERN, EDIN, MANZ, ORSA, PISA, SIEG)
ETAFIT	90	RPP		
PATTERSON	90	PRL (to be pub.)	+Barker+	(EFI, ELMT, CHIC, FNAL, PRIN, SACL)
INAGAKI	89	PR D40 1712	+Kobayashi, Sato, Shinkawa+	(KEK, TOKY, KYOT)
MATHIAZHA...	89	PRL 63 2181	Mathiazhagan+	(UCI, UCLA, LANL, PENN, STAN+)
MATHIAZHA...	89B	PRL 63 2185	Mathiazhagan+	(UCI, UCLA, LANL, PENN, STAN+)
PAPADIMITR...	89	PRL 63 28	Papadimitriou, Gibbons+	(EFI, ELMT, FNAL, PRIN, SACL)
SCHAFFNER	89	PR D39 990	+Greenlee, Kasha, Mannelli, Ohl+	(YALE, BNL)
WAHL	89	CERN-EP/89-86, H. Wahl — Rare Decay Symposium, Vancouver		(CERN)
BARR	88	PL B214 303	+Clarke+	(CERN, EDIN, MANZ, ORSA, PISA, SIEG)
BURKHARDT	88	PL B206 169	+	(CERN, DORT, EDIN, MANZ, ORSA, PISA, SIEG)
COUSINS	88	PR D38 2914	+Konigsberg+	(UCLA, LASL, PENN, STAN, TEMP, WILL)
GIBBONS	88	PRL 61 2661	+Papadimitriou+	(EFI, ELMT, FNAL, PRIN, SACL)
GREENLEE	88	PRL 60 893	+Kasha, Mannelli, Mannelli+	(YALE, BNL)
JASTRZEM...	88	PRL 61 2300	Jastrzembski, Larsen, Leipuner, Morse+	(BNL, YALE)
WOODS	88	PRL 60 1695	+Nishikawa+	(EFI, CHIC, FNAL, PRIN, SACL)
BURKHARDT	87	PL B199 139	+	(CERN, DORT, EDIN, MANZ, ORSA, PISA, SIEG)
ARONSON	86	PR D33 3180	+Bernstein, Bock+	(BNL, CHIC, STAN, WISC)
Also	82	PRL 48 1078	Aronson, Bernstein+	(BNL, CHIC, STAN, WISC)
BERNSTEIN	85B	PRL 54 1631	+Bock, Carlsmith, Coupal+	(CHIC, SACL)
BLACK	85	PRL 54 1628	+Blatt, Campbell, Kasha, Mannelli+	(BNL, YALE)
COUPAL	85	PRL 55 566	+Bernstein, Bock, Carlsmith+	(CHIC, SACL)
BALATS	83	SJNP 38 556 Translated from YAF 38 927.	+Berezin, Bogdanov, Vishnevsky+	(ITEP)
ARONSON	82	PRL 48 1078	+Bernstein+	(BNL, CHIC, STAN, WISC)
ARONSON	82B	PRL 48 1306	+Bock, Cheng, Fischbach	(BNL, CHIC, PURD)
Also	82B	PL 116B 73	Fischbach, Cheng+	(PURD, BNL, CHIC)
Also	83	PR D28 476	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
Also	83B	PR D28 495	Aronson, Bock, Cheng+	(BNL, CHIC, PURD)
BIRULEV	81	NP B182 1	+Dzhordzhadze, Genchev, Grigalashvili+	(JINR)
Also	80	SJNP 31 622 Translated from YAF 31 1204.	Birulev, Vestergombi, Genchev+	(JINR)
CARROLL	80B	PRL 44 529	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CARROLL	80C	PL 96B 407	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CARROLL	80D	PRL 44 525	+Chiang, Kycia, Li, Littenberg, Marx+	(BNL, ROCH)
CHO	80	PR D22 2688	+Derrick, Miller, Schlereth, Engler+	(ANL, CMU)
MORSE	80	PR D21 1750	+Leipuner, Larsen, Schmidt, Blatt+	(BNL, YALE)
BIRULEV	79	SJNP 29 778 Translated from YAF 29 1516.	+Vestergombi, Gvakhariya, Genchev+	(JINR)
CHRISTENSON	79	PRL 43 1209	+Goldman, Hummel, Roth+	(NYU)
CHRISTENSON	79B	PRL 43 1212	+Goldman, Hummel, Roth+	(NYU)
HILL	79	NP B153 39	+Sakitt, Snape, Stevens+	(BNL, SLAC, SBER)
SCHMIDT	79	PRL 43 556	+Blatt, Campbell, Grannan+	(YALE, BNL)
SHOCHET	79	PR D19 1965	+Linsay, Grosso-Pilcher, Frisch+	(EFI, ANL)
Also	77	PRL 39 59	Shochet, Linsay, Grosso-Pilcher+	(EFI, ANL)
ENGLER	78B	PR D18 623	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
HILL	78	PL 73B 483	+Sakitt, Snape, Stevens+	(BNL, SLAC, SBER)
CHO	77	PR D15 587	+Derrick, Lissauer, Miller, Engler+	(ANL, CMU)
CLARK	77	PR D15 553	+Field, Holley, Johnson, Kerth, Sah, Shen	(LBL)
Also	75	LBL-4275 Thesis	Shen	(LBL)
DEVOE	77	PR D16 565	+Cronin, Frisch, Grosso-Pilcher+	(EFI, ANL)
DZHORD...	77	SJNP 26 478 Translated from YAF 26 910.	Dzhordzhadze, Kekelidze, Krivokhizhin+	(JINR)
PEACH	77	NP B127 399	+Cameron+	(BGNA, EDIN, GLAS, PISA, RHEL)
BIRULEV	76	SJNP 24 178 Translated from YAF 24 340.	+Vestergombi, Vovenko, Votruba+	(JINR)
COOMBES	76	PRL 37 249	+Flexer, Hall, Kennelly, Kirkby+	(STAN, NYU)
DONALDSON	76	PR D14 2839	+Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
Also	74	SLAC-184 Thesis	Donaldson	(SLAC)
FUKUSHIMA	76	PRL 36 348	+Jensen, Surko, Thaler+	(PRIN, MASA)
GJESDAL	76	NP B109 118	+Kamae, Presser, Steffen+	(CERN, HEID)
REY	76	PR D13 1161	+Cence, Jones, Parker+	(NDAM, HAWA, LBL)
Also	69	PRL 22 1210	Cence, Jones, Peterson, Stenger+	(HAWA, LRL)
BALDO-...	75	NC 25A 688	Baldo-Ceolin, Bobisut, Calimani+	(PADO, WISC)
BLUMENTHAL	75	PRL 34 164	+Frankel, Nagy+	(PENN, CHIC, TEMP)
BUCHANAN	75	PR D11 457	+Drickey, Pepper, Rudnick+	(UCLA, SLAC, JHU)
CARITHERS	75	PRL 34 1244	+Modis, Nygren, Pun+	(COLU, NYU)
SMITH	75B	UCSD Thesis unpub.		(UCSD)
ALBRECHT	74	PL 48B 393		(JINR, BERL, BUDA, PRAG, SERP, SOFI)
BISI	74	PL 50B 504	+Ferrero	(TORI)
BOBISUT	74	LNC 11 646	+Huzita, Mattioli, Puglierin	(PADO)
DONALDSON	74	SLAC-184 Thesis		(SLAC)
Also	76	PR D14 2839	Donaldson, Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
DONALDSON	74B	PR D9 2960	+Fryberger, Hitlin, Liu+	(SLAC, UCSC)
Also	73B	PRL 31 337	Donaldson, Fryberger, Hitlin, Liu+	(SLAC, UCSC)
DONALDSON	74C	PRL 33 554	+Hitlin, Kennelly, Kirkby+	(SLAC)
Also	74	SLAC 184 Thesis	Donaldson	(SLAC)
Also	76	PR D14 2839	Donaldson, Hitlin, Kennelly, Kirkby, Liu+	(SLAC)
FIELD	74	SLAC PUB-1498 unpub.		(SLAC)
GEWENIGER	74	PL 48B 483	+Gjesdal, Kamae, Presser+	(CERN, HEID)
Also	74	CERN Int. 74-4 Thesis	Luth	(HEID)
GEWENIGER	74B	PL 48B 487	+Gjesdal, Presser+	(CERN, HEID)
Also	74B	PL 52B 119	Gjesdal, Presser, Steffen+	(CERN, HEID)
GEWENIGER	74C	PL 52B 108	+Gjesdal, Presser+	(CERN, HEID)

GJESDAL 74 PL 52B 113 +Presser, Kamae, Steffen+ (CERN, HEID)
MESSNER 74 PRL 33 1458 +Franklin, Morse+ (COLO, SLAC, UCSC)
NIEBERGALL 74 PL 49B 103 +Regler, Stier+ (CERN, ORSA, VIEN)
WANG 74 PR D9 540 +Smith, Whatley, Zorn, Hornbostel (UMD, BNL)
WILLIAMS 74 PRL 33 240 +Larsen, Leipuner, Sapp, Sessoms+ (BNL, YALE)
WOO 74 LNC 10 38 +Buchanan, Pepper (UCLA)
ALBROW 73 NP B58 22 +Aston, Barber, Bird, Ellison+ (MCHS, DARE)
ALEXANDER 73B NP B65 301 +Benary, Borowitz, Lande+ (TELA, HEID)
ANIKINA 73 JINR P1 7539 +Balashov, Bannik+ (JINR)
BARBIELLINI 73 PL 43B 529 +Darriulat, Fainberg+ (CERN)
BRANDENB... 73 PR D8 1978 Brandenburg, Johnson, Leith, Loos+ (SLAC)
CARITHERS 73 PRL 31 1025 +Nygren, Gordon+ (COLU, BNL, CERN)
Also 73B PRL 30 1336 Carithers, Modis, Nygren+ (COLU, CERN, NYU)
EVANS 73 PR D7 36 +Muir, Peach, Budagov+ (EDIN, CERN)
Also 69 PRL 23 427 Evans, Golden, Muir, Peach+ (EDIN, CERN)
FACKLER 73 PRL 31 847 +Frisch, Martin, Smoot, Sompayrac (MIT)
FITCH 73 PRL 31 1524 +Hepp, Jensen, Strovink, Webb (PRIN)
Also 72 COO-3072-13 Thesis Webb (PRIN)
GINSBERG 73 PR D8 3887 +Smith (MIT, STON)
HART 73 NP B66 317 +Hutton, Field, Sharp, Blackmore+ (CAVE, RHEL)
MALLARY 73 PR D7 1953 +Binnie, Gallivan, Gomez, Peck, Sciulli+ (CIT)
Also 70 PRL 25 1214 Sciulli, Gallivan, Binnie, Gomez+ (CIT)
MCCARTHY 73 PR D7 687 +Brewer, Budnitz, Entis, Graven, Miller+ (LBL)
Also 72 PL 42B 291 McCarthy, Brewer, Budnitz, Entis, Graven+ (LBL)
Also 71 LBL-550 Thesis McCarthy (LBL)
MESSNER 73 PRL 30 876 +Morse, Nauenberg, Hitlin+ (COLO, SLAC, UCSC)
PEACH 73 PL 43B 441 +Evans, Muir, Hopkins, Krenz (EDIN, CERN, AACH)
SANDWEISS 73 PRL 30 1002 +Sunderland, Turner, Willis, Keller (YALE, ANL)
WILLIAMS 73 PRL 31 1521 +Larsen, Leipuner, Sapp, Sessoms+ (BNL, YALE)
ALBROW 72 NP B44 1 +Aston, Barber, Bird, Ellison+ (MCHS, DARE)
ASHFORD 72 PL 38B 47 +Brown, Masek, Maung, Miller, Ruderman+ (UCSD)
BANNER 72 PRL 28 1597 +Cronin, Hoffman, Knapp, Shochet (PRIN)
BANNER 72B PRL 29 237 +Cronin, Hoffman, Knapp, Shochet (PRIN)
BARMIN 72 SJNP 15 636 +Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 15 1149.
BARMIN 72B SJNP 15 638 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 15 1152.
BURGUN 72 NP B50 194 +Lesquoy, Muller, Pauli+ (SACL, CERN, OSLO)
CARNEGIE 72 PR D6 2335 +Cester, Fitch, Strovink, Sulak (PRIN)
DALLY 72 PL 41B 647 +Innocenti, Seppi+ (SLAC, JHU, UCLA)
Also 70 PL 33B 627 Chien, Cox, Ettlinger+ (JHU, SLAC, UCLA)
Also 71 PL 35B 261 Chien, Cox, Ettlinger+ (JHU, SLAC, UCLA)
GRAHAM 72 NC 9A 166 +Abashian, Jones, Mantsch, Orr+ (ILL, NEAS)
HOLDER 72 PL 40B 141 +Radermacher, Staude+ (AACH, CERN, TORI)
JAMES 72 NP B49 1 +Montanet, Paul, Saetre+ (CERN, SACL, OSLO)
KRENZ 72 LNC 4 213 +Hopkins, Evans, Muir, Peach (AACH, CERN, EDIN)
MANN 72 PR D6 137 +Kofler, Meisner, Hertzbach+ (MASA, BNL, YALE)
MANTSCH 72 NC 9A 160 +Abashian, Graham, Jones, Orr+ (ILL, NEAS)
MCCARTHY 72 PL 42B 291 +Brewer, Budnitz, Entis, Graven+ (LBL)
METCALF 72 PL 40B 703 +Neuhofer, Niebergall+ (CERN, IPN, WIEN)
NEUHOFER 72 PL 41B 642 +Niebergall, Regler, Stier+ (CERN, ORSA, VIEN)
PICCIONI 72 PRL 29 1412 +Coombes, Donaldson, Dorfan, Fryberger+ (SLAC)
Also 74 PR D9 2939 Piccioni, Donaldson+ (SLAC, UCSC, COLO)
VOSBURGH 72 PR D6 1834 +Devlin, Esterling, Goz, Bryman+ (RUTG, MASA)
Also 71 PRL 26 866 Vosburgh, Devlin, Esterling, Goz+ (RUTG, MASA)
BALATS 71 SJNP 13 53 +Berezin, Vishnevsky, Galanina+ (ITEP)
Translated from YAF 13 93.
BARMIN 71 PL 35B 604 +Barylov, Veselovsky, Davidenko+ (ITEP)
BISI 71 PL 36B 533 +Darriulat, Ferrero, Rubbia+ (AACH, CERN, TORI)
BURGUN 71 LNC 2 1169 +Lesquoy, Muller, Pauli+ (SACL, CERN, OSLO)
CARNEGIE 71 PR D4 1 +Cester, Fitch, Strovink, Sulak (PRIN)
CHAN 71 LBL-350 Thesis (LBL)
CHIEN 71 PL 35B 261 +Cox, Ettlinger+ (JHU, SLAC, UCLA)
Also 72 PL 41B 647 Dally, Innocenti, Seppi+ (SLAC, JHU, UCLA)
CHO 71 PR D3 1557 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
CLARK 71 PRL 26 1667 +Elioff, Field, Frisch, Johnson, Kerth+ (LRL)
Also 70 UCRL 19709 Thesis Johnson (LRL)
Also 71 UCRL 20264 Thesis Frisch (LRL)
Also 74 SLAC-PUB-1498 unpub. Field (SLAC)
ENSTROM 71 PR D4 2629 +Akavia, Coombes, Dorfan+ (SLAC, STAN)
Also 70 SLAC-125 Thesis Enstrom (STAN)
JAMES 71 PL 35B 265 +Montanet, Paul, Pauli+ (CERN, SACL, OSLO)
MEISNER 71 PR D3 59 +Mann, Hertzbach, Kofler+ (MASA, BNL, YALE)
PEACH 71 PL 35B 351 +Evans, Muir, Budagov, Hopkins+ (EDIN, CERN)
REPELLIN 71 PL 36B 603 +Wolff, Chollet, Gaillard, Jane+ (ORSA, CERN)
WEBBER 71 PR D3 64 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 68 PRL 21 498 Webber, Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 UCRL 19226 Thesis Webber (LRL)
WOLFF 71 PL 36B 517 +Chollet, Repellin, Gaillard+ (ORSA, CERN)
ALBROW 70 PL 33B 516 +Aston, Barber, Bird, Ellison+ (MCHS, DARE)
ARONSON 70 PRL 25 1057 +Ehrlich, Hofer, Jensen+ (EFI, ILLC, SLAC)
BARMIN 70 PL 33B 377 +Barylov, Borisov, Bysheva+ (ITEP, JINR)
BASILE 70 PR D2 78 +Cronin, Thevent, Turlay, Zylberajch+ (SACL)
BECHERRAWY 70 PR D1 1452 (ROCH)
BUCHANAN 70 PL 33B 623 +Drickey, Rudnick, Shepard+ (SLAC, JHU, UCLA)
Also 71 Private Comm. Cox
BUDAGOV 70 PR D2 815 +Cundy, Myatt, Nezrick+ (CERN, ORSA, EPOL)
Also 68B PL 28B 215 Budagov, Cundy, Myatt+ (CERN, ORSA, EPOL)
CHIEN 70 PL 33B 627 +Cox, Ettlinger+ (JHU, SLAC, UCLA)
Also 71 Private Comm. Cox
CHO 70 PR D1 3031 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
Also 67 PRL 19 668 Hill, Luers, Robinson, Sakitt+ (BNL, CMU)
CHOLLET 70 PL 31B 658 +Gaillard, Jane, Ratcliffe, Repellin+ (CERN)
CULLEN 70 PL 32B 523 +Darriulat, Deutsch, Foeth+ (AACH, CERN, TORI)
DARRIULAT 70 PL 33B 249 +Ferrero, Grosso, Holder+ (AACH, CERN, TORI)
FAISSNER 70 NC 70A 57 +Reithler, Thome, Gaillard+ (AACH, CERN, RHEL)
GINSBERG 70 PR D1 229 (HAIF)
JENSEN 70 Thesis (EFI)
Also 69 PRL 23 615 Jensen, Aronson, Ehrlich, Fryberger+ (EFI, ILL)
MARX 70 PL 32B 219 +Nygren, Peoples+ (COLU, HARV, CERN)
Also 70B Nevis 179 Thesis Marx (COLU)
SCRIBANO 70 PL 32B 224 +Mannelli, Pierazzini, Marx+ (PISA, COLU, HARV)
SMITH 70 PL 32B 133 +Wang, Whatley, Zorn, Hornbostel (UMD, BNL)
WEBBER 70 PR D1 1967 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 UCRL 19226 Thesis Webber (LRL)
BANNER 69 PR 188 2033 +Cronin, Liu, Pilcher (PRIN)
Also 68 PRL 21 1103 Banner, Cronin, Liu, Pilcher (PRIN)
Also 68 PRL 21 1107 Cronin, Liu, Pilcher (PRIN)
BEILLIERE 69 PL 30B 202 +Boutang, Limon (EPOL)
BENNETT 69 PL 29B 317 +Nygren, Saal, Steinberger+ (COLU, BNL)
BOHM 69B NP B9 605 +Darriulat, Grosso, Kaftanov+ (CERN)
Also 68 PL 27B 321 Bohm, Darriulat, Grosso, Kaftanov (CERN)
CENCE 69 PRL 22 1210 +Jones, Peterson, Stenger+ (HAWA, LRL)
EVANS 69 PRL 23 427 +Golden, Muir, Peach+ (EDIN, CERN)
FAISSNER 69 PL 30B 204 +Foeth, Staude, Tittel+ (AACH, CERN, TORI)
FOETH 69 PL 30B 282 +Holder, Radermacher+ (AACH, CERN, TORI)
GAILLARD 69 NC 59A 453 +Galbraith, Hussri, Jane+ (CERN, RHEL, AACH)
Also 67 PRL 18 20 Gaillard, Krienen, Galbraith+ (CERN, RHEL, AACH)
GOBBI 69B PRL 22 685 +Green, Hakel, Moffett, Rosen, Goz+ (ROCH, RUTG)
LITTENBERG 69 PRL 22 654 +Field, Piccioni, Mehlhop+ (UCSD)
LONGO 69 PR 181 1808 +Young, Helland (MICH, UCLA)
PACIOTTI 69 UCRL 19446 Thesis (LRL)
SAAL 69 Thesis (COLU)
ABRAMS 68B PR 176 1603 +Abashian, Mischke, Nefkens, Smith+ (ILL)
ARNOLD 68B PL 28B 56 +Budagov, Cundy, Aubert+ (CERN, ORSA)
ARONSON 68 PRL 20 287 +Chen (PRIN)
Also 69 PR 175 1708 Aronson, Chen (PRIN)
BARTLETT 68 PRL 21 558 +Carnegie, Fitch+ (PRIN)
BASILE 68 PL 26B 542 +Cronin, Thevenet, Turlay+ (SACL)
BASILE 68B PL 28B 58 +Cronin, Thevenet, Turlay, Zylberajch+ (SACL)
BENNETT 68 PL 27B 244 +Nygren, Steinberger+ (COLU, CERN)
BENNETT 68B PL 27B 248 +Nygren, Steinberger+ (COLU, CERN)
BLANPIED 68 PRL 21 1650 +Levit, Engels+ (CASE, HARV, MCGI)
BUDAGOV 68 NC 57A 182 +Burmeister, Cundy+ (CERN, ORSA, IPNP)
Also 68B PL 28B 215 Budagov, Cundy, Myatt+ (CERN, ORSA, EPOL)
JAMES 68 NP B8 365 +Briand (IPNP, CERN)
Also 68 PRL 21 257 Helland, Longo, Young (UCLA, MICH)
KULYUKINA 68 JETP 26 20 +Mestvirishvili, Nyagu+ (JINR)
Translated from ZETF 53 29.
KUNZ 68 PU 46 Thesis (PRIN)
THATCHER 68 PR 174 1674 +Abashian, Abrams, Carpenter+ (ILL)
BENNETT 67 PRL 19 993 +Nygren, Saal, Steinberger+ (COLU)
BOTT-... 67 PL 24B 194 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
BOTT-... 67B PL 24B 438 Bott-Bodenhausen, Debouard, Dekkers+ (CERN)
Also 66B PL 20 212 Bott-Bodenhausen, Debouard, Cassel+ (CERN)
Also 66 PL 23 277 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
CRONIN 67 PRL 18 25 +Kunz, Risk, Wheeler (PRIN)
CRONIN 67B Princeton 11/67 +Kunz, Risk, Wheeler (PRIN)
DEBOUARD 67 NC 52A 662 +Dekkers, Jordan, Mermod+ (CERN)
Also 65 PL 15 58 DeBouard, Dekkers, Scharff+ (CERN, ORSA, MPIM)
DEVLIN 67 PRL 18 54 +Solomon, Shepard, Beall+ (PRIN, UMD)
Also 68 PR 169 1045 Sayer, Beall, Devlin, Shephard+ (UMD, PPA, PRIN)
DORFAN 67 PRL 19 987 +Enstrom, Raymond, Schwartz+ (SLAC, LRL)
FELDMAN 67B PR 155 1611 +Frankel, Highland, Sloan (PENN)
FIRESTONE 67 PRL 18 176 +Kim, Lach, Sandweiss+ (YALE, BNL)
FITCH 67 PR 164 1711 +Roth, Russ, Vernon (PRIN)
GINSBERG 67 PR 162 1570 (MASB)
HAWKINS 67 PR 156 1444 (YALE)
HILL 67 PRL 19 668 +Luers, Robinson, Sakitt+ (BNL, CMU)
HOPKINS 67 PRL 19 185 +Bacon, Eisler (BNL)
KADYK 67 PRL 19 597 +Chan, Drijard, Oren, Sheldon (LRL)
KULYUKINA 67 Preprint +Mestvirishvili, Nyagu+ (JINR)
LOWYS 67 PL 24B 75 +Aubert, Chounet, Pascaud+ (EPOL, ORSA)
MISCHKE 67 PRL 18 138 +Abashian, Abrams+ (ILL)
NEFKENS 67 PR 157 1233 +Abashian, Abrams, Carpenter, Fisher+ (ILL)
SCHMIDT 67 Nevis 160 Thesis (COLU)
TODOROFF 67 Thesis (ILL)
ALFF-... 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
ANIKINA 66 SJNP 2 339 +Vardenga, Zhuravleva+ (JINR)
Translated from YAF 2 471.
AUERBACH 66B PRL 17 980 +Mann, McFarlane, Sciulli (PENN)
BASILE 66 Balaton Conf. +Cronin, Thevenet+ (SACL)
BEHR 66 PL 22 540 +Brisson, Petiau+ (EPOL, MILA, PADO, ORSA)
BELLOTTI 66 NC 45A 737 +Pullia, Baldo-Ceolin+ (MILA, PADO)
BOTT-... 66 PL 23 277 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
CARPENTER 66 PR 142 871 +Abashian, Abrams, Fisher (ILL)
CRIEGEE 66 PRL 17 150 +Fox, Frauenfelder, Hanson, Moscat+ (ILL)
FIRESTONE 66 PRL 16 556 +Kim, Lach, Sandweiss+ (YALE, BNL)
HAWKINS 66 PL 21 238 (YALE)
Also 67 PR 156 1444 Hawkins (YALE)
NEFKENS 66 PL 19 706 +Abashian, Abrams, Carpenter+ (ILL)
ANDERSON 65 PRL 14 475 +Crawford, Golden, Stern, Binford+ (LRL, WISC)
ANIKINA 65 JINR P 2488 +Vardenga, Zhuravleva, Kotlya+ (JINR)
ASTBURY 65 PL 16 80 +Finocchiaro, Beusch+ (CERN, ZURI)
Also 65 HPA 39 523 Pepin
ASTBURY 65B PL 18 175 +Michelini, Beusch+ (CERN, ZURI)
ASTBURY 65C PL 18 178 +Michelini, Beusch+ (CERN, ZURI)
AUBERT 65 PL 17 59 +Behr, Canavan, Chounet+ (EPOL, ORSA)
Also 67 PL 24B 75 Lowys, Aubert, Chounet, Pascaud+ (EPOL, ORSA)
BALDO-... 65 NC 38 684 Baldo-Ceolin, Calimani, Ciampolillo+ (PADO)
FISHER 65 ANL 7130 83 +Abashian, Abrams, Carpenter+ (ILL)
FITCH 65 PRL 15 73 +Roth, Russ, Vernon (PRIN)
FRANZINI 65 PR 140B 127 +Kirsch, Plano+ (COLU, RUTG)
GALBRAITH 65 PRL 14 383 +Manning, Jones+ (AERE, BRIS, RHEL)
GUIDONI 65 Argonne Conf. 49 +Barnes, Foelsche, Ferbel, Firestone+ (BNL, YALE)
HOPKINS 65 Argonne Conf. 67 +Bacon, Eisler (VAND, RUTG)
ADAIR 64 PL 12 67 +Leipuner (YALE, BNL)
ALEKSANYAN 64B Dubna Conf. 2 102 +Alikhanyan, Vartazaryan+ (YERE)
Also 64 JETP 19 1019 Aleksanyan+ (LEBD, MPEI, YERE)
Translated from ZETF 46 1504.
ANIKINA 64 JETP 19 42 +Zhuravleva+ (GEOR, JINR)
Translated from ZETF 46 59.
CHRISTENSON 64 PRL 13 138 +Cronin, Fitch, Turlay (PRIN)
FUJII 64 Dubna Conf. 2 146 +Jovanovich, Turkot+ (BNL, UMD, MIT)
LUERS 64 PR 133B 1276 +Mittra, Willis, Yamamoto (BNL)
DARMON 62 PL 3 57 +Rousset, Six (EPOL)
ASTIER 61 Aix Conf. 1 227 +Blaskovic, Rivet, Siaud+ (EPOL)
FITCH 61 NC 22 1160 +Piroue, Perkins (PRIN, LASL)
GOOD 61 PR 124 1223 +Matsen, Muller, Piccioni+ (LRL)
NYAGU 61 PRL 6 552 +Okonov, Petrov, Rosanova, Rusakov (JINR)
Also 61B JETP 13 1138 Nyagu, Okonov, Petrov, Rozanova+ (JINR)
Translated from ZETF 40 1618.
BARDON 58 ANP 5 156 +Lande, Lederman (COLU, BNL)

OTHER RELATED PAPERS

KLEINKNECHT 76 ARNS 26 1 (DORT)
GINSBERG 73 PR D8 3887 +Smith (MIT, STON)
GINSBERG 70 PR D1 229 (HAIF)
HEUSSE 70 LNC 3 449 +Aubert, Pascaud, Vialle (ORSA)
CRONIN 68C Vienna Conf. 281 (PRIN)
RUBBIA 67 PL 24B 531 +Steinberger (CERN, COLU)
Also 66C PL 23 167 Rubbia, Steinberger (CERN, COLU)
Also 66C PL 20 207 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
Also 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
AUERBACH 66 PR 149 1052 +Dobbs, Lande, Mann, Sciulli+ (PENN)
Also 65 PRL 14 192 Auerbach, Lande, Mann, Sciulli, Uto+ (PENN)
FIRESTONE 66B PRL 17 116 +Kim, Lach, Sandweiss+ (YALE, BNL)
BEHR 65 Argonne Conf. 59 +Brisson, Bellotti+ (EPOL, MILA, PADO)
MESTVIRISH... 65 JINR P 2449 Mestvirishvili, Nyagu, Petrov, Rusakov+ (JINR)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
JOVANOV... 63 BNL Conf. 42 Jovanovich, Fischer, Burris+ (BNL, UMD)

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(892)$ MASS

CHARGED ONLY

This is what appears in the Meson Summary Table.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
891.83±0.24 OUR AVERAGE						
890.4 ±2 ±5	79709 ± 801	[1] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
892.6 ±0.5	5840	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
888.0 ±3.0		NAPIER	84	SPEC	+	200 $\pi^- p \to 2K^0_S X$
891.0 ±1.0		NAPIER	84	SPEC	−	200 $\pi^- p \to 2K^0_S X$
891.7 ±2.1	3700	BARTH	83	HBC	+	70 $K^+ p \to K^0 \pi^+ X$
891.0 ±1.0	4100	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
892.8 ±1.6		AJINENKO	80	HBC	+	32 $K^+ p \to K^0 \pi^+ X$
890.7 ±0.9	1800	AGUILAR-...	78B	HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
886.6 ±2.4	1225	BALAND	78	HBC	±	12 $\overline{p} p \to (K\pi)^\pm X$
891.7 ±0.6	6706	COOPER	78	HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
891.9 ±0.7	9000	[2] PALER	75	HBC	−	14.3 $K^- p \to (K\pi)^- X$
892.2 ±1.5	4404	AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
891.0 ±2.0	1000	CRENNELL	69D	DBC	−	3.9 $K^- N \to K^0 \pi^- X$
894 ±1.0	2886	[3] FRIEDMAN	69	HBC	−	2.1 $K^- p \to \overline{K}^0 \pi^- p$
892 ±2	728	FRIEDMAN	69	HBC	−	2.45 $K^- p \to \overline{K}^0 \pi^- p$
892 ±1.0	3229	FRIEDMAN	69	HBC	−	2.6 $K^- p \to \overline{K}^0 \pi^- p$
892 ±1.6	1027	FRIEDMAN	69	HBC	−	2.7 $K^- p \to \overline{K}^0 \pi^- p$
890 ±3.0	720	BARLOW	67	HBC	±	1.2 $\overline{p} p \to (K^0\pi)^\pm K^\mp$
889 ±3.0	600	BARLOW	67	HBC	±	1.2 $\overline{p} p \to (K^0\pi)^\pm K\pi$
891 ±2.3	620	[3] DEBAERE	67B	HBC	+	3.5 $K^+ p \to K^0 \pi^+ p$
891.0 ±1.2	1700	[4] WOJCICKI	64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

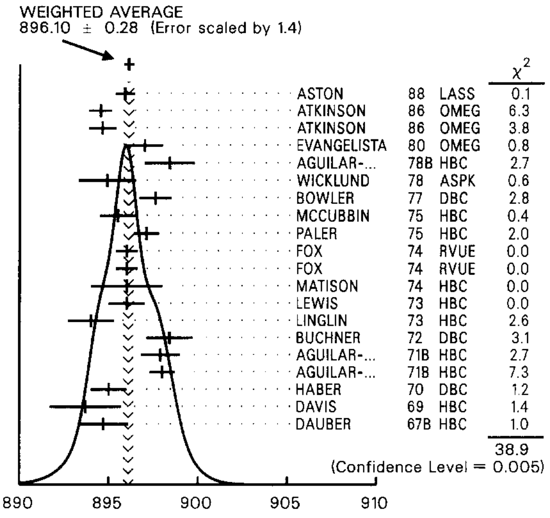
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
890.0 ±2.3	800	[3,4] CLELAND	82	SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
896.0 ±1.1	3200	[3,4] CLELAND	82	SPEC	+	50 $K^+ p \to K^0_S \pi^+ p$
893.0 ±1.0	3600	[3,4] CLELAND	82	SPEC	−	50 $K^+ p \to K^0_S \pi^- p$
896.0 ±1.9	380	DELFOSSE	81	SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
886.0 ±2.3	187	DELFOSSE	81	SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$
894.2 ±2.0	765	[3] CLARK	73	HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
894.3 ±1.5	1150	[3,4] CLARK	73	HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
888 ±2.5	540	[3] DEWIT	68	HBC	−	3 $K^- n \to \overline{K}^0 \pi^- n$
892.0 ±2.6	341	[3] SCHWEING...	68	HBC	−	5.5 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
896.10±0.28 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.					
895.9 ±0.5 ±0.2		ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
894.52±0.63	25k	[2] ATKINSON	86	OMEG		20–70 γp
894.63±0.76	20k	[2] ATKINSON	86	OMEG		20–70 γp
897 ±1	28k	EVANGELISTA	80	OMEG	0	10 $\pi^- p \to K^+ \pi^- (\Lambda,\Sigma)$
898.4 ±1.4	1180	AGUILAR-...	78B	HBC	0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
894.9 ±1.6		WICKLUND	78	ASPK	0	3,4,6 $K^\pm N \to (K\pi)^0 N$
897.6 ±0.9		BOWLER	77	DBC	0	5.4 $K^+ d \to K^+ \pi^- p p$
895.5 ±1.0	3600	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
897.1 ±0.7	22k	[2] PALER	75	HBC	0	14.3 $K^- p \to (K\pi)^0 X$
896.0 ±0.6	10k	FOX	74	RVUE	0	2 $K^- p \to K^- \pi^+ n$
896.0 ±0.6		FOX	74	RVUE	0	2 $K^+ n \to K^+ \pi^- p$
896 ±2		[5] MATISON	74	HBC	0	12 $K^+ p \to K^+ \pi^- \Delta$
896.0 ±1.0	3186	LEWIS	73	HBC	0	2.1–2.7 $K^+ p \to K \pi \pi p$
894.0 ±1.3		[5] LINGLIN	73	HBC	0	2–13 $K^+ p \to K^+ \pi^- \pi^+ p$
898.4 ±1.3	1700	[3] BUCHNER	72	DBC	0	4.6 $K^+ n \to K^+ \pi^- p$
897.9 ±1.1	2934	[3] AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ n$
898.0 ±0.7	5362	[3] AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ \pi^- p$
895.0 ±1.0	4300	[4] HABER	70	DBC	0	3 $K^- N \to K^- \pi^+ X$
893.7 ±2.0	10k	DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$
894.7 ±1.4	1040	[3] DAUBER	67B	HBC	0	2.0 $K^- p \to K^- \pi^+ \pi^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
900.7 ±1.1	5900	BARTH	83	HBC	0	70 $K^+ p \to K^+ \pi^- X$



$K^*(892)^0$ mass (MeV)

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[1] From a partial wave amplitude analysis.
[2] Inclusive reaction. Complicated background and phase-space effects.
[3] Mass errors enlarged by us to $\Gamma/N^{1/2}$. See note.
[4] Number of events in peak reevaluated by us.
[5] From pole extrapolation.

NOTE ON $K^*(892)$ MASSES AND MASS DIFFERENCES

Unrealistically small errors are reported by some experiments. We use simple "realistic" tests for the minimum errors on the determination of mass and width from a sample of N events:

$$\delta_{\min}(m) = \frac{\Gamma}{\sqrt{N}}, \quad \delta_{\min}(\Gamma) = 4\frac{\Gamma}{\sqrt{N}} .$$

(For a detailed discussion, see the 1971 edition of this note.) We consistently increase unrealistic errors before averaging.

$K^*(892)^0$ – $K^*(892)^\pm$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
6.7±1.2 OUR AVERAGE						
7.7±1.7	2980	AGUILAR-...	78B	HBC	±0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
5.7±1.7	7338	AGUILAR-...	71B	HBC	−0	3.9,4.6 $K^- p$
6.3±4.1	283	[6] BARASH	67B	HBC		0.0 $\overline{p} p$

---

[6] Number of events in peak reevaluated by us.

$K^*(892)$ RANGE PARAMETER

VALUE (GeV^{-1})	DOCUMENT ID		TECN	CHG	COMMENT
3.6±0.7 OUR AVERAGE					
12.1±3.2±3.0	[7] BIRD	89	LASS	+	11 $K^- p \to \overline{K}^0 \pi^- p$
3.4±0.7	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[7] From a partial wave amplitude analysis.

$K^*(892)$ WIDTH

CHARGED ONLY

This is what appears in the Meson Summary Table.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
49.8±0.8 OUR FIT						
49.8±0.8 OUR AVERAGE						
45.2±1 ±2	79709 ± 801	[8] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
49.0±2.0	5840	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
56.0±4.0		NAPIER	84	SPEC	−	200 $\pi^- p \to 2K^0_S$ X
51.0±2.0	4100	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
50.5±5.6		AJINENKO	80	HBC	+	32 $K^+ p \to K^0 \pi^+$ X
45.8±3.6	1800	AGUILAR-...	78B	HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
52.0±2.5	6706	[9] COOPER	78	HBC	±	.76 $\overline{p} p \to (K\pi)^\pm$ X
52.1±2.2	9000	[10] PALER	75	HBC	−	14.3 $K^- p \to (K\pi)^-$ X
46.3±6.7	765	[9] CLARK	73	HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
48.2±5.7	1150	[9,11] CLARK	73	HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
54.3±3.3	4404	[9] AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
53 ±4.0	2886	[9] FRIEDMAN	69	HBC	−	2.1 $K^- p \to \overline{K}^0 \pi^- p$
49 ±7.3	728	[9] FRIEDMAN	69	HBC	−	2.45 $K^- p \to \overline{K}^0 \pi^- p$
46 ±3.2	3229	[9] FRIEDMAN	69	HBC	−	2.6 $K^- p \to \overline{K}^0 \pi^- p$
49 ±6.1	1027	[9] FRIEDMAN	69	HBC	−	2.7 $K^- p \to \overline{K}^0 \pi^- p$
46.0±5.0	1700	[9,11] WOJCICKI	64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
42.8±7.1	3700	BARTH	83	HBC	+	70 $K^+ p \to K^0 \pi^+$ X
64.0±9.2	800	[9,11] CLELAND	82	SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
62.0±4.4	3200	[9,11] CLELAND	82	SPEC	+	50 $K^+ p \to K^0_S \pi^+ p$
55.0±4.0	3600	[9,11] CLELAND	82	SPEC	−	50 $K^+ p \to K^0_S \pi^- p$
62.6±3.8	380	DELFOSSE	81	SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
50.5±3.9	187	DELFOSSE	81	SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
50.5±0.6 OUR FIT Error includes scale factor of 1.1.						
50.5±0.6 OUR AVERAGE Error includes scale factor of 1.1.						
50.8±0.8±0.9		ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
46.5±4.3	5900	BARTH	83	HBC	0	70 $K^+ p \to K^+ \pi^-$ X
54 ±2	28k	EVANGELISTA	80	OMEG	0	10 $\pi^- p \to K^+ \pi^- (\Lambda,\Sigma)$
45.9±4.8	1180	AGUILAR-...	78B	HBC	0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
51.2±1.7		WICKLUND	78	ASPK	0	3,4,6 $K^\pm N \to (K\pi)^0 N$
48.9±2.5		BOWLER	77	DBC	0	5.4 $K^+ d \to K^+ \pi^- pp$
48 $^{+3}_{-2}$	3600	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
50.6±2.5	22k	[10] PALER	75	HBC	0	14.3 $K^- p \to (K\pi)^0$ X
47 ±2	10k	FOX	74	RVUE	0	2 $K^- p \to K^- \pi^+ n$
51 ±2		FOX	74	RVUE	0	2 $K^+ n \to K^+ \pi^- p$
46.0±3.3	3186	[9] LEWIS	73	HBC	0	2.1–2.7 $K^+ p \to K\pi\pi p$
51.4±5.0	1700	[9] BUCHNER	72	DBC	0	4.6 $K^+ n \to K^+ \pi^- p$
55.8$^{+4.2}_{-3.4}$	2934	[9] AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ n$
48.5±2.7	5362	AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ \pi^- p$
54.0±3.3	4300	[9,11] HABER	70	DBC	0	3 $K^- N \to K^- \pi^+$ X
53.2±2.1	10k	[9] DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$
44 ±5.5	1040	[9] DAUBER	67B	HBC	0	2.0 $K^- p \to K^- \pi^+ \pi^- p$

[8] From a partial wave amplitude analysis.

[9] Width errors enlarged by us to $4\times\Gamma/N^{1/2}$; see note.

[10] Inclusive reaction. Complicated background and phase-space effects.

[11] Number of events in peak reevaluated by us.

$K^*(892)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K\pi$	~ 100 %	
Γ_2	$(K\pi)^\pm$	(99.899±0.009) %	
Γ_3	$(K\pi)^0$	(99.770±0.020) %	
Γ_4	$K^0\gamma$	(2.30 ±0.20) × 10^{-3}	
Γ_5	$K^\pm\gamma$	(1.01 ±0.09) × 10^{-3}	
Γ_6	$K\pi\pi$	< 7 × 10^{-4}	95%

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 15.2$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i{\cdot}\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{rrr} x_5 & -100 & \\ \Gamma & 17 & -17 \\ & x_2 & x_5 \end{array}$$

	Mode	Rate (MeV)
Γ_2	$(K\pi)^\pm$	49.8 ±0.8
Γ_5	$K^\pm\gamma$	0.050±0.005

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 18.4$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta p_i \delta p_j\right\rangle/(\delta p_i{\cdot}\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{rrr} x_4 & -100 & \\ \Gamma & 14 & -14 \\ & x_3 & x_4 \end{array}$$

	Mode	Rate (MeV)	Scale factor
Γ_3	$(K\pi)^0$	50.4 ±0.6	1.1
Γ_4	$K^0\gamma$	0.117±0.010	

$K^*(892)$ PARTIAL WIDTHS

$\Gamma(K^0\gamma)$ Γ_4

VALUE (keV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
117 ±10 OUR FIT						
116.5± 9.9	584	CARLSMITH	86	SPEC	0	$K^0_L A \to K^0_S \pi^0 A$

$\Gamma(K^{\pm}\gamma)$ Γ_5

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
50 ± 5 OUR FIT				
50 ± 5 OUR AVERAGE				
48.0±11.0	BERG 83	SPEC	−	156 $K^- A \to K\pi A$
51.0± 5.0	CHANDLEE 83	SPEC	+	200 $K^+ A \to K\pi A$

$K^*(892)$ BRANCHING RATIOS

$\Gamma(K^0\gamma)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	CHG	COMMENT
2.30±0.20 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5 ±0.7	CARITHERS 75B	CNTR	0	8–16 $\overline{K}^0 A$

$\Gamma(K^{\pm}\gamma)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	CHG	COMMENT
1.01±0.09 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	95	BEMPORAD 73	CNTR	−	10–16 $K^+ A$

$\Gamma(K\pi\pi)/\Gamma((K\pi)^{\pm})$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.0007	95	JONGEJANS 78	HBC		4 $K^- p \to p\overline{K}^0 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.002		WOJCICKI 64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$

$K^*(892)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
CARLSMITH	86	PRL 56 18	+Bernstein, Peyaud, Turlay	(EFI, SACL)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, LPNP)
NAPIER	84	PL 149B 514	+Chen+	(TUFT, ARIZ, FNAL, FLOR, NDAM+)
BARTH	83	NP B223 296	+Drevermann+	(BRUX, CERN, GENO, MONS+)
BERG	83	Thesis		(ROCH)
CHANDLEE	83	PRL 51 168	+Berg, Cihangir, Collick+	(ROCH, FNAL, MINN)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
AJINENKO	80	ZPHY 5 177	+Barth, Dujardin+	(SERP, LIBH, MONS, SACL)
EVANGELISTA	80	NP B165 383	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
AGUILAR-...	78B	NP B141 101	Aguilar-Benitez+	(MADR, TATA, CERN+)
BALAND	78	NP B140 220	+Grard+	(MONS, BELG, CERN, LOIC, LALO)
COOPER	78	NP B136 365	+Gurtu+	(TATA, CERN, CDEF+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
CARITHERS	75B	PRL 35 349	+Muhlemann, Underwood+	(ROCH, MCGI)
MCCUBBIN	75	NP B86 13	+Lyons	(OXF)
PALER	75	NP B96 1	+Tovey, Shah, Spiro+	(RHEL, SACL, EPOL)
FOX	74	NP B80 403	+Griss	(CIT)
MATISON	74	PR D9 1872	+Galtieri, Alston-Garnjost, Flatte, Friedman+	(LBL)
BEMPORAD	73	NP B51 1	+Beusch, Freudenreich+	(CERN, ETH, LOIC)
CLARK	73	NP B54 432	+Lyons, Radojicic	(OXF)
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)
LINGLIN	73	NP B55 408		(CERN)
BUCHNER	72	NP B45 333	+Dehm, Charriere, Cornet+	(MPIM, CERN, BRUX)
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)
HABER	70	NP B17 289	+Shapira, Alexander+	(REHO, SACL, BGNA, EPOL)
CRENNELL	69D	PRL 22 487	+Karshon, Lai, O'Neall, Scarr	(BNL)
DAVIS	69	PRL 23 1071	+Derenzo, Flatte, Garnjost, Lynch, Solmitz	(LRL)
FRIEDMAN	69	UCRL 18860 Thesis		(LRL)
DEWIT	68	Thesis		(ANIK)
SCHWEING...	68	PR 166 1317	Schweingruber, Derrick, Fields+	(ANL, NWES)
BARASH	67B	PR 156 1399	+Kirsch, Miller, Tan	(COLU)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
DAUBER	67B	PR 153 1403	+Schlein, Slater, Ticho	(UCLA)
DEBAERE	67B	NC 51A 401	+Goldschmidt-Clermont, Henri+	(BRUX, CERN)
WOJCICKI	64	PR 135B 484		(LRL)

OTHER RELATED PAPERS

NAPIER	84	PL 149B 514	+Chen+	(TUFT, ARIZ, FNAL, FLOR, NDAM+)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
BERG	81	PL 98B 119	+Chandlee, Biel+	(ROCH, FNAL, MINN)
LANG	79	PR D19 956	+Mas-Parareda	(GRAZ)
BALAND	78	NP B140 220	+Grard+	(MONS, BELG, CERN, LOIC, LALO)
BALDI	78B	NP B134 365	+Bohringer, Dorsaz, Hungerbuhler+	(GEVA)
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC)
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MONT, CARL, DURH+)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)
MATISON	74	PR D9 1872	+Galtieri, Alston-Garnjost, Flatte, Friedman+	(LBL)
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)
BINGHAM	72	NP B41 1	+Dunwoodie, Drijard+	(International K^+ Collab.)
MERCER	71	NP B32 381	+Antich, Callahan, Chien, Cox+	(JHU)
YUTA	71	PRL 26 1502	+Derrick, Engelmann, Musgrave	(ANL, EFI)
DEWIT	68	Thesis		(ANIK)
FICENEC	68	PR 169 1034	+Hulsizer, Swanson, Trower	(ILL)
FICENEC	68B	PR 175 1725	+Gordon, Trower	(ILL)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
CONFORTO	67	NP B3 469	+Marechal+	(CERN, CDEF, IPNP, LIVP)
DEBAERE	67B	NC 51A 401	+Goldschmidt-Clermont, Henri+	(BRUX, CERN)
ALEXANDER	62	PRL 8 447	+Kalbfleisch, Miller, Smith	(LRL)
ALSTON	62B	CERN Conf. 291	+Ticho, Wojcicki+	(LRL)
ARMENTEROS	62C	CERN conf 295	+Astrer, Montanet+	(CERN, CDEF)
COLLEY	62B	CERN Conf. 315	+Gelfand+	(COLU, RUTG)
ALSTON	61	PRL 6 300	+Alvarez, Eberhard, Good+	(LRL)

$K_1(1270)$
was $Q(1280)$

$I(J^P) = \frac{1}{2}(1^+)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_1(1270)$ MASS

VALUE (MeV)	DOCUMENT ID
1270±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY BEAMS OTHER THAN K MESONS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$1242.0^{+\ 9.0}_{-10.0}$		[1] ASTIER 69	HBC	0	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1294 ±10	310	RODEBACK 81	HBC		4 $\pi^- p \to \Lambda K 2\pi$
1300	40	CRENNELL 72	HBC	0	4.5 $\pi^- p \to \Lambda K 2\pi$
1300	45	CRENNELL 67	HBC	0	6 $\pi^- p \to \Lambda K 2\pi$

[1] This was called the C meson.

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1275.0±10.0	700	GAVILLET 78	HBC	+	4.2 $K^- p \to \Xi^-(K\pi\pi)^+$

PRODUCED BY K BEAMS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1270 ±10	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1276.0	[2] TORNQVIST 82B	RVUE		
~ 1300.0	VERGEEST 79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
1289.0±25.0	[3] CARNEGIE 77	ASPK	±	13 $K^{\pm} p \to (K\pi\pi)^{\mp} p$
~ 1300	BRANDENB... 76	ASPK	±	13 $K^{\pm} p \to (K\pi\pi)^{\pm} p$
~ 1270.0	OTTER 76	HBC	−	10,14,16 $K^- p \to (\overline{K}\pi\pi)^- p$
1260	DAVIS 72	HBC	+	12 $K^+ p$
1234 ±12	FIRESTONE 72B	DBC	+	12 $K^+ d$

[2] From a unitarized quark-model calculation.

[3] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

$K_1(1270)$ WIDTH

VALUE (MeV)	DOCUMENT ID
90±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY BEAMS OTHER THAN K MESONS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$127.0^{+\ 7.0}_{-25.0}$		ASTIER 69	HBC	0	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
66 ±15	310	RODEBACK 81	HBC		4 $\pi^- p \to \Lambda K 2\pi$
60	40	CRENNELL 72	HBC	0	4.5 $\pi^- p \to \Lambda K 2\pi$
60	45	CRENNELL 67	HBC	0	6 $\pi^- p \to \Lambda K 2\pi$

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
75.0±15.0	700	GAVILLET 78	HBC	+	4.2 $K^- p \to \Xi^- K\pi\pi$

PRODUCED BY K BEAMS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
90 ± 8	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 150.0	VERGEEST 79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
150.00±71.0	[4] CARNEGIE 77	ASPK	±	13 $K^{\pm} p \to (K\pi\pi)^{\pm} p$
~ 200	BRANDENB... 76	ASPK	±	13 $K^{\mp} p \to (K\pi\pi)^{\pm} p$
120	DAVIS 72	HBC	+	12 $K^+ p$
188 ±21	FIRESTONE 72B	DBC	+	12 $K^+ d$

[4] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

$K_1(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\rho$	(42 ±6) %
Γ_2	$K_0^*(1430)\pi$	(28 ±4) %
Γ_3	$K^*(892)\pi$	(16 ±5) %
Γ_4	$K\omega$	(11.0±2.0) %
Γ_5	$K f_0(1400)$	(3.0±2.0) %

$K_1(1270)$ PARTIAL WIDTHS

$\Gamma(K\rho)$ Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
57.0±5.0	MAZZUCATO	79	HBC	+	4.2 $K^- p \rightarrow \Xi^-(K\pi\pi)^+$
75.0±6.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K_0^*(1430)\pi)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
26.0±6.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K^*(892)\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
14.0±11.0	MAZZUCATO	79	HBC	+	4.2 $K^- p \rightarrow \Xi^-(K\pi\pi)^+$
2.0± 2.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ Γ_4

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.0±4.00	MAZZUCATO	79	HBC	+	4.2 $K^- p \rightarrow \Xi^-(K\pi\pi)^+$
24.0±3.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K f_0(1400))$ Γ_5

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
22.0±5.0	CARNEGIE	77B	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$K_1(1270)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.42±0.06	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow \overline{K} 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
dominant	RODEBACK	81	HBC	4 $\pi^- p \rightarrow \Lambda K 2\pi$

$\Gamma(K_0^*(1430)\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.28±0.04	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow \overline{K} 2\pi p$

$\Gamma(K^*(892)\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.05	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow \overline{K} 2\pi p$

$\Gamma(K\omega)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.11±0.02	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow \overline{K} 2\pi p$

$\Gamma(K\omega)/\Gamma(K\rho)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	95	RODEBACK	81	HBC	4 $\pi^- p \rightarrow \Lambda K 2\pi$

$\Gamma(K f_0(1400))/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03±0.02	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow \overline{K} 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1270) \rightarrow K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
1.0±0.7	[5] DAUM	81C	CNTR	63 $K^- p \rightarrow \overline{K} 2\pi p$

[5] Average from low and high t data.

$K_1(1270)$ REFERENCES

TORNQVIST	82B	NP B203 268		(HELS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
RODEBACK	81	ZPHY C9 9	+Sjogren+	(CERN, CDEF, MADR, STOH)
MAZZUCATO	79	NP B156 532	+Pennington+	(CERN, ZEEM, NIJM, OXF)
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
GAVILLET	78	PL 76B 517	+Diaz, Dionisi+	(AMST, CERN, NIJM, OXF) JP
CARNEGIE	77	NP B127 509	+Cashmore, Davier, Dunwoodie, Lasinski+	(SLAC)
CARNEGIE	77B	PL 68B 287	+Cashmore, Dunwoodie, Lasinski+	(SLAC)
BRANDENB...	76	PRL 26 703	Brandenburg, Carnegie, Cashmore+	(SLAC) JP
OTTER	76	NP B106 77	+	(AACH, BERL, CERN, LOIC, VIEN, LPNP+) JP
CRENNELL	72	PR D6 1220	+Gordon, Lai, Scarr	(BNL)
DAVIS	72	PR D5 2688	+Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+	(LBL)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)
ASTIER	69	NP B10 65	+Marechal, Montanet+	(CDEF, CERN, IPNP, LIVP) IJP
CRENNELL	67	PRL 19 44	+Kalbfleisch, Lai, Scarr, Schumann	(BNL) I

OTHER RELATED PAPERS

BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
FERNANDEZ	82	ZPHY C16 95	+Aguilar-Benitez+	(MADR, CERN, CDEF, STOH) JP
GAVILLET	82	ZPHY C16 119	+Armenteros+	(CERN, CDEF, PADO, ROMA)
OTTER	81	NP B181 1		(AACH, BERL, LOIC, VIEN, BIRM, BELG, CERN+)
BACON	80	NP B162 189	+Barrey, Butterworth, Ansorge+	(LOIC, CAVE)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
IRVING	80	JP G6 153		(LIVP)
RADFORD	80	NP B167 181	+Brandenburg	(MIT)
BASDEVANT	79	PR D19 246	+Berger	(ANL)
BEUSCH	78	PL 74B 282	+Birman, Konigs, Otter+	(CERN, AACH, ETH) JP
WOHL	78	NP B132 401	+Paler, Chaurand+	(LPNP, RHEL, SACL)
BASDEVANT	76	PRL 37 977	+Berger	(FNAL, ANL)
BOAL	76	PR D14 2998	+Edwards, Kamal, Torgeson	(ALBE)
BOWLER	76	JP G3 775		(OXF)
VERGEEST	76	PL 62B 471	+Engelen, Jongejans+	(AMST, CERN, NIJM, OXF) JP
ANTIPOV	75	NP B86 381	+Ascoli, Busnello, Kienzle+	(SERP, CERN, ILL) JP
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXF, DARE)
DORE	75	LNC 13 265	+Guidoni, Laakso, Marini, Conforto+	(ROMA, RHEL)
DREVILLON	75	PL 55B 245	+Borenstein+	(EPOL, BOHR, CDEF) JP
DUNWOODIE	75	NP B91 189	+Grant+	(CERN, BELG, MONS, MPIM) JP
OTTER	75	NP B84 333	+	(AACH, BERL, CERN, LOIC, VIEN, ATHU+) JP
OTTER	75B	NP B93 365	+Rudolph+	(AACH, BERL, CERN, LOIC, VIEN) JP
OTTER	75C	NP B96 29	+Rudolph+	(AACH, BERL, CERN, LOIC, VIEN) IJP
TOVEY	75	NP B95 109	+Hansen, Borenstein, Borg+	(RHEL, EPOL, SACL) IJP
ANGELOPO...	74	NC 20A 49	Angelopoulos+	(ATHU, ATEN, LIVP, VIEN) JP
BOWLER	74	NP B74 493	+Dainton, Kaddoura, Aitchison	(OXF)
DAVIDSON	74B	PR D9 77	+Chapman, Green, Lys, Roe	(MICH)
DEUTSCH...	74	PL 49B 388	Deutschmann+	(AACH, BERL, CERN, LOIC, VIEN) JP
BARLOUTAUD	73	NP B59 374	+Drevillon, Shah+	(SACL, EPOL, RHEL) JP
BINGHAM	73	NP B52 31	+Farwell+	(LBL, ORSA, BNL, SACL, MILA) JP
DEJONGH	73	NP B58 110	+Cornet, Charriere+	(BRUX, MONS, CERN, MPIM)
JONES	73	NP B52 383		(CERN) JP
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)
WERNER	73	PR D7 1275	+Slattery, Ferbel	(ROCH)
ANDERSON	72	PR D6 1823	+Franklin, Godden, Kopelman, Libby, Tan	(COLO)
BINGHAM	72C	NP B48 589	+Eisenstein, Grard, Herquet+	(CERN, BRUX)
BRANDENB...	72	PRL 28 932	Brandenburg, Johnson, Leith, Loos+	(SLAC)
BRANDENB...	72B	NP B45 397	Brandenburg, Brody, Johnson, Leith+	(SLAC)
FIRESTONE	72	NP B47 348		(CIT)
FRATI	72	PR D6 2361	+Halpern, Hargis, Snape+	(PENN, CINC)
HAATUFT	72	NP B48 78	+Arnold, Haguenauer+	(BERG, STRB, EPOL, MADR)
BARNHAM	71B	NP B25 49	+Colley, Griffiths, Alper+	(BIRM, GLAS, OXF)
DENEGRI	71	NP B28 13	+Antich, Callahan, Carson, Chien, Cox+	(JHU)
FORMAN	71	PR D3 2610	+Gelfand, Leary, Moser, Seidl, Wolfson	(EFI)
GARFINKEL	71	PRL 26 1505	+Holland, Carmony, Lander+	(PURD, UCD)
ABRAMS	70B	PR D1 2433	+Eisenstein, Kim, Marshall, O'Halloran+	(ILL)
ANTICH	70	NP B20 201	+Carson, Chien, Cox, Denegri, Ettlinger+	(JHU)
BOWLER	70	PL 31B 318		(OXF)
FARBER	70	PR D1 78	+Ferbel, Slattery, Yuta	(ROCH)
ALEXANDER	69B	NP B13 503	+Firestone, Goldhaber+	(LRL)
ANDREWS	69	PRL 22 731	+Lach, Ludlam, Sandweiss, Berger+	(YALE, LRL)
BARBARO-...	69	PRL 22 1207	Barbaro-Galtieri, Davis, Flatte+	(LRL)
BETTINI	69	NC 62A 1038	+Cresti, Limentani, Bertanza, Bigi+	(PADO, PISA) I
BISHOP	69	NP B9 403	+Goshaw, Erwin, Walker	(WISC)
CHIEN	69	PL 29B 433	+Malamud, Mellema, Rudnick, Schlein+	(UCLA)
CHUNG	69	PR 182 1443	+Eisner, Bali, Luers	(BNL)
COLLEY	69	NC 59A 519	+Eastwood+	(BIRM, GLAS, LOIC, MPIM, OXF+)
ERWIN	69	NP B9 364	+Walker, Goshaw, Weinberg	(WISC, PRIN, VAND)
FRIEDMAN	69	UCRL 18860 Thesis		(LRL)
WERNER	69	PR 188 2023	+Ammar, Davis, Kropac, Yarger+	(NWES, ANL)
BARTSCH	68B	NP B8 9	+Cocconi+	(AACH, BERL, CERN, LOIC, VIEN)
BOMSE	68	PRL 20 1519	+Borenstein, Callahan, Cole, Cox+	(JHU)
DENEGRI	68	PRL 20 1194	+Callahan, Ettlinger, Gillespie+	(JHU)
BASSOMPIE...	67B	PL 26B 30	Bassompierre, Goldschmidt+	(CERN, BRUX, BIRM) IJP
BERLINGHIERI	67	PRL 18 1087	+Farber, Ferbel, Forman	(ROCH) IJP
DEBAERE	67	NC 49A 374	+Debaisieux, Fast, Filippas+	(CERN, BRUX)
Also	67	Private Comm.	Jongejans	
GOLDHABER	67B	PRL 19 976		(LBL)
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)
Also	66	Private Comm.	Goldhaber	(LRL)
ALMEIDA	65	PL 16 184	+Atherton, Byer, Dornan, Forson+	(CAVE)
ARMENTEROS	64	PL 9 207	+Edwards, D'Andlau+	(CERN, CDEF)
Also	66	PR 145 1095	Barash, Kirsch, Miller, Tan	(COLU)
ARMENTEROS	64B	Dubna Conf. 1 577	+Edwards, D'Andlau+	(CERN, CDEF)
Also	64C	Dubna Conf. 1 617	Armenteros	

$K^*(1370)$
was $K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1370)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1367±54	[1] BIRD 89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1380±21±19	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1420± 7±10	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1474±25	BAUBILLIER 82B	HBC	0	8.25 $K^- p \to \overline{K}^0 2\pi n$
1500±30	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

[1] From a partial wave amplitude analysis.

$K^*(1370)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
114±101	[2] BIRD 89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
176± 52±22	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
240± 18±12	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
275± 65	BAUBILLIER 82B	HBC	0	8.25 $K^- p \to \overline{K}^0 2\pi n$
500±100	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

[2] From a partial wave amplitude analysis.

$K^*(1370)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K^*(892)\pi$	> 40 %	95%
Γ_2	$K\pi$	(6.6±1.3) %	
Γ_3	$K\rho$	< 7 %	95%

$K^*(1370)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.17	95	ASTON 84	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.16	95	ASTON 84	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.066±0.010±0.008	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$K^*(1370)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP

$K_1(1400)$
was $Q(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

$K_1(1400)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1402 ± 7 OUR AVERAGE				
1373 ±14 ±18	[1] ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1392 ±18	BAUBILLIER 82B	HBC	0	8.25 $K^- p \to K^0_S \pi^+ \pi^- n$
1410 ±25	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
1415 ±15	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1404.0±10.0	[2] CARNEGIE 77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1350	[3] TORNQVIST 82B	RVUE		
~ 1400.0	VERGEEST 79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
~ 1400	BRANDENB... 76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
1420	DAVIS 72	HBC	+	12 $K^+ p$
1368 ±18	FIRESTONE 72B	DBC	+	12 $K^+ d$

[1] From partial-wave analysis of $K^0 \pi^+ \pi^-$ system.

[2] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

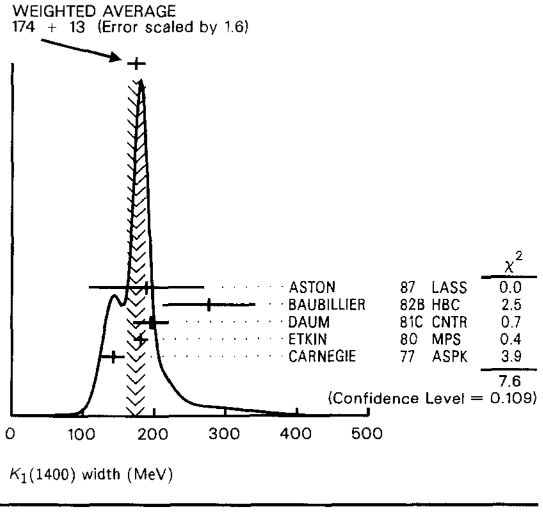
[3] From a unitarized quark-model calculation.

$K_1(1400)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
174 ±13 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			
188 ±54 ±60	[4] ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
276 ±65	BAUBILLIER 82B	HBC	0	8.25 $K^- p \to K^0_S \pi^+ \pi^- n$
195 ±25	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
180 ±10	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
142.0±16.0	[5] CARNEGIE 77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 200.0	VERGEEST 79	HBC	−	4.2 $K^- p \to (\overline{K}\pi\pi)^- p$
~ 160	BRANDENB... 76	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$
80	DAVIS 72	HBC	+	12 $K^+ p$
241 ±30	FIRESTONE 72B	DBC	+	12 $K^+ d$

[4] From partial-wave analysis of $K^0 \pi^+ \pi^-$ system.

[5] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.



$K_1(1400)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	(94 ±6) %
Γ_2	$K\rho$	(3.0±3.0) %
Γ_3	$K f_0(1400)$	(2.0±2.0) %
Γ_4	$K\omega$	(1.0±1.0) %
Γ_5	$K_0^*(1430)\pi$	

$K_1(1400)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ Γ_1

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
117.0±10.0	CARNEGIE	77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2.0±1.0	CARNEGIE	77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ Γ_4

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
23.0±12.0	CARNEGIE	77	ASPK	±	13 $K^\pm p \to (K\pi\pi)^\pm p$

$K_1(1400)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.94±0.06	[6] DAUM	81C	CNTR	63 $K^- p \to \overline{K}2\pi p$

$\Gamma(K\rho)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.03±0.03	[6] DAUM	81C	CNTR	63 $K^- p \to \overline{K}2\pi p$

$\Gamma(K f_0(1400))/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.02±0.02	[6] DAUM	81C	CNTR	63 $K^- p \to \overline{K}2\pi p$

$\Gamma(K\omega)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.01±0.01	[6] DAUM	81C	CNTR	63 $K^- p \to \overline{K}2\pi p$

$\Gamma(K_0^*(1430)\pi)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.00	[6] DAUM	81C	CNTR	63 $K^- p \to \overline{K}2\pi p$

D-wave/S-wave RATIO FOR $K_1(1400) \to K^*(892)\pi$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.04±0.01	[6] DAUM	81C	CNTR	63 $K^- p \to \overline{K}2\pi p$

[6] Average from low and high t data.

$K_1(1400)$ REFERENCES

ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)	
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)	
TORNQVIST	82B	NP B203 268		(HELS)	
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)	
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY)	JP
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)	
CARNEGIE	77	NP B127 509	+Cashmore, Davier, Dunwoodie, Lasinski+	(SLAC)	
BRANDENB...	76	PRL 26 703	Brandenburg, Carnegie, Cashmore+	(SLAC)	JP
DAVIS	72	PR D5 2688	+Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+	(LBL)	
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)	

OTHER RELATED PAPERS

FERNANDEZ	82	ZPHY C16 95	+Aguilar-Benitez+	(MADR, CERN, CDEF, STOH)	
OTTER	81	NP B181 1		(AACH, BERL, LOIC, VIEN, BIRM, BELG, CERN+)	
RODEBACK	81	ZPHY C9 9	+Sjogren+	(CERN, CDEF, MADR, STOH)	
BACON	80	NP B162 189	+Barrey, Butterworth, Ansorge+	(LOIC, CAVE)	
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)	
IRVING	80	JP G6 153		(LIVP)	
RADFORD	80	NP B167 181	+Brandenburg	(MIT)	
BASDEVANT	79	PR D19 246	+Berger	(ANL)	
MAZZUCATO	79	NP B156 532	+Pennington+	(CERN, ZEEM, NIJM, OXF)	
BEUSCH	78	PL 74B 282	+Birman, Konigs, Otter+	(CERN, AACH, ETH)	JP
GAVILLET	78	PL 76B 517	+Diaz, Dionisi+	(AMST, CERN, NIJM, OXF)	JP
WOHL	78	NP B132 401	+Paler, Chaurand+	(LPNP, RHEL, SACL)	
CARNEGIE	77B	PL 68B 287	+Cashmore, Dunwoodie, Lasinski+	(SLAC)	
BASDEVANT	76	PRL 37 977	+Berger	(FNAL, ANL)	
BOAL	76	PR D14 2998	+Edwards, Kamal, Torgeson	(ALBE)	
BOWLER	76	JP G3 775		(OXF)	
OTTER	76	NP B106 77	+	(AACH, BERL, CERN, LOIC, VIEN, LPNP+)	JP
VERGEEST	76	PL 62B 471	+Engelen, Jongejans+	(AMST, CERN, NIJM, OXF)	JP
ANTIPOV	75	NP B86 381	+Ascoli, Busnello, Kienzle+	(SERP, CERN, ILL)	JP
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXF, DARE)	
DORE	75	LNC 13 265	+Guidoni, Laakso, Marini, Conforto+	(ROMA, RHEL)	
DREVILLON	75	PL 55B 245	+Borenstein+	(EPOL, BOHR, CDEF)	JP
DUNWOODIE	75	NP B91 189	+Grant+	(CERN, BELG, MONS, MPIM)	JP
OTTER	75	NP B84 333	+	(AACH, BERL, CERN, LOIC, VIEN, ATHU+)	JP
OTTER	75B	NP B93 365	+Rudolph+	(AACH, BERL, CERN, LOIC, VIEN)	JP
OTTER	75C	NP B96 29	+Rudolph+	(AACH, BERL, CERN, LOIC, VIEN)	IJP
TOVEY	75	NP B95 109	+Hansen, Borenstein, Borg+	(RHEL, EPOL, SACL)	IJP
ANGELOPO...	74	NC 20A 49	Angelopoulos+	(ATHU, ATEN, LIVP, VIEN)	JP
BOWLER	74	NP B74 493	+Dainton, Kaddoura, Aitchison	(OXF)	
DAVIDSON	74B	PR D9 77	+Chapman, Green, Lys, Roe	(MICH)	
DEUTSCH...	74	PL 49B 388	Deutschmann+	(AACH, BERL, CERN, LOIC, VIEN)	JP
BARLOUTAUD	73	NP B59 374	+Drevillon, Shah+	(SACL, EPOL, RHEL)	JP
BINGHAM	73	NP B52 31	+Farwell+	(LBL, ORSA, BNL, SACL, MILA)	JP
DEJONGH	73	NP B58 110	+Cornet, Charriere+	(BRUX, MONS, CERN, MPIM)	
JONES	73	NP B52 383		(CERN)	JP
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)	
WERNER	73	PR D7 1275	+Slattery, Ferbel	(ROCH)	
ANDERSON	72	PR D6 1823	+Franklin, Godden, Kopelman, Libby, Tan	(COLO)	
BINGHAM	72C	NP B48 589	+Eisenstein, Grard, Herquet+	(CERN, BRUX)	
BRANDENB...	72	PRL 28 932	Brandenburg, Johnson, Leith, Loos+	(SLAC)	
BRANDENB...	72B	NP B45 397	Brandenburg, Brody, Johnson, Leith+	(SLAC)	
CRENNELL	72	PR D6 1220	+Gordon, Lai, Scarr	(BNL)	
FIRESTONE	72	NP B47 348		(CIT)	
FRATI	72	PR D6 2361	+Halpern, Hargis, Snape+	(PENN, CINC)	
HAATUFT	72	NP B48 78	+Arnold, Haguenauer+	(BERG, STRB, EPOL, MADR)	
BARNHAM	71B	NP B25 49	+Colley, Griffiths, Alper+	(BIRM, GLAS, OXF)	
DENEGRI	71	NP B28 13	+Antich, Callahan, Carson, Chien, Cox+	(JHU)	
FORMAN	71	PR D3 2610	+Gelfand, Leary, Moser, Seidl, Wolfson	(EFI)	
GARFINKEL	71	PRL 26 1505	+Holland, Carmony, Lander+	(PURD, UCD)	
ABRAMS	70B	PR D1 2433	+Eisenstein, Kim, Marshall, O'Halloran+	(ILL)	
ANTICH	70	NP B20 201	+Carson, Chien, Cox, Denegri, Ettlinger+	(JHU)	
BOWLER	70	PL 31B 318		(OXF)	
FARBER	70	PR D1 78	+Ferbel, Slattery, Yuta	(ROCH)	
ALEXANDER	69B	NP B13 503	+Firestone, Goldhaber+	(LRL)	
ANDREWS	69	PRL 22 731	+Lach, Ludlam, Sandweiss, Berger+	(YALE, LRL)	
ASTIER	69	NP B10 65	+Marechal, Montanet+	(CDEF, CERN, IPNP, LIVP)	IJP
BARBARO-...	69	PRL 22 1207	Barbaro-Galtieri, Davis, Flatte+	(LRL)	
BETTINI	69	NC 62A 1038	+Cresti, Limentani, Bertanza, Bigi+	(PADO, PISA)	I
BISHOP	69	NP B9 403	+Goshaw, Erwin, Walker	(WISC)	
CHIEN	69	PL 29B 433	+Malamud, Mellema, Rudnick, Schlein+	(UCLA)	
CHUNG	69	PR 182 1443	+Eisner, Bali, Luers	(BNL)	
COLLEY	69	NC 59A 519	+Eastwood+	(BIRM, GLAS, LOIC, MPIM, OXF+)	
ERWIN	69	NP B9 364	+Walker, Goshaw, Weinberg	(WISC, PRIN, VAND)	
FRIEDMAN	69	UCRL 18860 Thesis		(LRL)	
WERNER	69	PR 188 2023	+Ammar, Davis, Kropac, Yarger+	(NWES, ANL)	
BARTSCH	68B	NP B8 9	+Cocconi+	(AACH, BERL, CERN, LOIC, VIEN)	
BOMSE	68	PRL 20 1519	+Borenstein, Callahan, Cole, Cox+	(JHU)	
DENEGRI	68	PRL 20 1194	+Callahan, Ettlinger, Gillespie+	(JHU)	
BASSOMPIE...	67B	PL 26B 30	Bassompierre, Goldschmidt+	(CERN, BRUX, BIRM)	IJP
BERLINGHIERI	67	PRL 18 1087	+Farber, Ferbel, Forman	(ROCH)	IJP
CRENNELL	67	PRL 19 44	+Kalbfleisch, Lai, Scarr, Schumann	(BNL)	I
DEBAERE	67	NC 49A 374	+Debaisieux, Fast, Filippas+	(CERN, BRUX)	
Also	67	Private Comm.	Jongejans		
GOLDHABER	67B	PRL 19 976		(LBL)	
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)	
Also	66	Private Comm.	Goldhaber	(LRL)	
ALMEIDA	65	PL 16 184	+Atherton, Byer, Dornan, Forson+	(CAVE)	
ARMENTEROS	64	PL 9 207	+Edwards, D'Andlau+	(CERN, CDEF)	
Also	66	PR 145 1095	Barash, Kirsch, Miller, Tan	(COLU)	
ARMENTEROS	64B	Dubna Conf. 1 577	+Edwards, D'Andlau+	(CERN, CDEF)	
Also	64C	Dubna Conf. 1 617	Armenteros		

$K_0^*(1430)$
was $K_0^*(1350)$
was $\kappa(1350)$

$I(J^P) = \frac{1}{2}(0^+)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_0^*(1430)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1429 ±4±5	ASTON	88	LASS	0	11 $K^- p \to K^-\pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1430	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0\pi^- p$
~ 1425	[1,2] ESTABROOKS	78	ASPK		13 $K^\pm p \to K^\pm\pi^\pm(n,\Delta)$
~ 1450.0	MARTIN	78	SPEC		10 $K^\pm p \to K_S^0\pi p$

[1] Mass defined by pole position.

[2] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
287±10±21	ASTON	88	LASS	0	11 $K^- p \to K^-\pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 200	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0\pi^- p$
200 to 300	[3] ESTABROOKS	78	ASPK		13 $K^\pm p \to K^\pm\pi^\pm(n,\Delta)$

[3] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(93±10) %

$K_0^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.93±0.04±0.09	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$K_0^*(1430)$ REFERENCES

ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, LPNP)
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)

OTHER RELATED PAPERS

TORNQVIST	82	PRL 49 624		(HELS)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
ESTABROOKS	79	PR D19 2678		(CARL)
LANG	79	PR D19 956	+Mas-Parareda	(GRAZ)
BALDI	78B	NP B134 365	+Bohringer, Dorsaz, Hungerbuhler+	(GEVA)
ENGELEN	78	NP B134 14	+Jongejans+	(NIJM, ZEEM, CERN, OXF)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
SPIRO	77	NP B125 162	+Barloutaud, Comber, Paler+	(SACL, RHEL, EPOL)
CHIEN	76	NP B106 355	+Feiock, Lucas, Pevsner, Zoanis	(JHU)
BAKER	75	NP B99 211	+Banerjee, Campbell, Allen+	(LOIC, LOWC)
LAUSCHER	75	NP B86 189	+Otter, Wieczorek+	(ABCLV Collab.)
MORGAN	75	Argonne Conf. 45		(RHEL)
FOX	74	NP B80 403	+Griss	(CIT)
MORGAN	74	PL 51B 71		(RHEL)
CORDS	73	NP B54 109	+Carmony, Lander, Meiere+	(PURD, UCD, IUPU)
GALTIERI	73	LBL-1772	+Matison, Alston-Garnjost, Flatte, Friedman+	(LBL)
LINGLIN	73	NP B55 408		(CERN)
YUTA	73	NP B52 70	+Engelmann, Musgrave, Forman+	(ANL, EFI)
AGUILAR-...	72	PR D6 11	Aguilar-Benitez, Chung, Eisner	(BNL)
BINGHAM	72	NP B41 1	+Dunwoodie, Drijard+	(International K^- Collab.)
BUCHNER	72	NP B45 333	+Dehm, Charriere, Cornet+	(MPIM, CERN, BRUX)
CHUNG	72	PRL 29 1570	+Eisner, Aguilar-Benitez	(BNL)
CRENNELL	72	PR D6 1220	+Gordon, Lai, Scarr	(BNL)
DIEBOLD	72B	Batavia Conf. 3 17		(ANL)
ENGELMANN	72	PR D5 2162	+Musgrave, Forman+	(ANL, EFI)
FRATI	72	PR D6 2361	+Halpern, Hargis, Snape+	(PENN, CINC)
MATISON	72	LBL-1537 Thesis		(LBL)
ROUGE	72	NP B46 29	+Videau, Volte, DeBrion+	(EPOL, SACL)
FIRESTONE	71C	PRL 26 1460	+Goldhaber, Lissauer	(LRL)
MERCER	71	NP B32 381	+Antich, Callahan, Chien, Cox+	(JHU)
YUTA	71	PRL 26 1502	+Derrick, Engelmann, Musgrave	(ANL, EFI)
GOLDBERG	69	PL 30B 434	+Huffer, Laloum+	(SABRE Collab.)
SCHLEIN	69	Argonne Conf. 446		(UCLA)
TRIPPE	68	PL 28B 203	+Chien, Malamud, Mellema, Schlein+	(UCLA)

$K_2^*(1430)$
was $K^*(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

We consider that phase-shift analyses provide more reliable determinations of the mass and width.

$K_2^*(1430)$ MASS

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1425.4± 1.3 OUR AVERAGE	Error includes scale factor of 1.1.					
1423.4± 2 ±3	24809 ± 820	[1] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
1420 ± 4	1587	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
1436 ± 5.5	400	[2,3] CLELAND	82	SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
1430 ± 3.2	1500	[2,3] CLELAND	82	SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
1430 ± 3.2	1200	[2,3] CLELAND	82	SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
1423.0± 5.0	935	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
1428.0± 4.6		[4] MARTIN	78	SPEC	+	10 $K^\pm p \to K_S^0 \pi p$
1423.8± 4.6		[4] MARTIN	78	SPEC	−	10 $K^\pm p \to K_S^0 \pi p$
1420.0± 3.1	1400	AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p$
1425 ± 8.0	225	[2,3] BARNHAM	71C	HBC	+	$K^+ p \to K^0 \pi^+ p$
1416.0±10.0	220	CRENNELL	69D	DBC	−	3.9 $K^- N \to \overline{K}^0 \pi^- N$
1414 ±13.0	60	[2] LIND	69	HBC	+	9 $K^+ p \to K^0 \pi^+ p$
1427.0±12.0	63	[2] SCHWEING...	68	HBC	−	5.5 $K^- p \to \overline{K} \pi N$
1423 ±11.0	39	[2] BASSANO	67	HBC	−	4.6–5.0 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1432.4± 1.3 OUR AVERAGE						
1431.2± 1.8± 0.7		[5] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1434 ± 4 ± 6		[5] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1433 ± 6 ±10		[5] ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
1471 ±12		[5] BAUBILLIER	82B	HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
1428 ± 3		[5] ASTON	81C	LASS	0	11 $K^- p \to K^- \pi^+ n$
1434.0± 2.0		[5] ESTABROOKS	78	ASPK	0	13 $K^\pm p \to p K\pi$
1440.0±10.0		[5] BOWLER	77	DBC	0	5.5 $K^+ d \to K\pi p p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1420.0± 7.0	300	HENDRICK	76	DBC		8.25 $K^+ N \to K^+ \pi N$
1421.6± 4.2	800	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
1420.1± 4.3		[6] LINGLIN	73	HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
1419.1± 3.7	1800	AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p$
1416 ± 6	600	CORDS	71	DBC	0	9 $K^+ n \to K^+ \pi^- p$
1421.1± 2.6	2200	DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- X$

[1] From a partial wave amplitude analysis.

[2] Errors enlarged by us to $\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[3] Number of events in peak re-evaluated by us.

[4] Systematic error added by us.

[5] From phase shift or partial-wave analysis.

[6] From pole extrapolation, using world $K^\mp p$ data summary tape.

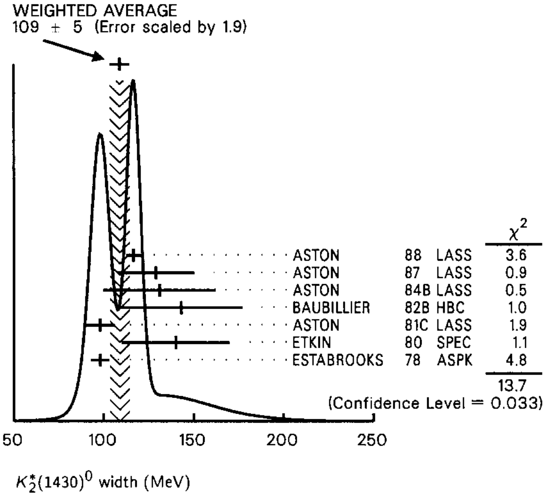
$K_2^*(1430)$ WIDTH

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
98.4± 2.3 OUR FIT						
98.4± 2.4 OUR AVERAGE						
98 ± 4 ±4	24809 ± 820	[7] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
109 ±22	400	[8,9] CLELAND	82	SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
124 ±12.8	1500	[8,9] CLELAND	82	SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
113 ±12.8	1200	[8,9] CLELAND	82	SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
85.0±16.0	935	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
96.5± 3.8		MARTIN	78	SPEC	+	10 $K^\pm p \to K_S^0 \pi p$
97.7± 4.0		MARTIN	78	SPEC	−	10 $K^\pm p \to K_S^0 \pi p$
$94.7^{+15.1}_{-12.5}$	1400	AGUILAR-...	71B	HBC	−	3.9,4.6 $K^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
109 ± 5 OUR AVERAGE	Error includes scale factor of 1.9. See the ideogram below.					
116.5± 3.6± 1.7		[10] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
129 ±15 ±15		[10] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
131 ±24 ±20		[10] ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
143 ±34		[10] BAUBILLIER	82B	HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
98 ± 8		[10] ASTON	81C	LASS	0	11 $K^- p \to K^- \pi^+ n$
140 ±30		[10] ETKIN	80	SPEC	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
98.0± 5.0		[10] ESTABROOKS	78	ASPK	0	13 $K^\pm p \to p K\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
125.0±29.0	300	[8] HENDRICK	76	DBC		8.25 $K^+ N \to K^+ \pi N$
116 ±18	800	MCCUBBIN	75	HBC	0	3.6 $K^- p \to K^- \pi^+ n$
61.0±14.0		[11] LINGLIN	73	HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
$116.6^{+10.3}_{-15.5}$	1800	AGUILAR-...	71B	HBC	0	3.9,4.6 $K^- p$
144 ±24.0	600	[8] CORDS	71	DBC	0	9 $K^+ n \to K^+ \pi^- p$
101 ±10	2200	DAVIS	69	HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$



[7] From a partial wave amplitude analysis.

[8] Errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[9] Number of events in peak re-evaluated by us.

[10] From phase shift or partial-wave analysis.

[11] From pole extrapolation, using world $K^+ p$ data summary tape.

$K_2^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\pi$	(49.7 ± 1.2) %	
Γ_2	$K^*(892)\pi$	(25.2 ± 1.7) %	
Γ_3	$K^*(892)\pi\pi$	(13.0 ± 2.3) %	
Γ_4	$K\rho$	(8.8 ± 0.8) %	S=1.2
Γ_5	$K\omega$	(2.9 ± 0.8) %	
Γ_6	$K^+\gamma$	$(2.4\pm0.5)\times10^{-3}$	
Γ_7	$K\eta$	$(1.4^{+2.8}_{-0.9})\times10^{-3}$	S=1.1
Γ_8	$K\omega\pi$	$<7.2\times10^{-4}$	CL=95%
Γ_9	$K^0\gamma$	$<9\times10^{-4}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 10 branching ratios uses 28 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 19.5$ for 21 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−16						
x_3	−33	−75					
x_4	−12	39	−54				
x_5	−11	−3	−25	−8			
x_6	−1	−1	−1	−1	0		
x_7	−3	−6	−4	−4	−2	0	
Γ	0	0	0	0	0	−13	0
	x_1	x_2	x_3	x_4	x_5	x_6	x_7

	Mode	Rate (MeV)	Scale factor
Γ_1	$K\pi$	48.9 ± 1.7	
Γ_2	$K^*(892)\pi$	24.8 ± 1.7	
Γ_3	$K^*(892)\pi\pi$	12.8 ± 2.3	
Γ_4	$K\rho$	8.7 ± 0.8	1.2
Γ_5	$K\omega$	2.9 ± 0.8	
Γ_6	$K^+\gamma$	0.24 ± 0.04	
Γ_7	$K\eta$	$0.14^{+0.28}_{-0.09}$	1.1

$K_2^*(1430)$ PARTIAL WIDTHS

$\Gamma(K^+\gamma)$ Γ_6

VALUE (keV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
240±40 OUR FIT				
240±45	CIHANGIR 82	SPEC	+	200 $K^+ Z \to Z K^+ \pi^0$, $Z K_S^0 \pi^+$

$\Gamma(K^0\gamma)$ Γ_9

VALUE (keV)	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<84	90	CARLSMITH 87	SPEC	0	60–200 $K_L^0 A \to K_S^0 \pi^0 A$

$K_2^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.497±0.012 OUR FIT				
0.488±0.014 OUR AVERAGE				
0.485±0.006±0.020	[12] ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
0.49 ±0.02	[12] ESTABROOKS 78	ASPK	±	13 $K^\pm p \to p K \pi$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47±0.10	BASSANO 67	HBC	−0	4.6,5.0 $K^- p$
0.45±0.13	[13] BADIER 65C	HBC	−	3 $K^- p$

$\Gamma(K\rho)/\Gamma(K\pi)$ $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.14±0.10	BASSANO 67	HBC	−0	4.6,5.0 $K^- p$
0.14±0.07	[13] BADIER 65C	HBC	−	3 $K^- p$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ Γ_2/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.51±0.04 OUR FIT				
0.48±0.05 OUR AVERAGE				
0.44±0.09	ASTON 84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
0.62±0.19	LAUSCHER 75	HBC	0	10,16 $K^- p \to K^- \pi^+ n$
0.54±0.16	DEHM 74	DBC	0	4.6 $K^+ N$
0.47±0.08	AGUILAR-... 71B	HBC		3.9,4.6 $K^- p$

$\Gamma(K\omega)/\Gamma(K\pi)$ Γ_5/Γ_1

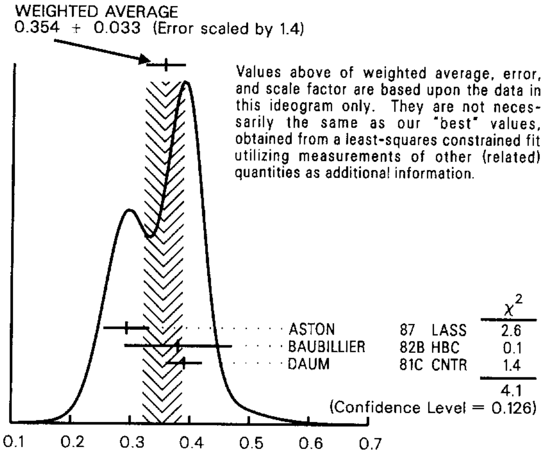
VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.059±0.017 OUR FIT				
0.070±0.035 OUR AVERAGE				
0.05 ±0.04	AGUILAR-... 71B	HBC		3.9,4.6 $K^- p$
0.13 ±0.07	BASSOMPIE... 69	HBC	0	5 $K^+ p$

$\Gamma(K\rho)/\Gamma(K\pi)$ Γ_4/Γ_1

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.178±0.018 OUR FIT Error includes scale factor of 1.2.				
$0.153^{+0.034}_{-0.018}$ OUR AVERAGE				
0.18 ±0.05	ASTON 84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
$0.02\ ^{+0.10}_{-0.02}$	DEHM 74	DBC	0	4.6 $K^+ N$
0.16 ±0.05	AGUILAR-... 71B	HBC		3.9,4.6 $K^- p$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_4/Γ_2

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.351±0.032 OUR FIT Error includes scale factor of 1.5.				
0.354±0.033 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
0.293±0.032±0.020	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
0.38 ±0.09	BAUBILLIER 82B	HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
0.39 ±0.03	DAUM 81C	CNTR		63 $K^- p \to \overline{K} 2\pi p$



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$

$\Gamma(K\omega)/\Gamma(K^*(892)\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.116±0.034 OUR FIT					
0.10 ±0.04	FIELD	67	HBC	−	3.8 $K^- p$

$\Gamma(K\eta)/\Gamma(K^*(892)\pi)$ — Γ_7/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$0.006^{+0.011}_{-0.004}$ OUR FIT					
0.07 ±0.04	FIELD	67	HBC	−	3.8 $K^- p$

$\Gamma(K\eta)/\Gamma(K\pi)$ — Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
$0.0028^{+0.0057}_{-0.0019}$ OUR FIT						
0 ±0.0056		[14] ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.04	95	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$
<0.065		[13] BASSOMPIE...	69	HBC		5.0 $K^+ p$
<0.02		BISHOP	69	HBC		3.5 $K^+ p$

$\Gamma(K^*(892)\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.130±0.023 OUR FIT					
0.12 ±0.04	[15] GOLDBERG	76	HBC	−	3 $K^- p \to p\overline{K}^0\pi\pi\pi$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.26±0.05 OUR FIT					
0.21±0.08	[13,15] JONGEJANS	78	HBC	−	4 $K^- p \to p\overline{K}^0\pi\pi\pi$

$\Gamma(K\omega\pi)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.72	95	0	JONGEJANS	78	HBC	4 $K^- p \to p\overline{K}^0 4\pi$

[12] From phase shift analysis.

[13] Restated by us.

[14] ASTON 88B quote < 0.0092 at CL=95%. We convert this to a central value and 1 sigma error in order to be abe to use it in our constrained fit.

[15] Assuming $\pi\pi$ system has isospin 1, which is supported by the data.

$K_2^*(1430)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ASTON	88B	PL B201 169	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
CARLSMITH	87	PR D36 3502	+Bernstein, Bock, Coupal, Peyaud, Turlay+	(EFI, SACL)
ASTON	84B	NP B247 261	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, LPNP)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
CIHANGIR	82	PL 117B 123	+Berg, Biel, Chandlee+	(FNAL, MINN, ROCH)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ASTON	81C	PL 106B 235	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC)
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MONT, CARL, DURH+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
GOLDBERG	76	LNC 17 253		(HAIF)
HENDRICK	76	NP B112 189	+Vignaud, Burlaud+	(MONS, SACL, LPNP, BELG)
LAUSCHER	75	NP B86 189	+Otter, Wieczorek+	(ABCLV Collab.) JP
MCCUBBIN	75	NP B86 13	+Lyons	(OXF)
DEHM	74	NP B75 47	+Goebel, Wittek+	(MPIM, BRUX, MONS, CERN)
LINGLIN	73	NP B55 408		(CERN)
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)
BARNHAM	71C	NP B28 171	+Colley, Jobes, Griffiths, Hughes+	(BIRM, GLAS)
CORDS	71	PR D4 1974	+Carmony, Erwin, Meiere+	(PURD, UCD, IUPU)
BASSOMPIE...	69	NP B13 189	Bassompierre+	(CERN, BRUX) JP
BISHOP	69	NP B9 403	+Goshaw, Erwin, Walker	(WISC)
CRENNELL	69D	PRL 22 487	+Karshon, Lai, O'Neall, Scarr	(BNL)
DAVIS	69	PRL 23 1071	+Derenzo, Flatte, Garnjost, Lynch, Solmitz	(LRL)
LIND	69	NP B14 1	+Alexander, Firestone, Fu, Goldhaber	(LRL) JP
SCHWEING...	68	PR 166 1317	Schweingruber, Derrick, Fields+	(ANL, NWES)
Also	67	Thesis	Schweingruber	(NWES, NWES)
BASSANO	67	PRL 19 968	+Goldberg, Goz, Barnes, Leitner+	(BNL, SYRA)
FIELD	67	PL 24B 638	+Hendricks, Piccioni, Yager	(UCSD)
BADIER	65C	PL 19 612	+Demoulin, Goldberg+	(EPOL, SACL, AMST)

OTHER RELATED PAPERS

ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP+)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, LPNP)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
ESTABROOKS	78	NP B133 490	+Carnegie+	(MONT, CARL, DURH, SLAC)
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MONT, CARL, DURH+)
ETKIN	76	PRL 36 1482	+Foley, Goldman, Lindenbaum, Kim+	(BNL, CUNY)
VERGEEST	76	PL 62B 471	+Engelen, Jongejans+	(AMST, CERN, NIJM, OXF) JP
OTTER	75	NP B84 333	+	(AACH, BERL, CERN, LOIC, VIEN, ATHU+)
FRATI	72	PR D6 2361	+Halpern, Hargis, Snape+	(PENN, CINC)
ABRAMS	70B	PR D1 2433	+Eisenstein, Kim, Marshall, O'Halloran+	(ILL)
HABER	70	NP B17 289	+Shapira, Alexander+	(REHO, SACL, BGNA, EPOL)
ANTICH	68	PRL 21 1842	+Callahan, Carson, Cox, Denegri+	(JHU)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)
Also	65	PRL 14 401	Hardy, Chung, Dahl, Hess, Kirz, Miller	(LRL)
GOLDHABER	67	PRL 19 972	+Firestone, Shen	(LRL)
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)
Also	66	Private Comm.	Goldhaber	(LRL)
CHUNG	65	PRL 15 325	+Dahl, Hardy, Hess, Jacobs, Kirz	(LRL)
FOCARDI	65	PL 16 351	+Ranzi, Serra+	(BGNA, SACL)
HAQUE	65	PL 14 338	Hague+	
HARDY	65	PRL 14 401	+Chung, Dahl, Hess, Kirz, Miller	(LRL)

$K(1460)$
was $K(1400)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Observed in $K\pi\pi$ partial-wave analysis. Not seen by VERGEEST 79. Wait confirmation.

$K(1460)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1460	DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
~ 1400	[1] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K\pi\pi N$

[1] Coupled mainly to $K f_0(1400)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 260	DAUM	81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$
~ 250	[2] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K\pi\pi N$

[2] Coupled mainly to $K f_0(1400)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$
Γ_3	$K_0^*(1430)\pi$

$K(1460)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ — Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 109	DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K\rho)$ — Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 34	DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K_0^*(1430)\pi)$ Γ_3

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 117	DAUM 81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$K(1460)$ REFERENCES

DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
BRANDENB...	76B	PRL 36 1239	Brandenburg, Carnegie, Cashmore+	(SLAC) JP

OTHER RELATED PAPERS

BARNES	82	PL 116B 365	+Close	(RHEL)
TANIMOTO	82	PL 116B 198		(BIEL)
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)

$K_2(1580)$

was $L(1580)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^-\pi^+\pi^-$ system. Needs confirmation.

$K_2(1580)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 1580	OTTER 79	−	10,14,16 $K^- p$

$K_2(1580)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 110	OTTER 79	−	10,14,16 $K^- p$

$K_2(1580)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	seen
Γ_2	$K_2^*(1430)\pi$	possibly seen

$K_2(1580)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
seen	OTTER 79	HBC	−	10,14,16 $K^- p$

$\Gamma(K_2^*(1430)\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
possibly seen	OTTER 79	HBC	−	10,14,16 $K^- p$

$K_2(1580)$ REFERENCES

OTTER	79	NP B147 1	+Rudolph+	(AACH, BERL, CERN, LOIC, WIEN) JP

$K_1(1650)$

$I(J^P) = \frac{1}{2}(1^+)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems ($K^+\phi$, $K\pi\pi$) reported in partial-wave analysis in the 1600–1900 mass region.

$K_1(1650)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1650±50	FRAME 86	OMEG	+	13 $K^+ p \to \phi K^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1840	ARMSTRONG 83	OMEG	−	18.5 $K^- p \to 3K p$
~ 1800	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$

$K_1(1650)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
150±50	FRAME 86	OMEG	+	13 $K^+ p \to \phi K^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 250	DAUM 81C	CNTR	−	63 $K^- p \to \overline{K} 2\pi p$

$K_1(1650)$ DECAY MODES

	Mode
Γ_1	$K\pi\pi$
Γ_2	$K\phi$

$K_1(1650)$ REFERENCES

FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
ARMSTRONG	83	NP B221 1	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$K^*(1680)$

was $K^*(1790)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1680)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1678±64	[1] BIRD 89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1677±10±32	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1735±10±20	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1800±70	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
~ 1650	ESTABROOKS 78	ASPK	0	13 $K^\pm p \to K^\pm \pi^\pm n$

[1] From a partial wave amplitude analysis.

$K^*(1680)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
454±270	[2] BIRD 89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
205± 16±34	ASTON 88	LASS	0	11 $K^- p \to K^- \pi^+ n$
423± 18±30	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
170± 30	ETKIN 80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
250 to 300	ESTABROOKS 78	ASPK	0	13 $K^\pm p \to K^\pm \pi^\pm n$

[2] From a partial wave amplitude analysis.

$K^*(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(38.7 ± 2.5) %
Γ_2	$K\rho$	$(31.4^{+4.7}_{-2.1})$ %
Γ_3	$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a χ^2 = 3.0 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−36	
x_3	−39	−72
	x_1	x_2

$K^*(1680)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.387±0.026 OUR FIT				
0.388±0.014±0.022	ASTON 88	LASS	0	11 $K^- p \to K^-\pi^+ n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ Γ_1/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
$1.30^{+0.23}_{-0.14}$ OUR FIT				
2.8 ±1.1	ASTON 84	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
$0.81^{+0.14}_{-0.09}$ OUR FIT				
1.2 ±0.4	ASTON 84	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
$1.05^{+0.27}_{-0.11}$ OUR FIT				
$0.97\pm0.09^{+0.30}_{-0.10}$	ASTON 87	LASS	0	11 $K^- p \to \overline{K}^0\pi^+\pi^- n$

$K^*(1680)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
ASTON 84 PL 149B 258 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA) JP
ETKIN 80 PR D22 42 +Foley, Lindenbaum, Kramer+ (BNL, CUNY) JP
ESTABROOKS 78 NP B133 490 +Carnegie+ (MONT, CARL, DURH, SLAC) JP

$K_2(1770)$
was $L(1770)$

$I(J^P) = \frac{1}{2}(2^-)$

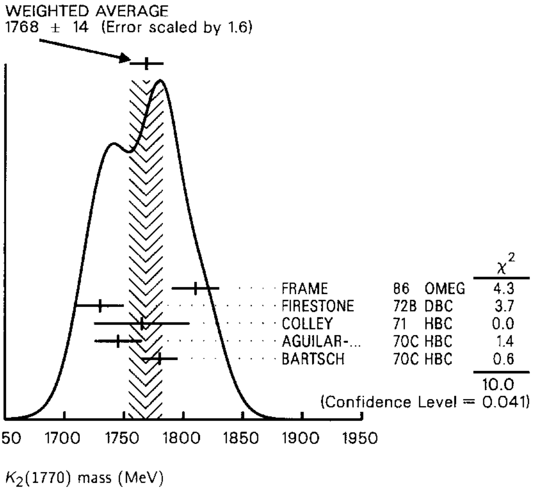
Our latest mini-review on this particle can be found in the 1984 edition.

$K_2(1770)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1768 ±14	**OUR AVERAGE**	Error includes scale factor of 1.6. See the ideogram below.			
1810 ±20		FRAME 86	OMEG	+	13 $K^+ p \to \phi K^+ p$
1730 ±20	306	[1] FIRESTONE 72B	DBC	+	12 $K^+ d$
1765.0±40.0		[2] COLLEY 71	HBC	+	10 $K^+ p \to K 2\pi N$
1745.0±20.0		AGUILAR-... 70C	HBC	−	4.6 $K^- p$
1780.0±15.0		BARTSCH 70C	HBC	−	10.1 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1730		ARMSTRONG 83	OMEG	−	18.5 $K^- p \to 3Kp$
~ 1820		DAUM 81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
1710 ±15	60	CHUNG 74	HBC	−	7.3 $K^- p \to K^-\omega p$
1767 ± 6		BLIEDEN 72	MMS	−	11–16 $K^- p$
1740.0		DENEGRI 71	DBC	−	12.6 $K^- d \to K^- 2\pi d$
1760.0±15.0		LUDLAM 70	HBC	−	12.6 $K^- p$

[1] Produced in conjunction with excited deuteron.

[2] Systematic errors added correspond to spread of different fits.



$K_2(1770)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
136 ±18	**OUR AVERAGE**	Error includes scale factor of 1.2.			
140 ±40		FRAME 86	OMEG	+	13 $K^+ p \to \phi K^+ p$
110 ±50	60	CHUNG 74	HBC	−	7.3 $K^- p \to K^-\omega p$
100 ±26		BLIEDEN 72	MMS	−	11–16 $K^- p$
210 ±30	306	[3] FIRESTONE 72B	DBC	+	12 $K^+ d$
90 ±70		[4] COLLEY 71	HBC	+	10 $K^+ p \to K 2\pi N$
100.0±50.0		AGUILAR-... 70C	HBC	−	4.6 $K^- p$
138.0±40.0		BARTSCH 70C	HBC	−	10.1 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 220		ARMSTRONG 83	OMEG	−	18.5 $K^- p \to 3Kp$
~ 200		DAUM 81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
130.0		DENEGRI 71	DBC	−	12.6 $K^- d \to K^- 2\pi d$
$50.0^{+40.0}_{-20.0}$		LUDLAM 70	HBC	−	12.6 $K^- p$

[3] Produced in conjunction with excited deuteron.

[4] Systematic errors added correspond to spread of different fits.

$K_2(1770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K_2^*(1430)\pi$	dominant
Γ_2	$K^*(892)\pi$	seen
Γ_3	$K f_2(1270)$	seen
Γ_4	$K\phi$	seen
Γ_5	$K\pi\pi$	
Γ_6	$K\omega$	seen

$K_2(1770)$ BRANCHING RATIOS

For discussion of the experimental evidence on other decay modes, see HUGHES 71, SLATTERY 71, EISNER 74.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K\pi\pi)$ Γ_1/Γ_5

$(K_2^*(1430) \to K\pi)$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.2±0.2	AGUILAR-... 70C	HBC	−	4.6 $K^- p$

• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 0.6	DAUM	81C	CNTR		63 $K^- p \to \overline{K} 2\pi p$
~ 1.0	[5] FIRESTONE	72B	DBC	+	12 $K^+ d$
<1.0	COLLEY	71	HBC		10 $K^+ p$
<1.0	BARTSCH	70C	HBC	−	10.1 $K^- p$
1.0	BARBARO-...	69	HBC	+	12.0 $K^+ p$

[5] Produced in conjunction with excited deuteron.

$\Gamma(K^*(892)\pi)/\Gamma(K\pi\pi)$ Γ_2/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.24	DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K f_2(1270))/\Gamma(K\pi\pi)$ Γ_3/Γ_5

$(f_2(1270) \to \pi\pi)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.16	DAUM	81C	CNTR	63 $K^- p \to \overline{K} 2\pi p$

$\Gamma(K\phi)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to K^- \phi N$

$\Gamma(K\omega)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	OTTER	81	HBC	±	8.25,10,16 $K^\pm p$
seen	CHUNG	74	HBC	−	7.3 $K^- p \to K^- \omega p$

$K_2(1770)$ REFERENCES

FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
ARMSTRONG	83	NP B221 1	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
OTTER	81	NP B181 1		(AACH, BERL, LOIC, VIEN, BIRM, BELG, CERN+)
CHUNG	74	PL 51B 413	+Eisner, Protopopescu, Samios, Strand	(BNL)
EISNER	74	Boston Conf. 140		(BNL)
BLIEDEN	72	PL 39B 668	+Finocchiaro, Bowen, Earles+	(STON, NEAS)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)
COLLEY	71	NP B26 71	+Jobes, Kenyon, Pathak, Hughes+	(BIRM, GLAS)
DENEGRI	71	NP B28 13	+Antich, Callahan, Carson, Chien, Cox+	(JHU) JP
HUGHES	71	Bologna Conf. 293		(GLAS)
SLATTERY	71	UR-875-332		(ROCH)
AGUILAR-...	70C	PRL 25 54	Aguilar-Benitez, Barnes, Bassano, Chung+	(BNL)
BARTSCH	70C	PL 33B 186	+Deutschmann+	(AACH, BERL, CERN, LOIC, VIEN)
LUDLAM	70	PR D2 1234	+Sandweiss, Slaughter	(YALE)
BARBARO-...	69	PRL 22 1207	Barbaro-Galtieri, Davis, Flatte+	(LRL)

OTHER RELATED PAPERS

OTTER	79	NP B147 1	+Rudolph+	(AACH, BERL, CERN, LOIC, WIEN) JP
ANTIPOV	75	NP B86 381	+Ascoli, Busnello, Kienzle+	(SERP, CERN, ILL) JP
OTTER	75B	NP B93 365	+Rudolph+	(AACH, BERL, CERN, LOIC, VIEN) JP
DEUTSCH...	74	PL 49B 388	Deutschmann+	(AACH, BERL, CERN, LOIC, VIEN) JP
BARLOUTAUD	73	NP B59 374	+Drevillon, Shah+	(SACL, EPOL, RHEL)
BINGHAM	73	NP B52 31	+Farwell+	(LBL, ORSA, BNL, SACL, MILA)
CHARRIERE	73	NP B51 317	+Drijard, DeBaere+	(CERN, BELG)
ANDERSON	72	PR D6 1823	+Franklin, Godden, Kopelman, Libby, Tan	(COLO)
ANDREWS	69	PRL 22 731	+Lach, Ludlam, Sandweiss, Berger+	(YALE, LRL)
COLLEY	69	NC 59A 519	+Eastwood+	(BIRM, GLAS, LOIC, MPIM, OXF+)
BARTSCH	68B	NP B8 9	+Cocconi+	(AACH, BERL, CERN, LOIC, VIEN)
DENEGRI	68	PRL 20 1194	+Callahan, Ettlinger, Gillespie+	(JHU)
BERLINGHIERI	67	PRL 18 1087	+Farber, Ferbel, Forman	(ROCH) I
CARMONY	67	PRL 18 615	+Hendricks, Lander	(UCSD)
JOBES	67	PL 26B 49	+Bassompierre, DeBaere+	(BIRM, CERN, BRUX)
BARTSCH	66	PL 22 357	+Deutschmann+	(AACH, BERL, CERN+)

$K_3^*(1780)$

was $K^*(1780)$

$I(J^P) = \frac{1}{2}(3^-)$

Our latest mini-review on this particle can be found in the 1984 edition.

$K_3^*(1780)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1774 ± 8 OUR AVERAGE Error includes scale factor of 1.2.						
1720 ±31 ±20	6111 ± 780	[1] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
1781 ± 8 ± 4		[2] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
1740 ±14 ±15		[2] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1779.0±11.0		[3] BALDI	76	SPEC	+	10 $K^+ p \to K^0 \pi^+ p$
1776 ±26		[4] BRANDENB...	76D	ASPK	0	13 $K^\pm p \to K^\pm \pi^\mp N$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1749 ±10		ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$
1780.0± 9.0	300	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
1790.0±15.0		BAUBILLIER	82B	HBC	0	8.25 $K^- p \to K_S^0 2\pi N$
1784.0± 9.0	2060	CLELAND	82	SPEC	±	50 $K^+ p \to K_S^0 \pi^\pm p$
1786 ±15		[5] ASTON	81D	LASS	0	11 $K^- p \to K^- \pi^+ n$
1762.0± 9.0	190	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
1850 ±50		ETKIN	80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^-$
1812.0±28.0		BEUSCH	78	OMEG		10 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1786.0± 8.0		CHUNG	78	MPS	0	6 $K^- p \to K^- \pi^+ n$

[1] From a partial wave amplitude analysis.

[2] From energy-independent partial-wave analysis.

[3] From a fit to Y_6^2 moment. $J^P = 3^-$ found.

[4] Confirmed by phase shift analysis of ESTABROOKS 78, yields $J^P = 3^-$.

[5] From a fit to the Y_6^0 moment.

$K_3^*(1780)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
164 ±17 OUR AVERAGE Error includes scale factor of 1.1.						
187 ±31 ±20	6111 ± 780	[6] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
203 ±30 ± 8		[7] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
171 ±42 ±20		[7] ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
135.0±22.0		[8] BALDI	76	SPEC	+	10 $K^+ p \to K^0 \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
193 $^{+51}_{-37}$		ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$
99.0±30.0	300	BAUBILLIER	84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
~ 130.0		BAUBILLIER	82B	HBC	0	8.25 $K^- p \to K_S^0 2\pi N$
191.0±24.0	2060	CLELAND	82	SPEC	±	50 $K^+ p \to K_S^0 \pi^\pm p$
225 ±60		[9] ASTON	81D	LASS	0	11 $K^- p \to K^- \pi^+ n$
~ 80	190	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
240 ±50		ETKIN	80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^-$
181.0±44.0		[10] BEUSCH	78	OMEG		10 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
96.0±31.0		CHUNG	78	MPS	0	6 $K^- p \to K^- \pi^+ n$
270 ±70		[11] BRANDENB...	76D	ASPK	0	13 $K^\pm p \to K^\pm \pi^\mp N$

[6] From a partial wave amplitude analysis.

[7] From energy-independent partial-wave analysis.

[8] From a fit to Y_6^2 moment. $J^P = 3^-$ found.

[9] From a fit to Y_6^0 moment.

[10] Errors enlarged by us to $4\Gamma/N^{1/2}$; see the note with the $K^*(892)$ mass.

[11] ESTABROOKS 78 find that BRANDENBURG 76D data are consistent with 175 MeV width. Not averaged.

$K_3^*(1780)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\rho$	(45 ±4) %	S=1.4
Γ_2	$K^*(892)\pi$	(27.3±3.2) %	S=1.5
Γ_3	$K\pi$	(19.3±1.0) %	
Γ_4	$K\eta$	(8.0±1.5) %	S=1.4
Γ_5	$K_2^*(1430)\pi$	< 21 %	CL=95%

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 5 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 2.2 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	-84		
x_3	-33	-4	
x_4	-35	-14	26
	x_1	x_2	x_3

$K_3^*(1780)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.66±0.31 OUR FIT Error includes scale factor of 1.5.					
1.52±0.21±0.10	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.42±0.19 OUR FIT Error includes scale factor of 1.4.					
1.09±0.26	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.193±0.010 OUR FIT					
0.188±0.010 OUR AVERAGE					
0.187±0.008±0.008	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
0.19 ±0.02	ESTABROOKS	78	ASPK	0	13 $K^\pm p \to K \pi N$

$\Gamma(K\eta)/\Gamma(K\pi)$ Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.41±0.07 OUR FIT Error includes scale factor of 1.5.					
0.41±0.050	[12] BIRD	89	LASS		11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.50±0.18	ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$

[12] This result supersedes ASTON 88B.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K^*(892)\pi)$ Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.78	95	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_3^*(1780)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)
ASTON 88B PL B201 169 +Awaji, Bienz+ (SLAC, NAGO, CINC, TOKY) JP
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
ASTON 84B NP B247 261 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA)
BAUBILLIER 84B ZPHY C26 37 + (BIRM, CERN, GLAS, MICH, LPNP)
BAUBILLIER 82B NP B202 21 + (BIRM, CERN, GLAS, MSU, LPNP)
CLELAND 82 NP B208 189 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
ASTON 81D PL 99B 502 +Dunwoodie, Durkin, Fieguth+ (SLAC, CARL, OTTA) JP
TOAFF 81 PR D23 1500 +Musgrave, Ammar, Davis, Ecklund+ (ANL, KANS)
ETKIN 80 PR D22 42 +Foley, Lindenbaum, Kramer+ (BNL, CUNY) JP
BEUSCH 78 PL 74B 282 +Birman, Konigs, Otter+ (CERN, AACH, ETH) JP
CHUNG 78 PRL 40 355 +Etkin+ (BNL, BRAN, CUNY, MASA, PENN) JP
ESTABROOKS 78 NP B133 490 +Carnegie+ (MONT, CARL, DURH, SLAC) JP
Also 78B PR D17 658 Estabrooks, Carnegie+ (MONT, CARL, DURH+)
BALDI 76 PL 63B 344 +Boehringer, Dorsaz, Hungerbuhler+ (GEVA) JP
BRANDENB... 76D PL 60B 478 Brandenburg, Carnegie, Cashmore+ (SLAC) JP

OTHER RELATED PAPERS

CLELAND 80 PL 97B 465 +Dorsaz, Martin, Nef+ (PITT, GEVA, LAUS, DURH) JP
ENGELEN 80 NP B167 61 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF) JP
BOWLER 77 NP B126 31 +Dainton, Drake, Williams (OXF) JP
GRASSLER 77B NP B125 189 +Klugow+ (AACH, BERL, CERN, LOIC, VIEN)
AGUILAR-... 73 PRL 30 672 Aguilar-Benitez, Chung, Eisner+ (BNL)
WALUCH 73 PR D8 2837 +Flatte, Friedman (LBL)
CARMONY 71 PRL 27 1160 +Cords, Clopp, Erwin, Meiere+ (PURD, UCD, IUPU)
FIRESTONE 71 PL 36B 513 +Goldhaber, Lissauer, Trilling (LBL)

$K(1830)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of $K^- \phi$ system. Needs confirmation.

$K(1830)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1830.0	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3K p$

$K(1830)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3K p$

$K(1830)$ DECAY MODES

	Mode
Γ_1	$K\phi$

$K(1830)$ REFERENCES

ARMSTRONG 83 NP B221 1 + (BARI, BIRM, CERN, MILA, LPNP, PAVI) JP

$K_0^*(1950)$

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

$K_0^*(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1945±10±20	[1] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[1] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
201±34±79	[2] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[2] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(52±14) %

$K_0^*(1950)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.52±0.08±0.12	[3] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[3] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)

$K_2^*(1980)$

$I(J^P) = \frac{1}{2}(2^+)$

OMITTED FROM SUMMARY TABLE

$K_2^*(1980)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1978±40	241 ± 47	[1] BIRD 89	LASS		$11\ K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1973± 8±25		ASTON 87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

[1] From a partial wave amplitude analysis.

$K_2^*(1980)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
398±47	241 ± 47	[2] BIRD 89	LASS		$11\ K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
373±33±60		ASTON 87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

[2] From a partial wave amplitude analysis.

$K_2^*(1980)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$

$K_2^*(1980)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
1.49±0.24±0.09	ASTON 87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)

$K_4^*(2045)$

was $K^*(2060)$

$I(J^P) = \frac{1}{2}(4^+)$

$K_4^*(2045)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
2045± 9 OUR AVERAGE Error includes scale factor of 1.1.					
2062± 14±13		[1] ASTON 86	LASS	0	$11\ K^- p \to K^- \pi^+ n$
2039± 10	400	[2,3] CLELAND 82	SPEC	±	$50\ K^+ p \to K_S^0 \pi^\pm p$
2070^{+100}_{-40}		[4] ASTON 81C	LASS	0	$11\ K^- p \to K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2079± 7	431	TORRES 86	MPSF		$400\ pA \to 4K\ X$
2088± 20	650	BAUBILLIER 82	HBC	−	$8.25\ K^- p \to K_S^0 \pi^- p$
2115± 46	488	CARMONY 77	HBC	0	$9\ K^+ d \to K^+ \pi\text{'s}\ X$

[1] From a fit to all moments.
[2] From a fit to 8 moments.
[3] Number of events evaluated by us.
[4] From energy-independent partial-wave analysis.

$K_4^*(2045)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
198± 30 OUR AVERAGE					
221± 48±27		[5] ASTON 86	LASS	0	$11\ K^- p \to K^- \pi^+ n$
189± 35	400	[6,7] CLELAND 82	SPEC	±	$50\ K^+ p \to K_S^0 \pi^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
61± 58	431	TORRES 86	MPSF		$400\ pA \to 4K\ X$
170^{+100}_{-50}	650	BAUBILLIER 82	HBC	−	$8.25\ K^- p \to K_S^0 \pi^- p$
240^{+500}_{-100}		[8] ASTON 81C	LASS	0	$11\ K^- p \to K^- \pi^+ n$
300±200		CARMONY 77	HBC	0	$9\ K^+ d \to K^+ \pi\text{'s}\ X$

[5] From a fit to all moments.
[6] From a fit to 8 moments.
[7] Number of events evaluated by us.
[8] From energy-independent partial-wave analysis.

$K_4^*(2045)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(9.9±1.2) %
Γ_2	$K^*(892)\pi\pi$	(9 ±5) %
Γ_3	$K^*(892)\pi\pi\pi$	(7 ±5) %
Γ_4	$\rho K\pi$	(5.7±3.2) %
Γ_5	$\omega K\pi$	(4.9±3.0) %
Γ_6	$\phi K\pi$	(2.8±1.4) %
Γ_7	$\phi K^*(892)$	(1.4±0.7) %

$K_4^*(2045)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.099±0.012	ASTON 88	LASS	0	$11\ K^- p \to K^- \pi^+ n$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.89±0.53	BAUBILLIER 82	HBC	−	$8.25\ K^- p \to p K_S^0 3\pi$

$\Gamma(K^*(892)\pi\pi\pi)/\Gamma(K\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.75±0.49	BAUBILLIER 82	HBC	−	$8.25\ K^- p \to p K_S^0 3\pi$

$\Gamma(\rho K\pi)/\Gamma(K\pi)$ Γ_4/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.58±0.32	BAUBILLIER 82	HBC	−	$8.25\ K^- p \to p K_S^0 3\pi$

$\Gamma(\omega K\pi)/\Gamma(K\pi)$ Γ_5/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.50±0.30	BAUBILLIER 82	HBC	−	$8.25\ K^- p \to p K_S^0 3\pi$

$\Gamma(\phi K\pi)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.028±0.014	[9] TORRES 86	MPSF	$400\ pA \to 4K\ X$

[9] Error determination is model dependent.

$\Gamma(\phi K^*(892))/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.014±0.007	[10] TORRES 86	MPSF	$400\ pA \to 4K\ X$

[10] Error determination is model dependent.

$K_4^*(2045)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, TOKY)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
TORRES 86 PR 34 707 +Lai+ (VPI, ARIZ, FNAL, FSU, NDAM, TUFT+)
BAUBILLIER 82 PL 118B 447 +Burns+ (BIRM, CERN, GLAS, MSU, LPNP)
CLELAND 82 NP B208 189 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
ASTON 81C PL 106B 235 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA) JP
CARMONY 77 PR D16 1251 +Clopp, Lander, Meiere, Yen+ (PURD, UCD, IUPU)

OTHER RELATED PAPERS

ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, TOKY)
BROMBERG 80 PR D22 1513 +Haggerty, Abrams, Dzierba (CIT, FNAL, ILLC, IND)
CLELAND 80 PL 97B 465 +Dorsaz, Martin, Nef+ (PITT, GEVA, LAUS, DURH) JP
CARMONY 71 PRL 27 1160 +Cords, Clopp, Erwin, Meiere+ (PURD, UCD, IUPU)

$K_2(2250)$
was $K(2250)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems reported in the 2100–2300 MeV region, as well as enhancements seen in the antihyperon-nucleon system, either in the mass spectra or in the $J^P = 2^-$ wave.

$K_2(2250)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2247 ±17 OUR AVERAGE						
2200.0±40.0		[1] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
2235 ±50		[1] BAUBILLIER	81	HBC	−	8 $K^- p \to \Lambda \bar{p} X$
2260 ±20		[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2147 ± 4	37	CHLIAPNIK...	79	HBC	+	32 $K^+ p \to \bar{\Lambda} p X$
2240 ±20	20	LISSAUER	70	HBC		9 $K^+ p$

[1] $J^P = 2^-$ from moments analysis.

$K_2(2250)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
180 ±30 OUR AVERAGE		Error includes scale factor of 1.4.				
150.0±30.0		[2] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
210 ±30		[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 200		[2] BAUBILLIER	81	HBC	−	8 $K^- p \to \Lambda \bar{p} X$
~ 40	37	CHLIAPNIK...	79	HBC	+	32 $K^+ p \to \bar{\Lambda} p X$
80 ±20	20	LISSAUER	70	HBC		9 $K^+ p$

[2] $J^P = 2^-$ from moments analysis.

$K_2(2250)$ DECAY MODES

	Mode
Γ_1	$K \pi \pi$
Γ_2	$\Lambda \bar{p}$

$K_2(2250)$ REFERENCES

ARMSTRONG	83C	NP B227 365	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
BAUBILLIER	81	NP B183 1	+	(BIRM, CERN, GLAS, MSU, LPNP) JP
CLELAND	81	NP B184 1	+Nef, Martin+	(PITT, GEVA, LAUS, DURH) JP
CHLIAPNIK...	79	NP B158 253	Chliapnikov, Gerdyukov+	(CERN, BELG, MONS)
LISSAUER	70	NP B18 491	+Alexander, Firestone, Goldhaber	(LBL)

OTHER RELATED PAPERS

ALEXANDER	68B	PRL 20 755	+Firestone, Goldhaber, Shen	(LRL)

$K_3(2320)$
was $K(2320)$

$I(J^P) = \frac{1}{2}(3^+)$

OMITTED FROM SUMMARY TABLE

This entry contains enhancements seen in the $J^P = 3^+$ wave of the antihyperon-nucleon system.

$K_3(2320)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2324 ±24 OUR AVERAGE					
2330.0±40.0	[1] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
2320.0±30.0	[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$

[1] $J^P = 3^+$ from moments analysis.

$K_3(2320)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
150.0±30.0	[2] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda \bar{p} X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p} X$

[2] $J^P = 3^+$ from moments analysis.

$K_3(2320)$ DECAY MODES

	Mode
Γ_1	$\Lambda \bar{p}$

$K_3(2320)$ REFERENCES

ARMSTRONG	83C	NP B227 365	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
CLELAND	81	NP B184 1	+Nef, Martin+	(PITT, GEVA, LAUS, DURH)

$K_5^*(2380)$

$I(J^P) = \frac{1}{2}(5^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial wave analysis of the $K^- \pi^+$ system. Needs confirmation.

$K_5^*(2380)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2382±14±19	[1] ASTON	86	LASS	0	11 $K^- p \to K^- \pi^+ n$

[1] From a fit to all the moments.

$K_5^*(2380)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
178±37±32	[2] ASTON	86	LASS	0	11 $K^- p \to K^- \pi^+ n$

[2] From a fit to all the moments.

$K_5^*(2380)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K \pi$	(6.1±1.2) %

$K_5^*(2380)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.061±0.012	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

$K_5^*(2380)$ REFERENCES

ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
ASTON	86	PL B180 308	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)

$K_4(2500)$
was $K(2500)$

$I(J^P) = \frac{1}{2}(4^-)$

OMITTED FROM SUMMARY TABLE

This entry contains enhancements seen in the $J^P = 4^-$ wave of the antihyperon-nucleon system.

$K_4(2500)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2490.0±20.0	[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p}$

[1] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250.0	[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda \bar{p}$

[2] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ DECAY MODES

	Mode
Γ_1	$\Lambda \bar{p}$

$K_4(2500)$ REFERENCES

CLELAND	81	NP B184 1	+Nef, Martin+	(PITT, GEVA, LAUS, DURH)

CHARMED MESONS
$(C = \pm 1)$
$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}u$, $D^- = \overline{c}d$, similarly for D^*'s

$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

$D^{\pm}$ MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1869.3± 0.4 OUR FIT						
1869.4± 0.5 OUR AVERAGE						
1870.0± 0.5±1.0	317	BARLAG	90C	CCD		π^- Cu 230 GeV
1875 ±10	9	ADAMOVICH	87	EMUL		Photoproduction
1863 ± 4		DERRICK	84	HRS		E^{ee}_{cm}= 29 GeV
1869.4± 0.6		[1] TRILLING	81	RVUE	±	E^{ee}_{cm}= 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1860 ±16	6	ADAMOVICH	84	EMUL		Photoproduction
1868.4± 0.5		[1] SCHINDLER	81	MRK2	±	E^{ee}_{cm}= 3.77 GeV
1874 ± 5		GOLDHABER	77	MRK1	±	D^0, D^+ recoil spectra
1868.3± 0.9		[1] PERUZZI	77	MRK1	±	E^{ee}_{cm}= 3.77 GeV
1874 ±11		PICCOLO	77	MRK1	±	E^{ee}_{cm}= 4.03, 4.41 GeV
1876 ±15	50	PERUZZI	76	MRK1	±	$K^{\mp}\pi^{\pm}\pi^{\pm}$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted.

$D^{\pm}$ MEAN LIFE

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
10.62±0.28 OUR AVERAGE					
$10.5\ ^{+0.77}_{-0.72}$	317	[2] BARLAG	90C	CCD	π^- Cu 230 GeV
$9.2\ ^{+1.7}_{-1.3}\ \pm1.6$		AVERILL	89	HRS	E^{ee}_{cm}= 29 GeV
10.5 ±0.8 ±0.7		ALBRECHT	88I	ARG	E^{ee}_{cm}= 10 GeV
10.90±0.30±0.25	3000	RAAB	88	SILI	Photoproduction
$5.0\ ^{+1.5}_{-1.0}\ \pm1.9$	27	ADAMOVICH	87	EMUL	Photoproduction
$11.2\ ^{+1.4}_{-1.1}$	149	AGUILAR-...	87D	HYBR	$\pi^- p$ and pp
$10.9\ ^{+1.9}_{-1.5}$	59	BARLAG	87B	SILI	K^- and π^- 200 GeV
11.4 ±1.6 ±0.7	526	CSORNA	87	CLEO	E^{ee}_{cm}= 10 GeV
10.9 ±1.4	74	[3] PALKA	87B	SILI	π Be 200 GeV
$8.6\ \pm1.3\ ^{+0.7}_{-0.3}$	48	ABE	86	HYBR	SLAC γp 20 GeV
$8.9\ ^{+3.8}_{-2.7}\ \pm1.3$	23	GLADNEY	86	MRK2	E^{ee}_{cm}= 29 GeV
$11.1\ ^{+4.4}_{-2.9}$	28	USHIDA	86	EMUL	ν wideband
$10.6\ ^{+3.6}_{-2.4}$	28	BAILEY	85	SILI	π^- Be 200 GeV
$9.5\ ^{+3.1}_{-1.9}$	70	[4] ALBINI	82	SILI	CERN γSi
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$6.3\ ^{+5.0}_{-2.7}$	7	BADERT...	83	HYBR	CERN π^- N
$2.2\ ^{+2.3}_{-1.1}$	1	[5] BALLAGH	81	HYBR	FNAL 15-ft, ν He-^{2}H
$2.5\ ^{+2.2}_{-1.1}$	4	ALLASIA	80	EMUL	ν wideband
$10.4\ ^{+3.9}_{-2.9}$		[6] BACINO	80	DLCO	E^{ee}_{cm}= 3.77 GeV

[2] BARLAG 90C estimate systematic error to be negligible.
[3] PALKA 87B observed this in $D^+ \rightarrow K^*(892)e\nu$.
[4] ALBINI 82 assumes D momentum is 1/2 beam momentum.
[5] BALLAGH 81 value quoted here assumes that all dilepton events contain D^0 or D^+, each with equal numbers of semileptonic decays.
[6] Uses theoretical rate $D \rightarrow (K e \nu) = 1.4 \times 10^{11}$ s^{-1}.

D^+ DECAY MODES

D^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes		
Γ_1	e^+ anything	$(19.2^{+1.7}_{-1.4})$ %	
Γ_2	K^- anything	(16.2± 3.5) %	
Γ_3	K^+ anything	(6.6± 2.8) %	
Γ_4	K^0 any + $\overline{K}^0$ any	(48 ±15) %	
Γ_5	η anything	[a] < 13 %	CL=90%
Γ_6	μ^+ anything		
Γ_7	$\mu^+\mu^-$ anything		
	Leptonic and semileptonic modes		
Γ_8	$\mu^+\nu_\mu$	< 7.2 $\times 10^{-4}$	CL=90%
Γ_9	$\overline{K}^0\mu^+\nu_\mu$		
Γ_{10}	$K^-\pi^+e^+\nu_e$	< 5.7 %	CL=90%
Γ_{11}	$\overline{K}^*(892)^0 e^+\nu_e$ $\times$ B($\overline{K}^*(892)^0 \rightarrow K^-\pi^+$)	(2.5± 0.5) %	
Γ_{12}	$K^-\pi^+e^+\nu_e$ (non-resonant)	< 7 $\times 10^{-3}$	CL=90%
Γ_{13}	$\overline{K}^0\pi^+\pi^-e^+\nu_e$	$(2.2^{+5.0}_{-0.7})$ %	
Γ_{14}	$K^-\pi^+\pi^0e^+\nu_e$	$(4.4^{+5.2}_{-1.5})$ %	
Γ_{15}	$\pi^+\pi^-e^+\nu_e$	< 5.7 %	CL=90%
	A fraction of the following mode has already appeared above.		
Γ_{16}	$\overline{K}^*(892)^0 e^+\nu_e$	(3.8± 0.7) %	
	Hadronic modes with one K		
Γ_{17}	$\overline{K}^0\pi^+$	(2.8± 0.4) %	S=1.1
Γ_{18}	$\overline{K}^0\pi^+\pi^0$	(8.3± 1.9) %	
	In the fit as $\frac{1}{3}\Gamma_{30} + \Gamma_{20} + \Gamma_{21}$, where $\frac{1}{3}\Gamma_{30} = \Gamma_{19}$.		
Γ_{19}	$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^*(892)^0 \rightarrow \overline{K}^0\pi^0$)	(0.6± 0.3) %	
Γ_{20}	$\overline{K}^0\rho^+$	(6.6± 1.7) %	
Γ_{21}	$\overline{K}^0\pi^+\pi^0$ (non-resonant)	$(1.2^{+1.0}_{-0.7})$ %	
Γ_{22}	$K^-\pi^+\pi^+$	(7.7± 1.0) %	S=1.2
	In the fit as $\frac{2}{3}\Gamma_{30} + \Gamma_{24}$, where $\frac{2}{3}\Gamma_{30} = \Gamma_{23}$.		
Γ_{23}	$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^*(892)^0 \rightarrow K^-\pi^+$)	(1.1± 0.5) %	
Γ_{24}	$K^-\pi^+\pi^+$ (non-resonant)	(6.6± 1.1) %	S=1.2
Γ_{25}	$\overline{K}^0\pi^+\pi^+\pi^-$	(7.0± 1.5) %	S=1.2
Γ_{26}	$K^-\pi^+\pi^+\pi^0$	(4.2± 1.0) %	S=1.1
Γ_{27}	$\overline{K}^0\pi^+\pi^+\pi^-\pi^0$	$(4.4^{+5.2}_{-1.5})$ %	
Γ_{28}	$K^-\pi^+\pi^+\pi^0\pi^0$	$(2.2^{+5.0}_{-0.9})$ %	
Γ_{29}	$K^-\pi^+\pi^+\pi^+\pi^-$	< 5 %	CL=90%
	A fraction of the following mode has already appeared above.		
Γ_{30}	$\overline{K}^*(892)^0\pi^+$	(1.7± 0.8) %	
	Pionic modes		
Γ_{31}	$\pi^+\pi^0$	< 5.3 $\times 10^{-3}$	CL=90%
Γ_{32}	$\pi^+\pi^+\pi^-$	(2.8± 0.7) $\times 10^{-3}$	
Γ_{33}	$\rho^0\pi^+$	< 1.2 $\times 10^{-3}$	CL=90%
Γ_{34}	$\pi^+\pi^+\pi^-$ (non-resonant)	(2.1± 0.6) $\times 10^{-3}$	
Γ_{35}	$\pi^+\pi^+\pi^-\pi^0$	< 3.1 %	CL=90%
Γ_{36}	$\eta\pi^+$ $\times$ B($\eta \rightarrow \pi^+\pi^-\pi^0$)	< 2.1 $\times 10^{-3}$	CL=90%
Γ_{37}	$\omega\pi^+$ $\times$ B($\omega \rightarrow \pi^+\pi^-\pi^0$)	< 5 $\times 10^{-3}$	CL=90%
Γ_{38}	$\pi^+\pi^+\pi^+\pi^-\pi^-$	< 1.5 $\times 10^{-3}$	CL=90%
Γ_{39}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	seen	
	Fractions of the following modes have already appeared above.		
Γ_{40}	$\eta\pi^+$	< 9 $\times 10^{-3}$	CL=90%
Γ_{41}	$\omega\pi^+$	< 6 $\times 10^{-3}$	CL=90%

Hadronic modes with two K's

Γ_{42}	$\overline{K}^0 K^+$	$(\ 8.4\pm\ 2.7)\times 10^{-3}$		
Γ_{43}	$K^+K^-\pi^+$	$(\ 9.6\pm\ 1.6)\times 10^{-3}$		S=1.2
	In the fit as $\frac{1}{2}\Gamma_{53}+\frac{2}{3}\Gamma_{54}+\Gamma_{46}$, where $\frac{1}{2}\Gamma_{53}=\Gamma_{44}$ and $\frac{2}{3}\Gamma_{54}=\Gamma_{45}$.			
Γ_{44}	$\phi\pi^+ \times B(\phi\to K^+K^-)$	$(\ 2.9\pm\ 0.6)\times 10^{-3}$		
Γ_{45}	$\overline{K}^*(892)^0 K^+ \times B(\overline{K}^*(892)^0 \to K^-\pi^+)$	$(\ 2.9\pm\ 0.7)\times 10^{-3}$		
Γ_{46}	$K^+K^-\pi^+$ (non-resonant)	$(\ 3.9\pm\ 0.9)\times 10^{-3}$		S=1.1
Γ_{47}	$K^+K^-\pi^+\pi^0$			
Γ_{48}	$\phi\pi^+\pi^0 \times B(\phi\to K^+K^-)$	$<$ 1.1	%	CL=90%
Γ_{49}	$K^+K^-\pi^+\pi^0$ (non-ϕ)	$<$ 1.9	%	CL=90%
Γ_{50}	$K^+K^-\pi^+\pi^+\pi^-$			
Γ_{51}	$K^+K^-\pi^+\pi^+\pi^-$ (non-res.)	$<$ 3	%	CL=90%
Γ_{52}	$\phi\pi^+\pi^+\pi^- \times B(\phi\to K^+K^-)$	$<$ 1	$\times 10^{-3}$	CL=90%

Fractions of the following modes have already appeared above.

Γ_{53}	$\phi\pi^+$	$(\ 5.7\pm\ 1.1)\times 10^{-3}$		S=1.1
Γ_{54}	$\overline{K}^*(892)^0 K^+$	$(\ 4.3\pm\ 1.0)\times 10^{-3}$		S=1.1
Γ_{55}	$\phi\pi^+\pi^0$	$<$ 2.2	%	CL=90%
Γ_{56}	$\phi\pi^+\pi^+\pi^-$	$<$ 2	$\times 10^{-3}$	CL=90%

Lepton Family number (LF) violating, Flavor-Changing neutral current (FC), or Doubly Cabibbo suppressed (DC) modes

Γ_{57}	$\pi^+e^{\pm}\mu^{\mp}$	LF	$<$ 3.8	$\times 10^{-3}$	CL=90%
Γ_{58}	$\pi^+e^+e^-$	FC	$<$ 2.6	$\times 10^{-3}$	CL=90%
Γ_{59}	$\pi^+\mu^+\mu^-$	FC	$<$ 2.9	$\times 10^{-3}$	CL=90%
Γ_{60}	$K^+\pi^+\pi^-$	DC	$<$ 4	$\times 10^{-3}$	CL=90%

Mode needed for fitting purposes

Γ_{61}	other fit modes	$(68\ \pm\ 4\ )$ %	S=1.2

[a] This is a weighted average of $D^{\pm}$ (44%) and D^0 (56%) branching fractions. See $D^{\pm}$ section for $D^{\pm}$ and $D^0 \to \eta$.

CONSTRAINED FIT INFORMATION

An overall fit to 9 products of a cross section and a partial width, a cross section, and 8 branching ratios uses 30 measurements and one constraint to determine 12 parameters. The overall fit has a $\chi^2 = 16.0$ for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_{20}	34										
x_{21}	10	−18									
x_{24}	56	35	11								
x_{25}	39	22	7	37							
x_{26}	40	23	7	44	27						
x_{30}	17	4	0	−34	12	12					
x_{46}	39	22	7	50	26	30	12				
x_{53}	48	27	9	61	32	37	14	41			
x_{54}	41	23	7	52	27	32	12	35	43		
x_{61}	−69	−63	−24	−67	−68	−62	−22	−49	−59	−51	
σ	−77	−44	−14	−72	−51	−52	−23	−51	−62	−53	84
	x_{17}	x_{20}	x_{21}	x_{24}	x_{25}	x_{26}	x_{30}	x_{46}	x_{53}	x_{54}	x_{61}

NOTE ON CHARM MESON BRANCHING FRACTIONS AND NEW RESULTS ON CHARM MESON DECAYS

Beginning in the previous edition of the Particle Data Book, we have restructured the listings to both clarify and reduce the uncertainty in the normalization of D meson branching fractions. In addition, we have improved the propagation of errors in the fits for the branching ratios. Wherever possible we have entered only the information actually measured by an experiment and have not used *derived* quantities. Topological normalizations (e.g. AGUILAR-BENITEZ 84) have been retained, but where experiments have measured only relative branching fractions, only those ratios have been included in the fits. Experiments that measure production cross sections times branching fractions in e^+e^- annihilation at the $\psi(3770)$ have been listed separately as $\sigma \cdot B$ at the $\psi(3770)$. They are normalized by averaging the cross section at the $\psi(3770)$, derived either by resonance scans or by the direct method of BALTRUSAITIS 86 updated in ADLER 88C. A separate section heading titled **Charm Production Cross Sections** is now included. The effect of this technique can best be seen by comparison of direct D^0 or D^+ branching fractions (ADLER 88C) with the PDG fit. For example $B(D^0 \to K^-\pi^+) = 0.042 \pm 0.004 \pm 0.004$ and $B(D^+ \to K^-\pi^+\pi^+) = 0.091 \pm 0.013 \pm 0.004$ from ADLER 88C become $0.038^{+0.004}_{-0.003}$ and $0.078^{+0.011}_{-0.008}$, respectively, in the PDG fit. See SCHINDLER 87 for further discussion.

This year's Listings show improved measurements from the Mark III and the TPS experiments on values for the semileptonic decays of D mesons. TPS results on $D^0 \to K^-e^+\nu_e$ and $D^+ \to \overline{K}^*(892)^0 e^+\nu_e$ decays suggest the $D_{\ell 4}$ decays are dominated ($\geq 80\%$) by a single resonance, and the branching fraction compared to the $D_{\ell 3}$ channel is considerably smaller than expected from simple models for the form factors. The data of the TPS also suggest that the vector meson in the decay is longitudinally polarized, in the $D_{\ell 4}$ channel.

The first observation of the Cabibbo-suppressed semileptonic decay $D^0 \to \pi^-e^+\nu_e$ by the Mark III experiment allows a measurement of the ratio of $\mid V_{cd}/V_{cs} \mid^2$ which is consistent with the C-K-M angle from strange-particle decays and unitarity.

In the spectroscopy of weak-hadronic decays, detailed measurements of the resonant substructure of the four-body $D^0 \to K^-\pi^+\pi^+\pi^-$ final states have been made by the Mark III (Ref. 1). The data suggest that, as previously found in the three-body final states, the nonresonant portion is small (about 25%) and the final state is dominated by quasi-two-body modes consisting of two vectors or a pseudoscalar and an axial vector. This pattern is also predicted by the factorization models which describe well the three-body final states of the D mesons.

In the previous issue of the PDG, the first measurements of rare D decays (flavor-changing and family-violating decays) were presented. In this issue, small improvements in these limits have been made, both by both fixed-target and e^+e^- collider experiments.

Reference

1. J. Adler et al., SLAC-PUB-5130 (1989), submitted to Phys. Rev. Lett.

D^+ BRANCHING RATIOS

$\Gamma(e^+\text{ anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.192^{+0.017}_{-0.014}$ OUR AVERAGE					
$0.20\ ^{+0.09}_{-0.07}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
$0.170 \pm 0.019 \pm 0.007$	158	BALTRUSAIT...	85B	MRK3	$E^{ee}_{cm} = 3.77$ GeV
0.168 ± 0.064	23	SCHINDLER	81	MRK2	$E^{ee}_{cm} = 3.771$ GeV
$0.220^{+0.044}_{-0.022}$		BACINO	80	DLCO	$E^{ee}_{cm} = 3.77$ GeV

D^+ and $D^0 \to$ (e^+ anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44 percent) and D^0 (56 percent) branching fractions. Only experiments at $E_{\rm cm}$ = 3.77 GeV are included in the average.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.110±0.011 OUR AVERAGE		Error includes scale factor of 1.1.		
0.117±0.011	295	BALTRUSAIT...85B	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
0.10 ±0.032		[7] SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.072±0.028		FELLER 78	MRK1	$E^{ee}_{\rm cm}$ = 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.096±0.007±0.015		[8] ONG 88	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV
$0.116^{+0.011}_{-0.009}$		PAL 86	DLCO	$E^{ee}_{\rm cm}$ = 29 GeV
0.091±0.009±0.013		[8] AIHARA 85	TPC	$E^{ee}_{\rm cm}$ = 29 GeV
0.092±0.046		[8] ALTHOFF 84J	TASS	$E^{ee}_{\rm cm}$ = 34.6 GeV
0.091±0.013		[8] KOOP 84	DLCO	Repl. by PAL 86
0.08 ±0.015		[9] BACINO 79	DLCO	$E^{ee}_{\rm cm}$ = 3.772 GeV

[7] Isolates D^+ and $D^0 \to e^+ X$ and weights for relative production (44%–56%).

[8] Average BR for charm $\to e^+ X$. Unlike $E_{\rm cm}$ = 3.77 GeV, the admixture of charmed mesons is unknown.

[9] Not independent of BACINO 80 $\Gamma(e^+$ anything$)/\Gamma_{\rm total}$ (D^+) and $\Gamma(e^+$ anything$)/\Gamma_{\rm total}$ (D^0).

$\Gamma(K^-$ anything$)/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.162±0.035 OUR AVERAGE				
0.17 ±0.07		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.19 ±0.05	26	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.10 ±0.07	3	VUILLEMIN 78	MRK1	$E^{ee}_{\rm cm}$ = 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.16\ ^{+0.08}_{-0.07}$		AGUILAR-... 86B	HYBR	Repl. by AGUILAR-BENITEZ 87E

$\Gamma(K^+$ anything$)/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.066±0.028 OUR AVERAGE				
$0.08\ ^{+0.06}_{-0.05}$		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.06 ±0.04	12	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.06 ±0.06	2	VUILLEMIN 78	MRK1	$E^{ee}_{\rm cm}$ = 3.772 GeV

$[\Gamma(K^0$ any$) + \Gamma(\overline{K}^0$ any$)]/\Gamma_{\rm total}$ Γ_4/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.48±0.15 OUR AVERAGE				
0.52±0.18	15	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.39±0.29	3	VUILLEMIN 78	MRK1	$E^{ee}_{\rm cm}$ = 3.772 GeV

D^+ and $D^0 \to$ (η anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44 percent) and D^0 (56 percent) branching fractions. Only the experiment at $E_{\rm cm}$ = 3.77 GeV is used.

VALUE	DOCUMENT ID	TECN	COMMENT
<0.13	PARTRIDGE 81	CBAL	$E^{ee}_{\rm cm}$ = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.02	[10] BRANDELIK 79	DASP	$E^{ee}_{\rm cm}$ = 4.03 GeV

[10] BRANDELIK 79 result based on absence of η signal at $E_{\rm cm}$ = 4.03 GeV. PARTRIDGE 81 observe substantially higher η cross section at $E_{\rm cm}$ = 4.03 GeV.

$\Gamma(c/\overline{c} \to \mu^+$ anything$)/\Gamma(c/\overline{c} \to$ anything$)$

VALUE	DOCUMENT ID	TECN	COMMENT
$0.079^{+0.011}_{-0.010}$ OUR AVERAGE			
0.078±0.009±0.012	[11] ONG 88	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV
0.078±0.015±0.02	[11] BARTEL 87	JADE	$E^{ee}_{\rm cm}$ = 34.6 GeV
$0.082^{+0.023}_{-0.016}$	[11] ALTHOFF 84G	TASS	$E^{ee}_{\rm cm}$ = 34.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.089±0.018±0.025	[11] BARTEL 85J	JADE	Repl. by BARTEL 87

[11] Average BR for charm $\to \mu^+ X$. The mixture of charmed particles is unknown and may actually contain states other than D mesons.

$\Gamma(c/\overline{c} \to \mu^+\mu^-$ anything$)/\Gamma(c/\overline{c} \to$ anything$)$

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.8 \times 10^{-2}$	90	0.3	[12] HAAS 88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV
<0.007	95		[13] ALTHOFF 84G	TASS	$E^{ee}_{\rm cm}$ = 34.5 GeV

[12] The normalization uses a continuum charm production estimate.

[13] Average BR for charm $\to \mu^+\mu^- X$. The mixture of charmed particles is unknown and may actually contain states other than D mesons.

$\Gamma(\mu^+\nu_\mu)/\Gamma_{\rm total}$ Γ_8/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.00072	90		[14] ADLER 88B	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	90	0	[15] AUBERT 83	SPEC	μ^+ Fe, 250 GeV

[14] Using 10.9 ps for the D^+ lifetime and $|V_{cd}|^2 = 0.0493$ ADLER 88B find the weak hadronic axial vector decay constant of the D^+ to be $f_D < 290$ MeV/c at 90% CL.

[15] AUBERT 83 obtain upper limit 0.014 assuming that final state contains equal mixture of (D^+,D^-), $(D^+,\overline{D}^0)$, (D^-,D^0), and $(D^0,\overline{D}^0)$. We quote the limit which they get under more general assumptions.

$\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma(\mu^+$ anything$)$ Γ_9/Γ_6

VALUE	EVTS	DOCUMENT ID	COMMENT
0.76±0.06	84	[16] AOKI 88	π^- emulsion

[16] From topological branching ratios in emulsion with identified muon.

$\Gamma(c/\overline{c} \to e^+e^-$ anything$)/\Gamma(c/\overline{c} \to$ anything$)$

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.2 \times 10^{-3}$	90	0.1	[17] HAAS 88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[17] The normalization uses a continuum charm production estimate.

$\Gamma(c/\overline{c} \to e^+\mu^-$ anything$)/\Gamma(c/\overline{c} \to$ anything$)$

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.7 \times 10^{-3}$	90	0.2	[18] HAAS 88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[18] The normalization uses a continuum charm production estimate.

$\Gamma(K^-\pi^+e^+\nu_e)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.057	90	[19] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[19] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^-\pi^+e^+\nu_e$ (non-resonant)$)/\Gamma_{\rm total}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	[20] ANJOS 89B	TPS	Photoproduction

[20] ANJOS 89B have assumed a B$(D^+ \to K^-\pi^+\pi^+) = 9.1 \pm 1.3 \pm 0.4\%$.

$\Gamma(\overline{K}^0\pi^+\pi^-e^+\nu_e)/\Gamma_{\rm total}$ Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[21] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[21] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^-\pi^+\pi^0e^+\nu_e)/\Gamma_{\rm total}$ Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.044^{+0.052}_{-0.013}\pm0.007$	2	[22] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[22] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(\pi^+\pi^-e^+\nu_e)/\Gamma_{\rm total}$ Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.057	90	[23] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[23] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(\overline{K}^*(892)^0e^+\nu_e)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{16}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.49±0.04±0.05	[24] ANJOS 89B	TPS	Photoproduction

[24] $K^*(892)$ polarization $\sigma_L/\sigma_S = 2.4^{+1.7}_{-0.9} \pm 0.2$.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\pi^+)/\Gamma_{\rm total}$ $\sigma\Gamma_{17}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.136±0.013 OUR FIT				
0.136±0.013 OUR AVERAGE				
0.135±0.012±0.010	161	BALTRUSAIT...86E	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
0.14 ±0.03	36	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.14 ±0.05	17	PERUZZI 77	MRK1	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(\overline{K}^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{17}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.45	90	[25] PICCOLO 77	MRK1	$E^{ee}_{\rm cm}$ = 4.03 GeV

[25] Obtained from $\sigma \times$ BR values of table I.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\rho^+)/\Gamma_{\rm total}$ $\sigma\Gamma_{20}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.32±0.07 OUR FIT			
0.29±0.03±0.09	ADLER 87	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(\overline{K}^0\pi^+\pi^0)/\Gamma_{\rm total}$ $\qquad\sigma(\Gamma_{20}+\Gamma_{21}+\frac{1}{3}\Gamma_{30})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.40 ±0.08 OUR FIT					
0.44 ±0.11 OUR AVERAGE					
0.417±0.081±0.075	159	BALTRUSAIT..	86E	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV
0.78 ±0.48	10	SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV

$\Gamma(\overline{K}^0\pi^+\pi^0)/\Gamma_{\rm total}$ $\qquad(\Gamma_{20}+\Gamma_{21}+\frac{1}{3}\Gamma_{30})/\Gamma$

VALUE	DOCUMENT ID
0.083±0.019 OUR FIT	

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(\overline{K}^0\pi^+\pi^0\ \text{(non-resonant)})/\Gamma_{\rm total}$ $\qquad\sigma\Gamma_{21}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
$0.057^{+0.047}_{-0.034}$ OUR FIT				
0.05 ±0.03 ±0.04	ADLER	87	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(K^-\pi^+\pi^+\ \text{(non-resonant)})/\Gamma_{\rm total}$ $\qquad\sigma\Gamma_{24}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.32±0.04 OUR FIT Error includes scale factor of 1.1.				
0.31±0.03±0.10	ADLER	87	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(K^-\pi^+\pi^+)/\Gamma_{\rm total}$ $\qquad\sigma(\Gamma_{24}+\frac{2}{3}\Gamma_{30})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.373±0.024 OUR FIT					
0.381±0.024 OUR AVERAGE					
0.388±0.013±0.029	1164	BALTRUSAIT..	86E	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV
0.38 ±0.05	239	SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV
0.36 ±0.06	85	PERUZZI	77	MRK1	$E^{ee}_{\rm cm}=3.77$ GeV

$\Gamma(K^-\pi^+\pi^+)/\Gamma_{\rm total}$ $\qquad(\Gamma_{24}+\frac{2}{3}\Gamma_{30})/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.077±0.010 OUR FIT Error includes scale factor of 1.2.					
$0.063^{+0.028}_{-0.014}$±0.011	8	[26] AGUILAR-...	87F	HYBR	πp, pp 360,400 GeV

[26] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ $\qquad\sigma\Gamma_{25}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.34 ±0.06 OUR FIT Error includes scale factor of 1.2.					
0.31 ±0.06 OUR AVERAGE Error includes scale factor of 1.2.					
0.291±0.047±0.029	168	ADLER	88C	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV
0.51 ±0.18	21	SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ $\qquad\Gamma_{25}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.070±0.015 OUR FIT Error includes scale factor of 1.2.					
$0.243^{+0.064}_{-0.041}$±0.041	11	[27] AGUILAR-...	87F	HYBR	πp, pp 360,400 GeV

[27] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma_{\rm total}$ $\qquad\sigma\Gamma_{26}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID		TECN	COMMENT
0.20±0.04 OUR FIT Error includes scale factor of 1.1.					
0.18±0.04±0.04	175	BALTRUSAIT..	86E	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV

$\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma_{\rm total}$ $\qquad\Gamma_{26}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.042±0.010 OUR FIT Error includes scale factor of 1.1.					
$0.022^{+0.047}_{-0.006}$±0.004	1	[28] AGUILAR-...	87F	HYBR	πp, pp 360,400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	7	AGUILAR-...	86B	HYBR	π^-p 360 GeV

[28] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{26}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.11 OUR FIT					
$0.66^{+0.18}_{-0.13}$ OUR AVERAGE					
0.69±0.10±0.16		ANJOS	89E	TPS	Photoproduction
$0.57^{+0.65}_{-0.17}$	1	AGUILAR-...	83B	HYBR	π^-p, 360 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\rm total}$ $\qquad\Gamma_{27}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.044^{+0.052}_{-0.013}$±0.007	2	[29] AGUILAR-...	87F	HYBR	πp, pp 360,400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	3	AGUILAR-...	86B	HYBR	π^-p 360 GeV

[29] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$ $\qquad\Gamma_{28}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.022^{+0.047}_{-0.008}$±0.004	1	[30] AGUILAR-...	87F	HYBR	πp, pp 360,400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	1	AGUILAR-...	86B	HYBR	π^-p 360 GeV

[30] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ $\qquad\sigma\Gamma_{29}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID		TECN	COMMENT
<0.23	90	SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ $\qquad\Gamma_{29}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	2	AGUILAR-...	86B	HYBR	π^-p 360 GeV

$\sigma(e^+e^-\to\psi(3770))\times\Gamma(\overline{K}^*(892)^0\pi^+)/\Gamma_{\rm total}$ $\qquad\sigma\Gamma_{30}/\Gamma$

VALUE (nanobarns)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.08±0.04 OUR FIT						
0.08±0.01±0.04			ADLER	87	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.27	90		SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV
		92	DRIJARD	79	SFM	pp $E_{\rm cm}=53$ GeV

$\Gamma(\pi^+\pi^0)/\Gamma_{\rm total}$ $\qquad\Gamma_{31}/\Gamma$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0053	90	1	BALTRUSAIT..	85E	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV

$\Gamma(\pi^+\pi^0)/\Gamma(\overline{K}^0\pi^+)$ $\qquad\Gamma_{31}/\Gamma_{17}$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	90	SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{32}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.036±0.007 OUR AVERAGE						
0.035±0.007±0.003			ANJOS	89	TPS	Photoproduction
0.042±0.016±0.010		57	BALTRUSAIT..	85E	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.084	90		SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV
<0.08	90		[31] PICCOLO	77	MRK1	$E^{ee}_{\rm cm}=4.03$ GeV

[31] Obtained from $\sigma\times$ BR values of table I.

$\Gamma(\rho^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{33}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	ANJOS	89	TPS	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\ \text{(non-resonant)})/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{34}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.027±0.007±0.002	ANJOS	89	TPS	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{35}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.4	90	ANJOS	89E	TPS	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{38}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.019	90	ANJOS	89	TPS	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\rm total}$ $\qquad\Gamma_{39}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	2	AGUILAR-...	86B	HYBR	π^-p 360 GeV

$\Gamma(\eta\pi^+)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{40}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	ANJOS	89E	TPS	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(K^-\pi^+\pi^+)$ $\qquad\Gamma_{41}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	ANJOS	89E	TPS	Photoproduction

$\Gamma(\overline{K}^0K^+)/\Gamma(\overline{K}^0\pi^+)$ $\qquad\Gamma_{42}/\Gamma_{17}$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.30 ±0.08 OUR AVERAGE					
0.317±0.086±0.048	31	BALTRUSAIT..	85E	MRK3	$E^{ee}_{\rm cm}=3.77$ GeV
0.25 ±0.15	6	SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}=3.771$ GeV

$\Gamma(K^+K^-\pi^+)/\Gamma_{\rm total}$ $\qquad(\Gamma_{46}+\frac{1}{2}\Gamma_{53}+\frac{2}{3}\Gamma_{54})/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0096±0.0016 OUR FIT Error includes scale factor of 1.2.					
0.008 $^{+0.017}_{-0.002}$ ±0.001	1	[32] AGUILAR-...	87F	HYBR	πp, pp 360,400 GeV

[32] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^+K^-\pi^+)/\Gamma(K^-\pi^+\pi^+)$ $(\Gamma_{46}+\frac{1}{2}\Gamma_{53}+\frac{2}{3}\Gamma_{54})/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

These measurement do not distinguish possible resonant substructure.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.124±0.012 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.25 ±0.20		5	[33] BAILEY	84	SILI	Hadroproduction
<0.14	90		SCHINDLER	81	MRK2	$E^{ee}_{\rm cm}$= 3.771 GeV
<0.15	90		[34] PICCOLO	77	MRK1	$E^{ee}_{\rm cm}$= 4.03 GeV

[33] One event consistent with $D^{\pm} \rightarrow \phi\pi^+$.
[34] Obtained from $\sigma \times$ BR values of table I.

$\Gamma(K^+K^-\pi^+ \text{ (non-resonant)})/\Gamma_{\rm total}$ Γ_{46}/Γ

VALUE	*DOCUMENT ID*
0.0039±0.0009 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(K^+K^-\pi^+ \text{ (non-resonant)})/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{46}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.050±0.009 OUR FIT					
0.050±0.009 OUR AVERAGE					
0.049±0.008±0.006	95	ANJOS	88	SILI	Photoproduction
0.059±0.026±0.009	37	[35] BALTRUSAIT...	85E	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

[35] This measurement excludes contributions to $K^+K^-\pi^+$ from $\phi\pi^+$ and $K^*(892)^0K^+$.

$\Gamma(K^+K^-\pi^+\pi^0 \text{ (non-}\phi))/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{49}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.25	90	[36] ANJOS	89E	TPS	Photoproduction

[36] Total minus ϕ component.

$\Gamma(K^+K^-\pi^+\pi^+\pi^- \text{ (non-res.)})/\Gamma_{\rm total}$ Γ_{51}/Γ

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.03	90	12	ANJOS	88	SILI	Photoproduction

$\Gamma(\phi\pi^+)/\Gamma_{\rm total}$ Γ_{53}/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.0057±0.0011 OUR FIT Error includes scale factor of 1.1.						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
seen	234	GEORGIO...	85	SPEC	+	pN 400 GeV

$\Gamma(\phi\pi^+)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{53}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.073±0.010 OUR FIT					
0.073±0.010 OUR AVERAGE					
0.071±0.008±0.007	84	ANJOS	88	SILI	Photoproduction
0.084±0.021±0.011	21	BALTRUSAIT...	85E	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(\overline{K}^*(892)^0K^+)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{54}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.056±0.010 OUR FIT					
0.056±0.010 OUR AVERAGE					
0.058±0.009±0.006	73	ANJOS	88	SILI	Photoproduction
0.048±0.021±0.011	14	BALTRUSAIT...	85E	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{55}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.28	90	ANJOS	89E	TPS	Photoproduction

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{56}/Γ

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.002	90	0	ANJOS	88	SILI	Photoproduction

$\Gamma(\pi^+e^{\pm}\mu^{\mp})/\Gamma_{\rm total}$ Γ_{57}/Γ

Test of lepton family number conservation.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<3.8 \times 10^{-3}$	90	58	[37] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[37] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+e^+e^-)/\Gamma_{\rm total}$ Γ_{58}/Γ

Test for $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<2.6 \times 10^{-3}$	90	39	[38] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[38] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{\rm total}$ Γ_{59}/Γ

Test for $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<2.9 \times 10^{-3}$	90	36	[39] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[39] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

$\Gamma(K^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ $\Gamma_{60}/(\Gamma_{24}+\frac{2}{3}\Gamma_{30})$

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.05	90	[40] PICCOLO	77	MRK1	$E^{ee}_{\rm cm}$= 4.03 GeV

[40] Obtained from $\sigma \times$ BR values of table I.

$D^{\pm}$ PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of $D^{\pm}$ mesons at or near the $\psi(3770)$ peak in e^+e^- production. These cross sections are used for normalization of product branching fractions.

VALUE (nanobarns)	*DOCUMENT ID*		*TECN*	*COMMENT*
4.8 ±0.6 OUR FIT Error includes scale factor of 1.2.				
4.8 ±0.5 OUR AVERAGE Error includes scale factor of 1.1.				
4.2 ±0.6 ±0.3	[41] ADLER	88C	MRK3	$E^{ee}_{\rm cm}$= 3.768 GeV
5.5 ±1.0	[42] PARTRIDGE	84	CBAL	$E^{ee}_{\rm cm}$= 3.771 GeV
6.00±0.72±1.02	[43] SCHINDLER	80	MRK2	$E^{ee}_{\rm cm}$= 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9.1 ±2.0	[44] PERUZZI	77	MRK1	$E^{ee}_{\rm cm}$= 3.774 GeV

[41] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C measure the ratio of cross sections (neutral to charged) to be 1.36 ± 0.23 ± 0.14. This measurement does not include the decays of the $\psi(3770)$ not associated with charmed particle production.

[42] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluated the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[43] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[44] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

REFERENCES FOR $D^{\pm}$

BARLAG	90C	ZPHY C (to be pub.)	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ANJOS	89	PRL 62 125	+Appel, Bean, Bracker+	(TPS Collab.)
ANJOS	89B	PRL 62 722	+Appel, Bean, Bracker+	(TPS Collab.)
ANJOS	89E	PL B223 267	+Appel, Bean, Bracker+	(TPS Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
ADLER	88B	PRL 60 1375	+Becker, Blaylock+	(Mark III Collab.)
ADLER	88C	PRL 60 89	+Becker, Blaylock+	(Mark III Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88	PRL 60 897	+Appel+	(Tagged Photon Spectrometer Collab.)
AOKI	88	PL B209 113	+Arnold, Baroni+	(WA75 Collab.)
HAAS	88	PRL 60 1614	+Hempstead, Jensen+	(CLEO Collab.)
ONG	88	PRL 60 2587	+Weir, Abrams, Amidei+	(Mark II Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL TPS Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
ADLER	87	PL B196 107	+Becker, Blaylock, Bolton+	(Mark III Collab.)
AGUILAR-...	87D	PL B193 140	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88C	ZPHY C40 321	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
AGUILAR-...	87E	ZPHY C36 551	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88C	ZPHY C40 321	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
AGUILAR-...	87F	ZPHY C36 559	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88	ZPHY C38 520 erratum		
BARLAG	87B	ZPHY C37 17	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
BARTEL	87	ZPHY C33 339	+Becker, Felst, Haidt+	(JADE Collab.)
CSORNA	87	PL B191 318	+Mestayer, Panvini, Word+	(CLEO Collab.)
PALKA	87B	ZPHY C35 151	+Bailey, Becker+	(ACCMOR Collab.)
ABE	86	PR D33 1	+	(SLAC Hybrid Facility Photon Collab.)
AGUILAR-...	86B	ZPHY C31 491	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
BALTRUSAIT...	86E	PRL 56 2140	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
GLADNEY	86	PR D34 2601	+Jaros, Ong, Barklow+	(Mark II Collab.)
PAL	86	PR D33 2708	+Atwood, Barish, Bonneaud+	(DELCO Collab.)
USHIDA	86	PRL 56 1767	+Kondo+	(AICH, FNAL, GIFU, GYEO, KOBE, SEOU+)
AIHARA	85	ZPHY C27 39	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
BAILEY	85	ZPHY C28 357	+Belau, Boehringer, Bosman+	(ABCCMR Collab.)
BALTRUSAIT...	85B	PRL 54 1976	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BALTRUSAIT...	85E	PRL 55 150	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BARTEL	85J	PL 163B 277	+Becker, Cords, Felst+	(JADE Collab.)
GEORGIO...	85	PL 152B 428	Georgiopoulos+	(TUFT, ARIZ, FNAL, FSU, NDAM+)
ADAMOVICH	84	PL 140B 119	+Alexandrov, Bolta, Bravo+	(WA58 Collab.)
ALTHOFF	84G	ZPHY C22 219	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84J	PL 146B 443	+Branschweig, Kirschfink+	(TASSO Collab.)
BAILEY	84	PL 139B 320	+Belau, Bohringer, Bosman+	(ACCMOR Collab.)
DERRICK	84	PRL 53 1971	+Fernandez, Fries, Hyman+	(HRS Collab.)
KOOP	84	PRL 52 970	+Sakuda, Atwood, Baillon+	(DELCO Collab.)
PARTRIDGE	84	Cal Tech 1984 Thesis		(Crystal Ball Collab.)
AGUILAR-...	83B	PL 123B 98	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
AUBERT	83	NP B213 31	+Bassompierre, Becks, Best+	(EMC Collab.)
BADERT...	83	PL 123B 471	Badertscher, Hahn, Hugentobler+	(BERN, MPIM)
ALBINI	82	PL 110B 339	+	(FRAS, MILA, PISA, ROMA, TORI, TRST)
BALLAGH	81	PR D24 7	+Bingham+	(LBL, UCB, FNAL, HAWA, WASH, WISC)
Also	80	PL 89B 423	Ballagh+	(LBL, UCB, FNAL, HAWA, WASH, WISC)
PARTRIDGE	81	PRL 47 760	+Peck, Porter, Gu+	(Crystal Ball Collab.)
SCHINDLER	81	PR D24 78	+Alam, Boyarski, Breidenbach+	(Mark II Collab.)
TRILLING	81	PRPL 75 57		(LBL, UCB) J
ALLASIA	80	NP B176 13	+	(ANKA, LIBH, CERN, DUUC, LOUC, KEYN+)
BACINO	80	PRL 45 329	+Ferguson+	(UCLA, SLAC, STAN, UCI, STON)
SCHINDLER	80	PR D21 2716	+Siegrist, Alam, Boyarski+	(Mark II Collab.)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)

BACINO	79	PRL 43 1073	+Ferguson, Nodulman+	(DELCO Collab.)
BRANDELIK	79	PL 80B 412	+Braunschweig, Martyn, Sander+	(DASP Collab.)
DRIJARD	79	PL 81B 250	+Fischer, Geist+	(CERN, CDEF, HEID, KARL)
FELLER	78	PRL 40 274	+Litke, Madaras, Ronan+	(LBL, SLAC, NWES, HAWA)
VUILLEMIN	78	PRL 41 1149	+Feldman, Feller+	(LBL, SLAC, NWES, HAWA)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(LBL, SLAC)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(SLAC, LBL, NWES, HAWA)
PICCOLO	77	PL 70B 260	+Peruzzi, Luth, Nguyen, Wiss, Abrams+	(SLAC, LBL)
RAPIDIS	77	PRL 39 526	+Gobbi, Luke, Barbaro-Galtieri+	(Mark I Collab.)
PERUZZI	76	PRL 37 569	+Piccolo, Feldman, Nguyen, Wiss+	(SLAC, LBL)

OTHER RELATED PAPERS

SCHINDLER	88	High Energy Electron-Positron Physics 234 Editors: A. Ali and P. Soeding, World Scientific, Singapore		(SLAC)
GRAB	87	SLAC-PUB-4372 EPS Conference – Uppsala		(SLAC)
SCHUBERT	87	IHEP-HD/87-7 EPS Conference – Uppsala, Proc., Vol. 2, p. 791		(HEID)
SNYDER	87	IUHEEE-87-11 Symp. on Prod. and Decay of Heavy Flavors, Stanford		(IND)
SCHINDLER	86	SLAC-PUB-4136 World Press International		(SLAC)
SCHINDLER	86B	SLAC-PUB-4248 SLAC Summer Institute		(SLAC)
KIRKBY	79	SLAC-PUB-2419 Batavia Lepton Photon Conference.		(SLAC)
BARBARO-...	78	LBL-8537 Erice 1978	Barbaro-Galtieri	(LBL)
WOJCICKI	78	SLAC-PUB-2232 SLAC Summer Institute. SLAC Summer Institute.		(SLAC)
GOLDHABER	76	PRL 37 255	+Pierre, Abrams, Alam+	(LBL, SLAC)
WISS	76	PRL 37 1531	+Goldhaber, Abrams, Alam, Boyarski+	(LBL, SLAC)

D^0

$I(J^P) = \frac{1}{2}(0^-)$

D^0 MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1864.5± 0.5 OUR FIT				
1864.1± 1.0 OUR AVERAGE				
1864.6± 0.3±1.0	641	BARLAG 90C	CCD	π^- Cu 230 GeV
1852 ± 7	16	ADAMOVICH 87	EMUL	Photoproduction
1861. ± 4.0		DERRICK 84	HRS	E^{ee}_{cm} = 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1856 ±36	22	ADAMOVICH 84B	EMUL	Photoproduction
1847 ± 7	1	FIORINO 81	EMUL	$\gamma N \rightarrow \overline{D}^0 +$
1863.8± 0.5		[1] SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.77 GeV
1864.7± 0.6		[1] TRILLING 81	RVUE	E^{ee}_{cm} = 3.77 GeV
1863.0± 2.5	238	ASTON 80E	OMEG	$\gamma p \rightarrow \overline{D}^0$
1860 ± 2	143	[2] AVERY 80	SPEC	$\gamma N \rightarrow D^{*+}$
1869 ± 4	35	[2] AVERY 80	SPEC	$\gamma N \rightarrow D^{*+}$
1854 ± 6	94	[2] ATIYA 79	SPEC	$\gamma N \rightarrow D^0 \overline{D}^0$
1850 ±15	64	BALTAY 78C	HBC	$\nu N \rightarrow K^0 \pi \pi$
1863 ± 3		GOLDHABER 77	MRK1	D^0, D^+ recoil spectra
1863.3± 0.9		[1] PERUZZI 77	MRK1	E^{ee}_{cm} = 3.77 GeV
1868 ±11		PICCOLO 77	MRK1	E^{ee}_{cm} = 4.03, 4.41 GeV
1865 ±15	234	GOLDHABER 76	MRK1	$K\pi$ and $K3\pi$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted. Omitted from the fit because it is redundant with the data on the $D^{\pm}$ mass and $D^{\pm} - D^0$ mass difference.

[2] Error does not include possible systematic mass scale shift, estimated to be less than 5 MeV.

$|m_{D_1^0} - m_{D_2^0}|$, MASS DIFFERENCE

D_1^0 and D_2^0 are the mass eigenstates of the D^0 meson.

VALUE (10^{-4} eV)	CL%	DOCUMENT ID	TECN	COMMENT
<1.3	90	[3,4] ANJOS 88C	SILI	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6	90	[3] ALBRECHT 87K	ARG	E^{ee}_{cm} = 10 GeV
<1.6	90	[5] LOUIS 86	SPEC	π^- W 225 GeV
<7	90	[3,6] YAMAMOTO 85	DLCO	E^{ee}_{cm} = 29 GeV
<6.5	90	[5] BODEK 82	SPEC	π^-, $pFe \rightarrow D^0$

[3] Limit inferred from D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ (via $\overline{D}^0$))/$\Gamma(K^-\pi^+)$ below.

[4] Calculated by us using $\Delta m = (2r/(1-r))^{1/2}\hbar/4.21 \times 10^{-13}$s where r is the D^0-$\overline{D}^0$ mixing ratio.

[5] Limit inferred from D^0-$\overline{D}^0$ mixing ratio $\Gamma(\mu^-$ anything (via $\overline{D}^0$))/$\Gamma(\mu^+$ anything) below.

[6] YAMAMOTO 85 gives $\Delta m/\Gamma < 0.44$. We use $\Gamma = \hbar/4.3 \times 10^{-13}$s.

$D^{\pm} - D^0$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4.77±0.27 OUR FIT			
4.74±0.28 OUR AVERAGE			
4.7 ±0.3	[7] SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.77 GeV
5.0 ±0.8	[7] PERUZZI 77	MRK1	E^{ee}_{cm} = 3.77 GeV

[7] See the footnote on TRILLING 81 in the D^0 and $D^{\pm}$ sections.

D^0 MEAN LIFE

VALUE (10^{-13} s)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
4.21±0.10 OUR AVERAGE					
$3.88^{+0.23}_{-0.21}$		641	[8] BARLAG 90C	CCD	π^- Cu 230 GeV
4.4 ±1.0 ±0.6			AVERILL 89	HRS	E^{ee}_{cm} = 29 GeV
4.8 ±0.4 ±0.3			ALBRECHT 88I	ARG	E^{ee}_{cm} = 10 GeV
$3.4^{+0.6}_{-0.5} \pm 0.3$			AMENDOLIA 88	SPEC	Photoproduction
4.22±0.08±0.10		4200	RAAB 88	SILI	Photoproduction
$3.6^{+1.2}_{-0.8} \pm 0.7$		44	ADAMOVICH 87	EMUL	Photoproduction
$4.6^{+0.6}_{-0.5}$		145	AGUILAR-... 87D	HYBR	$\pi^- p$ and pp
$4.3^{+2.0}_{-1.4} \pm 0.8$		15	ALTHOFF 87	TASS	$e^+ e^-$ 42.2 GeV
4.2 ±0.5		90	BARLAG 87B	SILI	K^- and π^- 200 GeV
5.0 ±0.7 ±0.4		345	CSORNA 87	CLEO	E^{ee}_{cm} = 10 GeV
$4.4^{+1.2}_{-1.1} \pm 0.6$		53	WAGNER 87	MRK2	E^{ee}_{cm} = 29 GeV
6.1 ±0.9 ±0.3		50	ABE 86	HYBR	SLAC γp 20 GeV
$4.7^{+0.9}_{-0.8} \pm 0.5$		74	GLADNEY 86	MRK2	E^{ee}_{cm} = 29 GeV
$4.3^{+0.7}_{-0.5}{}^{+0.1}_{-0.2}$		58	USHIDA 86B	EMUL	ν wideband
$3.7^{+1.0}_{-0.7}$		26	BAILEY 85	SILI	π^- Be 200 GeV
$4.6 \pm 1.5^{+0.6}_{-0.5}$		269	[9] YAMAMOTO 85B	DLCO	E^{ee}_{cm} = 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$4.1^{+0.7}_{-0.6}$		60	AGUILAR-... 87C	HYBR	Repl. by AGUILAR-BENITEZ 87D
4.35±0.15±0.10		1360	ANJOS 87	SILI	Repl. by RAAB 88
$6.8^{+2.3}_{-1.8}$		22	ABE 84	HYBR	Repl. by ABE 86
$2.11^{+1.21}_{-0.63}{}^{+0.8}_{-0.7}$		22	ADAMOVICH 84B	EMUL	Repl. by ADAMOVICH 87
$3.5^{+1.4}_{-0.9}$		11	AGUILAR-... 84B	HYBR	Repl. by AGUILAR-BENITEZ 87D
$4.2^{+1.6}_{-1.4}$		27	YELTON 84	MRK2	E^{ee}_{cm} = 29 GeV
$4.1^{+1.3}_{-0.9}$		16	AGUILAR-... 83	HYBR	Repl. by AGUILAR-BENITEZ 87D
$4.1^{+2.6}_{-1.4}$		9	BADERT... 83	HYBR	CERN $\pi^- N$
$2.3^{+0.8}_{-0.5}$		16	[10] USHIDA 82	EMUL	Repl. by USHIDA 86B
2.1		1	[11] ADEVA 81	HYBR	LEBC CERN-SPS $\pi^- p$
5.9		1	[11] ADEVA 81	HYBR	LEBC CERN-SPS $\pi^- p$
$2.8^{+2.2}_{-1.3}$		2	[12] BALLAGH 81	HYBR	FNAL 15-ft, ν Ne-^{2}H
$3.1^{+2.0}_{-1.6}$		5	FUCHI 81	EMUL	CERN-SPS $\pi^- N$
$0.53^{+0.57}_{-0.25}$		3	[13] ALLASIA 80	EMUL	ν wideband
<2.1	95		[14] BACINO 80	DLCO	E^{ee}_{cm} = 3.77 GeV
<8.0	90		ARMENISE 79	HYBR	$\nu p \rightarrow$ dimuons + X

[8] BARLAG 90C estimate systematic error to be negligible.

[9] Uses impact parameter technique.

[10] USHIDA 82 have 3 semi-leptonic decays not included in this number, but believed to have much longer lifetimes.

[11] ADEVA 81 first and second values are proper lifetimes of D^0 and $\overline{D}^0$ from single event. Detection efficiency low for lifetimes 10^{-13} sec or less.

[12] BALLAGH 81 value quoted here assumes that all dilepton events contain D^0 or D^+, each with equal numbers of semileptonic decays.

[13] ALLASIA 80 assumes no long-length losses. Visibility problems in the emulsion.

[14] Uses theoretical rate $D \rightarrow (K e \nu) = 1.4 \times 10^{11}$ s^{-1}.

$|\tau_{D_1^0} - \tau_{D_2^0}|/\tau_{D^0}$, MEAN LIFE DIFFERENCE/AVERAGE

D_1^0 and D_2^0 are the mass eigenstates of the D^0 meson.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.17	90	[15,16] ANJOS 88C	SILI	Photoproduction

• • • We do not use the following data for averages, fits, limits, etc. • • •

<0.21	90	[17] LOUIS	86	SPEC	π^- W 225 GeV
<0.8	90	[15] YAMAMOTO	85	DLCO	$E^{ee}_{cm} = 29$ GeV
<0.55	90	[17] BODEK	82	SPEC	π^-, pFe $\rightarrow$ D^0

[15] Limit inferred from D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ (via $\overline{D}^0$))/$\Gamma(K^-\pi^+)$ below.

[16] Calculated by us using $\Delta\Gamma = (8r/(1+r))^{1/2}\hbar/4.21 \times 10^{-13}$s where r is the D^0–$\overline{D}^0$ mixing ratio.

[17] Limit inferred from D^0-$\overline{D}^0$ mixing ratio $\Gamma(\mu^-$ anything (via $\overline{D}^0$))/$\Gamma(\mu^+$ anything) below.

D^0 DECAY MODES

$\overline{D}^0$ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes			
Γ_1	e^+ anything		$(7.7 \pm 1.2)\,\%$	S=1.1
Γ_2	μ^+ anything			
Γ_3	K^- anything		$(43 \pm 5)\,\%$	
Γ_4	K^+ anything		$(6.4^{+2.6}_{-1.7})\,\%$	
Γ_5	K^0 any + $\overline{K}^0$ any		$(33 \pm 10)\,\%$	
Γ_6	η anything	[a]	$< 13\,\%$	CL=90%
	Semileptonic modes			
Γ_7	$K^- e^+ \nu_e$		$(3.4 \pm 0.4)\,\%$	
Γ_8	$\pi^- e^+ \nu_e$		$(3.9^{+2.3}_{-1.2}) \times 10^{-3}$	
Γ_9	$K^- \pi^0 (\pi^0) e^+ \nu_e$		$(2.3^{+5.0}_{-0.6})\,\%$	
Γ_{10}	$\overline{K}^0 \pi^- \pi^- (\pi^0) e^+ \nu_e$		$(7.9^{+6.9}_{-2.4})\,\%$	
	Hadronic modes with one or three K's			
Γ_{11}	$\overline{K}^0 \pi^0$		$(2.7 \pm 1.2)\,\%$	
Γ_{12}	$K^- \pi^+$		$(3.71 \pm 0.25)\,\%$	S=1.1
Γ_{13}	$\overline{K}^0 \pi^+ \pi^-$		$(5.3 \pm 0.5)\,\%$	S=1.1
	In the fit as $\Gamma_{14} + \frac{2}{3}\Gamma_{39} + \Gamma_{16}$, where $\frac{2}{3}\Gamma_{39} = \Gamma_{15}$.			
Γ_{14}	$\overline{K}^0 \rho^0$		$(4.3^{+3.1}_{-1.9}) \times 10^{-3}$	
Γ_{15}	$K^*(892)^- \pi^+$ $\times$ B($K^*(892)^- \rightarrow \overline{K}^0 \pi^-$)		$(3.1 \pm 0.4)\,\%$	
Γ_{16}	$\overline{K}^0 \pi^+ \pi^-$ (non-resonant)		$(1.8 \pm 0.5)\,\%$	
Γ_{17}	$K^- \pi^+ \pi^0$		$(11.9 \pm 1.2)\,\%$	
	In the fit as $\Gamma_{18} + \frac{1}{3}\Gamma_{39} + \frac{2}{3}\Gamma_{40} + \Gamma_{21}$, where $\frac{1}{3}\Gamma_{39} = \Gamma_{19}$ and $\frac{2}{3}\Gamma_{40} = \Gamma_{20}$.			
Γ_{18}	$K^- \rho^+$		$(7.8 \pm 1.1)\,\%$	S=1.1
Γ_{19}	$K^*(892)^- \pi^+$ $\times$ B($\overline{K}^*(892)^- \rightarrow K^- \pi^0$)		$(1.5 \pm 0.2)\,\%$	
Γ_{20}	$\overline{K}^*(892)^0 \pi^0$ $\times$ B($\overline{K}^*(892)^0 \rightarrow K^- \pi^+$)		$(1.3 \pm 0.4)\,\%$	
Γ_{21}	$K^- \pi^+ \pi^0$ (non-resonant)		$(1.2 \pm 0.6)\,\%$	S=1.2
Γ_{22}	$K^- \pi^+ \pi^+ \pi^-$	[b]	$(7.8 \pm 0.6)\,\%$	S=1.1
Γ_{23}	$K^- \pi^+ \pi^+ \pi^-$ non-resonant		$(1.9 \pm 0.5)\,\%$	
Γ_{24}	$K^- \pi^+ \rho^0$ 3-body		$(7 \pm 4) \times 10^{-3}$	
Γ_{25}	$\overline{K}^*(892)^0 \pi^+ \pi^-$ 3-body $\times$ B($\overline{K}^*(892)^0 \rightarrow K^- \pi^+$)		$(1.1 \pm 0.4)\,\%$	
Γ_{26}	$\overline{K}^*(892)^0 \rho^0$ $\times$ B($\overline{K}^*(892)^0 \rightarrow K^- \pi^+$)		$(1.1 \pm 0.4)\,\%$	
Γ_{27}	$K^- a_1(1260)^+$ $\times$ B($a_1(1260)^+ \rightarrow \pi^+ \pi^+ \pi^-$)		$(3.8 \pm 0.8)\,\%$	
Γ_{28}	$K_1(1270)^- \pi^+$ $\times$ B($K_1(1270)^- \rightarrow K^- \pi^+ \pi^-$)		$(0.5 \pm 0.3)\,\%$	
Γ_{29}	$K^- \pi^+ \pi^0 \pi^0$		$(15 \pm 5)\,\%$	
Γ_{30}	$\overline{K}^0 \pi^+ \pi^- \pi^0 (\pi^0)$			
Γ_{31}	$\overline{K}^0 \omega \times$ B($\omega \rightarrow \pi^+ \pi^- \pi^0$)		$(3.3 \pm 1.3)\,\%$	
Γ_{32}	$K^- \pi^+ \pi^+ \pi^- \pi^0$		$(4.0^{+2.1}_{-1.5})\,\%$	
Γ_{33}	$\overline{K}^0 \pi^+ \pi^+ \pi^- \pi^-$		$(7 \pm 4) \times 10^{-3}$	
Γ_{34}	$\overline{K}^0 \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$		$(4.0^{+5.0}_{-3.0}) \times 10^{-3}$	
Γ_{35}	$\overline{K}^0 K^+ K^-$		$(1.16 \pm 0.21)\,\%$	
	In the fit as $\frac{1}{2}\Gamma_{54} + \Gamma_{37}$, where $\frac{1}{2}\Gamma_{54} = \Gamma_{36}$.			
Γ_{36}	$\overline{K}^0 \phi \times$ B($\phi \rightarrow K^+ K^-$)		$(4.0 \pm 0.8) \times 10^{-3}$	
Γ_{37}	$\overline{K}^0$ ($K^+ K^-$) non-resonant		$(7.6^{+2.0}_{-1.8}) \times 10^{-3}$	
Γ_{38}	$K^+ K^- \overline{K}^0 \pi^0$		$(2.4^{+3.3}_{-1.7})\,\%$	
	Fractions of many of the following modes have already appeared above.			
Γ_{39}	$K^*(892)^- \pi^+$		$(4.6 \pm 0.6)\,\%$	
Γ_{40}	$\overline{K}^*(892)^0 \pi^0$		$(2.0 \pm 0.6)\,\%$	
Γ_{41}	$K^- a_1(1260)^+$		$(7.8 \pm 1.5)\,\%$	
Γ_{42}	$K^- a_2(1320)^+$		$< 5 \times 10^{-3}$	CL=90%
Γ_{43}	$\overline{K}^*(892)^0 \pi^+ \pi^-$		$(1.7 \pm 0.5)\,\%$	
Γ_{44}	$\overline{K}^*(892)^0 \rho^0$		$(1.7 \pm 0.6)\,\%$	
Γ_{45}	$\overline{K}^*(892)^0 \rho^0$ (S-wave$_{\rm Transverse}$)		$(1.7 \pm 0.6)\,\%$	
Γ_{46}	$\overline{K}^*(892)^0 \rho^0$ (S-wave$_{\rm Longitud.}$)		$< 2.9 \times 10^{-3}$	CL=90%
Γ_{47}	$\overline{K}^*(892)^0 \rho^0$ (P-wave)		$< 2.9 \times 10^{-3}$	CL=90%
Γ_{48}	$K_1(1270)^- \pi^+$		$(1.6 \pm 0.8)\,\%$	
Γ_{49}	$K^*(1370)^- \pi^+$		$< 1.0\,\%$	CL=90%
Γ_{50}	$K_1(1400)^- \pi^+$		$< 1.0\,\%$	CL=90%
Γ_{51}	$\overline{K}^0 \omega$		$(3.7 \pm 1.5)\,\%$	
Γ_{52}	$\overline{K}^0 \eta$		$< 2.4\,\%$	CL=90%
Γ_{53}	$\overline{K}^*(892)^0 \eta$		$< 2.6\,\%$	CL=90%
Γ_{54}	$\overline{K}^0 \phi$		$(8.0 \pm 1.6) \times 10^{-3}$	
	Pionic modes			
Γ_{55}	$\pi^+ \pi^-$		$(1.14 \pm 0.31) \times 10^{-3}$	
Γ_{56}	$\pi^+ \pi^- \pi^0$		$(1.2 \pm 0.4)\,\%$	
Γ_{57}	$\pi^+ \pi^+ \pi^- \pi^-$		$(3.5^{+1.4}_{-1.2}) \times 10^{-3}$	S=1.5
Γ_{58}	$\pi^+ \pi^+ \pi^- \pi^- \pi^0$		$(4.8^{+2.8}_{-2.0})\,\%$	
Γ_{59}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$		$(4.0 \pm 3.0) \times 10^{-4}$	
	Hadronic modes with two K's			
Γ_{60}	$K^+ K^-$		$(4.5 \pm 0.7) \times 10^{-3}$	
Γ_{61}	$\overline{K}^0 K^0$		$< 4 \times 10^{-3}$	CL=90%
Γ_{62}	$\overline{K}^0_S K^0_S$		$(5 \pm 4) \times 10^{-4}$	
Γ_{63}	$K^0 K^- \pi^+$ + c.c.			
Γ_{64}	$\overline{K}^*(892)^0 K^0$ + c.c $\times$ B($\overline{K}^*(892)^0 \rightarrow K^- \pi^+$)		$< 4 \times 10^{-3}$	CL=90%
Γ_{65}	$K^*(892)^+ K^-$ + c.c $\times$ B($K^*(892)^+ \rightarrow K^0 \pi^+$)		$(5 \pm 3) \times 10^{-3}$	
Γ_{66}	$K^0 K^- \pi^+$ (non-res.)+c.c.		$< 1.2\,\%$	CL=90%
Γ_{67}	$K^+ K^- \pi^0 \pi^0$		seen	
Γ_{68}	($K^+ K^-$) $\pi^+ \pi^-$ non-res.		$(1.7 \pm 0.6) \times 10^{-3}$	
Γ_{69}	$\phi \pi^+ \pi^- \times$ B($\phi \rightarrow K^+ K^-$)		$(1.5 \pm 0.5) \times 10^{-3}$	
Γ_{70}	$K^0 K^- \pi^+ \pi^0$		seen	
	Fractions of the following modes have already appeared above.			
Γ_{71}	$\overline{K}^*(892)^0 K^0$ + c.c.		$< 5 \times 10^{-3}$	CL=90%
Γ_{72}	$K^*(892)^+ K^-$ + c.c.		$(8 \pm 4) \times 10^{-3}$	
Γ_{73}	$\phi \pi^+ \pi^-$		$(3.0 \pm 1.0) \times 10^{-3}$	

Lepton Family number (*LF*) violating, Flavor-Changing neutral current (*FC*), decay via Mixing (*MX*), or Doubly Cabibbo suppressed (*DC*) modes

	Mode			Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{74}	$K^+ \pi^-$	*DC*		$< 6 \times 10^{-4}$	CL=90%
Γ_{75}	$K^+ \pi^-$ (via $\overline{D}^0$)	*MX*		$< 1.4 \times 10^{-4}$	CL=90%
Γ_{76}	$K^+ \pi^+ \pi^- \pi^-$	*DC*		$< 1.8\,\%$	CL=90%
Γ_{77}	$\mu^+ \mu^-$	*FC*		$< 1.1 \times 10^{-5}$	CL=90%
Γ_{78}	$e^+ e^-$	*FC*		$< 1.3 \times 10^{-4}$	CL=90%
Γ_{79}	$\mu^\pm e^\mp$	*LF*	[c]	$< 1.0 \times 10^{-4}$	CL=90%
Γ_{80}	$\overline{K}^0 e^+ e^-$	*FC*		$< 1.7 \times 10^{-3}$	CL=90%
Γ_{81}	$\rho^0 e^+ e^-$	*FC*		$< 4.5 \times 10^{-4}$	CL=90%
Γ_{82}	$\rho^0 \mu^+ \mu^-$	*FC*		$< 8.1 \times 10^{-4}$	CL=90%
Γ_{83}	μ^- anything (via $\overline{D}^0$)	*MX*			
	Mode needed for fitting purposes				
Γ_{84}	other fit modes			$(61.6 \pm 2.8)\,\%$	S=1.1

[a] This is a weighted average of $D^\pm$ (44%) and D^0 (56%) branching fractions. See $D^\pm$ section for $D^\pm$ and $D^0 \rightarrow \eta$.

[b] The whole is less than the sum of the parts due to interference effects; see ADLER 90.

[c] Value is for the sum of the charge states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to 14 products of a cross section and a partial width, a cross section, and 21 branching ratios uses 66 measurements and one constraint to determine 17 parameters. The overall fit has a $\chi^2 = 30.2$ for 50 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_{11}	4									
x_{12}	35	11								
x_{14}	3	1	8							
x_{16}	6	3	17	−22						
x_{18}	12	6	35	6	14					
x_{21}	2	1	4	1	3	−27				
x_{22}	23	9	66	6	13	27	3			
x_{37}	6	3	19	6	14	10	1	14		
x_{39}	12	6	34	−10	−28	12	−1	26	16	
x_{40}	5	3	14	2	5	−6	−5	11	4	7
x_{54}	8	4	24	11	27	13	1	18	−3	25
x_{55}	7	2	19	1	3	6	1	12	3	6
x_{60}	14	4	39	3	7	13	2	26	7	13
x_{72}	3	2	10	1	3	6	1	8	3	6
x_{84}	−37	−54	−68	−10	−25	−53	−13	−62	−26	−41
σ	−27	−14	−77	−10	−23	−45	−6	−59	−24	−44
	x_7	x_{11}	x_{12}	x_{14}	x_{16}	x_{18}	x_{21}	x_{22}	x_{37}	x_{39}

x_{54}	5					
x_{55}	3	4				
x_{60}	6	9	7			
x_{72}	2	4	2	4		
x_{84}	−27	−33	−14	−28	−23	
σ	−19	−30	−14	−30	−13	74
	x_{40}	x_{54}	x_{55}	x_{60}	x_{72}	x_{84}

D^0 BRANCHING RATIOS

See note in $D^\pm$ section concerning revisions to hadronic branching fractions, and new measurements of D^+ and D^0 decays.

$\Gamma(e^+\,\text{anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.077±0.012 OUR AVERAGE Error includes scale factor of 1.1.					
0.15 ±0.05			AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.075±0.011±0.004		137	BALTRUSAIT...85B	MRK3	E^{ee}_{cm} = 3.77 GeV
0.055±0.037		12	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.17\,^{+0.08}_{-0.06}$		7	[18] AGUILAR-... 86	HYBR	$\pi^- p$ 360 GeV
$0.051\,^{+0.048}_{-0.014}$		3	AGUILAR-... 83	HYBR	πp, pp
<0.04	95	0	BACINO 80	DLCO	E^{ee}_{cm} = 3.77 GeV

[18] Includes (e^- anything) which is expected to be small.

$\Gamma(K^-\,\text{anything})/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.43±0.05 OUR AVERAGE				
0.42±0.08		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.55±0.11	121	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV
0.35±0.10	19	VUILLEMIN 78	MRK1	E^{ee}_{cm} = 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.44\,^{+0.11}_{-0.10}$		[19] AGUILAR-... 86	HYBR	$\pi^- p$ 360 GeV

[19] Includes K^+ anything.

$\Gamma(K^+\,\text{anything})/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.064\,^{+0.026}_{-0.017}$ OUR AVERAGE				
$0.03\,^{+0.05}_{-0.02}$		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.08 ±0.03	25	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV

$[\Gamma(K^0\,\text{any}) + \Gamma(\overline{K}^0\,\text{any})]/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.33±0.10 OUR AVERAGE				
0.29±0.11	13	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV
0.57±0.26	6	VUILLEMIN 78	MRK1	E^{ee}_{cm} = 3.772 GeV

$\Gamma(K^- e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
34±4 OUR FIT					
34±5±4		55	[20] ADLER 89	MRK3	E^{ee}_{cm} = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<50	90		[21] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[20] Experiment gives $|V_{cd}/V_{cs}|^2 = 0.057\,^{+0.038}_{-0.015} \pm 0.005$.

[21] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^- e^+ \nu_e)/\Gamma(K^- \pi^+)$ — Γ_7/Γ_{12}

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.91±0.11 OUR FIT			
0.91±0.07±0.11	ANJOS 89F	TPS	Photoproduction

$\Gamma(\pi^- e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$3.9\,^{+2.3}_{-1.1} \pm 0.4$		7	[22] ADLER 89	MRK3	E^{ee}_{cm} = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<54	90		[23] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[22] Experiment gives $|V_{cd}/V_{cs}|^2 = 0.057\,^{+0.038}_{-0.015} \pm 0.005$.

[23] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^- \pi^0 (\pi^0) e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.023\,^{+0.050}_{-0.006} \pm 0.001$	1	[24] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[24] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization. Does not distinguish presence of a second π^0.

$\Gamma(\overline{K}^0 \pi^- \pi^- (\pi^0) e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.079\,^{+0.069}_{-0.023} \pm 0.005$	3	[25] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[25] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization. Does not distinguish presence of a second π^0.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \pi^0)/\Gamma_{\text{total}}$ — $\sigma\Gamma_{11}/\Gamma$

VALUE (nanobarns)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.18±0.08 OUR FIT					
0.18±0.08		8	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.11±0.02±0.01		70	[26] SCHINDLER 86B	MRK3	E^{ee}_{cm} = 3.77 GeV
<0.7	90		SCHARRE 78	MRK1	E^{ee}_{cm} = 3.77 GeV

[26] The value has not been published as of this printing.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^- \pi^+)/\Gamma_{\text{total}}$ — $\sigma\Gamma_{12}/\Gamma$

VALUE (nanobarns)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.246±0.011 OUR FIT				
0.245±0.012 OUR AVERAGE				
0.248±0.009±0.014	930	BALTRUSAIT...86E	MRK3	E^{ee}_{cm} = 3.77 GeV
0.24 ±0.02	263	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV
0.25 ±0.05	130	PERUZZI 77	MRK1	E^{ee}_{cm} = 3.77 GeV

$\Gamma(K^- \pi^+)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0371±0.0025 OUR FIT Error includes scale factor of 1.1.				
0.041 ±0.005 OUR AVERAGE				
$0.040\,^{+0.007}_{-0.006}$	139	[27] BARLAG 89B	CCD	π^- Cu 230 GeV
0.045 ±0.008 ±0.005	56	[28] ABACHI 88	HRS	E^{ee}_{cm} = 29 GeV
$0.040\,^{+0.021}_{-0.010} \pm 0.002$	7	[29] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[27] BARLAG 89B computed the branching ratio using topological normalization.

[28] ABACHI 88 branching ratio computed by tagging $D^*(2010)^+ \to D^0 \pi^+$ through excess low momentum π^+ over background.

[29] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0 \rho^0)/\Gamma_{\text{total}}$ — $\sigma\Gamma_{14}/\Gamma$

VALUE (nanobarns)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.028\,^{+0.020}_{-0.012}$ OUR FIT				
$0.027\,^{+0.020}_{-0.008}$ OUR AVERAGE				
0.04 ±0.01 ±0.02		ADLER 87	MRK3	E^{ee}_{cm} = 3.77 GeV
$0.006\,^{+0.040}_{-0.009}$	1	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma_{\rm total}$ — $\sigma(\Gamma_{14}+\Gamma_{16}+\frac{2}{3}\Gamma_{39})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.349±0.028 OUR FIT Error includes scale factor of 1.1.				
0.36 ±0.04 OUR AVERAGE				
0.37 ±0.03 ±0.03		ADLER 87	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
0.30 ±0.08	32	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.46 ±0.12	28	PERUZZI 77	MRK1	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma_{\rm total}$ — $(\Gamma_{14}+\Gamma_{16}+\frac{2}{3}\Gamma_{39})/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.053±0.005 OUR FIT Error includes scale factor of 1.1.				
$0.039^{+0.011}_{-0.009}$ OUR AVERAGE				
0.037±0.011	25	[30] BARLAG 89B	CCD	π^- Cu 230 GeV
$0.045^{+0.059}_{-0.014}$±0.003	2	[31] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[30] BARLAG 89B computed the branching ratio using topological normalization.

[31] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — $(\Gamma_{14}+\Gamma_{16}+\frac{2}{3}\Gamma_{39})/\Gamma_{12}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.42±0.13 OUR FIT Error includes scale factor of 1.1.				
2.1 ±0.6 OUR AVERAGE				
1.7 ±0.8	35	AVERY 80	SPEC	$\gamma N \to D^{*+}$
2.8 ±1.0	116	PICCOLO 77	MRK1	$E^{ee}_{\rm cm}$ = 4.03, 4.41 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\pi^+\pi^-$ (non-resonant)$)/\Gamma_{\rm total}$ — $\sigma\Gamma_{16}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.117±0.030 OUR FIT				
0.11 ±0.04 OUR AVERAGE				
0.12 ±0.02 ±0.04		ADLER 87	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
$0.090^{+0.075}_{-0.069}$	10	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\rho^+)/\Gamma_{\rm total}$ — $\sigma\Gamma_{18}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.52±0.06 OUR FIT Error includes scale factor of 1.1.				
0.61±0.09 OUR AVERAGE				
0.62±0.02±0.09		ADLER 87	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
$0.58^{+0.22}_{-0.23}$	31	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\pi^0)/\Gamma_{\rm total}$ — $\sigma(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.79 ±0.06 OUR FIT				
0.75 ±0.09 OUR AVERAGE				
0.759±0.044±0.083	931	BALTRUSAIT...86E	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
0.68 ±0.23	37	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.4 ±0.6	7	SCHARRE 78	MRK1	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(K^-\pi^+\pi^0)/\Gamma_{\rm total}$ — $(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.119±0.012 OUR FIT				
$0.091^{+0.032}_{-0.023}$ OUR AVERAGE				
0.073±0.036±0.009	13	[32] BARLAG 89B	CCD	π^- Cu 230 GeV
$0.106^{+0.061}_{-0.028}$±0.006	5	[33] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[32] BARLAG 89B computed the branching ratio using topological normalization.

[33] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^-\pi^+\pi^0)/\Gamma(K^-\pi^+)$ — $(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})/\Gamma_{12}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
3.21±0.28 OUR FIT				
4.2 ±1.4	41	SUMMERS 84	TPS	Photoproduction

$\Gamma(K^-\rho^+)/\Gamma(K^-\pi^+\pi^0)$ — $\Gamma_{18}/(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.66±0.06 OUR FIT Error includes scale factor of 1.1.				
$0.31^{+0.20}_{-0.14}$	13	SUMMERS 84	TPS	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\pi^0$ (non-resonant)$)/\Gamma_{\rm total}$ — $\sigma\Gamma_{21}/\Gamma$

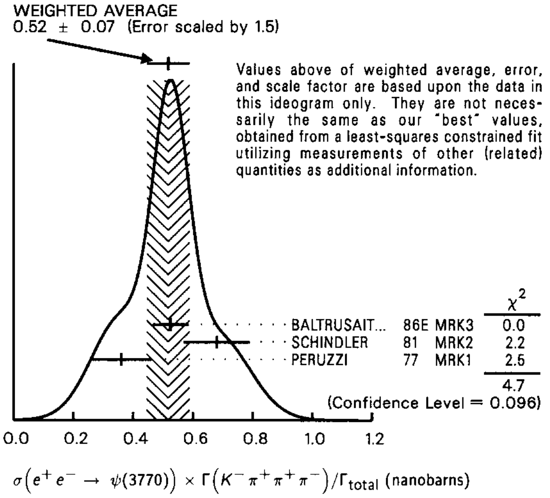
VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
0.08±0.04 OUR FIT Error includes scale factor of 1.2.				
0.07±0.02±0.03		ADLER 87	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.19	90	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV

$\Gamma(K^-\pi^+\pi^0$ (non-resonant)$)/\Gamma(K^-\pi^+\pi^0)$ — $\Gamma_{21}/(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.10±0.05 OUR FIT Error includes scale factor of 1.2.				
0.51±0.22	21	SUMMERS 84	TPS	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ — $\sigma\Gamma_{22}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.521±0.035 OUR FIT Error includes scale factor of 1.1.				
0.52 ±0.07 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
0.525±0.026±0.054	992	BALTRUSAIT...86E	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
0.68 ±0.11	185	SCHINDLER 81	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
0.36 ±0.10	44	PERUZZI 77	MRK1	$E^{ee}_{\rm cm}$ = 3.77 GeV



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{22}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.078±0.006 OUR FIT Error includes scale factor of 1.1.				
0.079±0.011 OUR AVERAGE				
0.082±0.012	399	[34] BARLAG 89B	CCD	π^- Cu 230 GeV
$0.065^{+0.017}_{-0.011}$±0.019	13	[35] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ±0.04	6	AGUILAR-... 84	HYBR	π^-p pp 360 GeV
0.071±0.025	8	AGUILAR-... 84B	HYBR	π^-p 360 GeV

[34] BARLAG 89B computed the branching ratio using topological normalization.

[35] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{22}/Γ_{12}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.12±0.13 OUR FIT Error includes scale factor of 1.1.				
2.13±0.16 OUR AVERAGE				
2.12±0.16±0.09		BORTOLETTO88	CLEO	$E^{ee}_{\rm cm}$ = 10.55 GeV
2.0 ±0.9	48	BAILEY 86	SILI	π^- Be fixed target
2.17±0.28±0.23		[36] ALBRECHT 85F	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
2.0 ±1.0	10	BAILEY 83B	SPEC	π^- Be $\to D^0$
2.2 ±0.8	214	[37] PICCOLO 77	MRK1	$E^{ee}_{\rm cm}$ = 4.03, 4.41 GeV

[36] Not independent of $(K^-3\pi)$/total.

[37] This channel dominated by $K^-\pi^+\rho^0$ (85 ± 15%). $K^*\pi^+\pi^-$ and $K^-a_2(1320)^+$ consistent with zero, $K^*\rho^0$ fraction is 0.1 ± 0.1.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\rho^0$ 3-body$)/\Gamma_{\rm total}$ — $\sigma\Gamma_{24}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.044±0.012±0.021	ADLER 90	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(K^-\pi^+\rho^0$ 3-body$)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{24}/Γ_{22}

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.2 ±0.2	90	2	BAILEY 83B	SPEC	π Be $\to D^0$
$0.85^{+0.11}_{-0.22}$		180	PICCOLO 77	MRK1	$E^{ee}_{\rm cm}$ = 4.03, 4.41 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-\pi^+\pi^+\pi^-$ non-resonant$)/\Gamma_{\rm total}$ — $\sigma\Gamma_{23}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.127±0.015±0.032	ADLER 90	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(K^-\pi^+\pi^0\pi^0)/\Gamma_{\rm total}$ — Γ_{29}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.149±0.037±0.030	24	[38] ADLER 88C	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.153\pm0.044\pm0.013$	23	[39] BARLAG 89B	CCD	π^- Cu 230 GeV
$0.209^{+0.074}_{-0.043}\pm0.012$	9	[39] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV
seen	6	AGUILAR-... 86B	HYBR	$\pi^- p$ 360 GeV
seen	1	ADEVA 81	HYBR	$\pi^- p \to D^0 \overline{D}^0$

[38] ADLER 88C uses an absolute normalization method finding this decay channel opposite a detected $D^0 \to K^-\pi^+$ in pure $D\overline{D}$ events.

[39] AGUILAR-BENITEZ 87F and BARLAG 89B computed the branching ratio by topological normalization. Does not distinguish presence of a third π^0 and thus is not included in the average.

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0(\pi^0))/\Gamma_{\text{total}}$ Γ_{30}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.148\pm0.063\pm0.015$	12	[40] BARLAG 89B	CCD	π^- Cu 230 GeV
$0.106^{+0.073}_{-0.029}\pm0.006$	4	[40] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV
seen	7	AGUILAR-... 86B	HYBR	$\pi^- p$ 360 GeV

[40] AGUILAR-BENITEZ 87F and BARLAG 89B computed the branching ratio by topological normalization. Does not distinguish presence of a third π^0 and thus is not included in the average.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{32}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.040^{+0.021}_{-0.015}}$	5	[41] BARLAG 89B	CCD	π^- Cu 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	6	AGUILAR-... 86B	HYBR	$\pi^- p$ 360 GeV

[41] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.0073^{+0.0045}_{-0.0043}}$	8	[42] BARLAG 89B	CCD	π^- Cu 230 GeV

[42] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.004^{+0.005}_{-0.003}}$	1	[43] BARLAG 89B	CCD	π^- Cu 230 GeV

[43] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(\overline{K}^0K^+K^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ $(\Gamma_{37}+\frac{1}{2}\Gamma_{54})/(\Gamma_{14}+\Gamma_{16}+\frac{2}{3}\Gamma_{39})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.220±0.034 OUR FIT				
0.20 ±0.05 OUR AVERAGE				
0.24 ± 0.08		[44] BEBEK 86	CLEO	e^+e^- near $\Upsilon(4S)$
0.185 ± 0.055	52	[44] ALBRECHT 85B	ARG	E^{ee}_{cm} = 10 GeV

[44] Resonant contributions to $\overline{K}^0K^+K^-$ are not distinguished ($\overline{K}^0\phi$ is included).

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^0\ (K^+K^-)\ \text{non-resonant})/\Gamma_{\text{total}}$ $\sigma\Gamma_{37}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.050^{+0.013}_{-0.011}}$ **OUR FIT**			
$\mathbf{0.05\ ^{+0.02}_{-0.01}\ \pm0.01}$	[45] BALTRUSAIT..86C	MRK3	E^{ee}_{cm} = 3.77 GeV

[45] Excludes contributions from $D^0 \to \overline{K}^0\phi$.

$\Gamma(\overline{K}^0\ (K^+K^-)\ \text{non-resonant})/\Gamma_{\text{total}}$ Γ_{37}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.0076^{+0.0020}_{-0.0018}}$ **OUR FIT**				
$\mathbf{0.016\ ^{+0.009}_{-0.007}}$	13	[46] BARLAG 89B	CCD	π^- Cu 230 GeV

[46] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(K^+K^-\overline{K}^0\pi^0)/\Gamma_{\text{total}}$ Γ_{38}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.024^{+0.033}_{-0.017}}$	1	[47] BARLAG 89B	CCD	π^- Cu 230 GeV

[47] BARLAG 89B computed the branching ratio using topological normalization.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K_1(1270)^-\pi^+)/\Gamma_{\text{total}}$ $\sigma\Gamma_{48}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.103±0.030±0.047	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^*(1370)^-\pi^+)/\Gamma_{\text{total}}$ $\sigma\Gamma_{49}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.066	90	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K_1(1400)^-\pi^+)/\Gamma_{\text{total}}$ $\sigma\Gamma_{50}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.066	90	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^*(892)^-\pi^+)/\Gamma_{\text{total}}$ $\sigma\Gamma_{39}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.31±0.04 OUR FIT				
0.30±0.04 OUR AVERAGE				
$0.28\pm0.04\pm0.08$		ADLER 87	MRK3	Using $K^{*-} \to K^-\pi^0$
$0.31\pm0.02\pm0.05$		ADLER 87	MRK3	Using $K^{*-} \to \overline{K}^0\pi^-$
$0.31^{+0.11}_{-0.12}$	25	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV

$\Gamma(K^*(892)^-\pi^+)/\Gamma(K^-\pi^+\pi^0)$ $\Gamma_{39}/(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.39±0.06 OUR FIT				
$0.33^{+0.36}_{-0.24}$	5	SUMMERS 84	TPS	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma_{\text{total}}$ $\sigma\Gamma_{40}/\Gamma$

VALUE (nanobarns)	EVTS	DOCUMENT ID	TECN	COMMENT
0.13±0.04 OUR FIT				
0.15±0.04 OUR AVERAGE				
$0.15\pm0.02\pm0.04$		ADLER 87	MRK3	E^{ee}_{cm} = 3.77 GeV
$0.11^{+0.18}_{-0.14}$	4	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV

$\Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma(K^-\pi^+\pi^0)$ $\Gamma_{40}/(\Gamma_{18}+\Gamma_{21}+\frac{1}{3}\Gamma_{39}+\frac{2}{3}\Gamma_{40})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.17±0.05 OUR FIT				
$0.09^{+0.14}_{-0.09}$	2	SUMMERS 84	TPS	Photoproduction

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-a_1(1260)^+)/\Gamma_{\text{total}}$ $\sigma\Gamma_{41}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.517±0.036±0.088	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(K^-a_2(1320)^+)/\Gamma_{\text{total}}$ $\sigma\Gamma_{42}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.036	90	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\Gamma(K^-a_2(1320)^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{42}/Γ_{22}

Followed by decay $a_2(1320)^+ \to \pi^-\pi^+\pi^-$ (BR = 0.35)

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.17	[48] PICCOLO 77	MRK1	E^{ee}_{cm} = 4.03, 4.41 GeV

[48] We have corrected the reported number < 0.06 to account for $B(a_2(1320)^+ \to \pi^+\pi^+\pi^-) = 0.35$.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^*(892)^0\pi^+\pi^-)/\Gamma_{\text{total}}$ $\sigma\Gamma_{43}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.110±0.015±0.032	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{43}/Γ_{22}

Followed by decay $\overline{K}^*(892)^0 \to K^-\pi^+$ (BR = 0.67)

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.27	90	0	[49] BAILEY 83B	SPEC	π Be $\to D^0$
$0.0\ ^{+0.3}_{-0.0}$		0	[50] PICCOLO 77	MRK1	E^{ee}_{cm} = 4.03, 4.41 GeV

[49] We have corrected the reported number < 0.18 to account for $B(\overline{K}^*(892)^0 \to K^-\pi^+) = 0.67$.

[50] Corresponds to < 0.5 at 90% CL. We have corrected the reported numbers to account for $B(\overline{K}^*(892)^0 \to K^-\pi^+) = 0.67$.

$\Gamma(\overline{K}^*(892)^0\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{44}/Γ_{22}

Followed by decay $\overline{K}^*(892)^0 \to K^-\pi^+$ (BR = 0.67)

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.75 ± 0.3	90	5	[51] BAILEY 83B	SPEC	π Be $\to D^0$
$0.15^{+0.16}_{-0.15}$		20	[52] PICCOLO 77	MRK1	E^{ee}_{cm} = 4.03, 4.41 GeV

[51] We have corrected the reported number (0.5 ± 0.2) to account for $B(\overline{K}^*(892)^0 \to K^-\pi^+) = 0.67$.

[52] We have corrected the reported number ($0.10^{+0.11}_{-0.10}$) to account for $B(\overline{K}^*(892)^0 \to K^-\pi^+) = 0.67$.

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^*(892)^0\rho^0\ (S\text{-wave}_{\text{Transverse}}))/\Gamma_{\text{total}}$ $\sigma\Gamma_{45}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID	TECN	COMMENT
0.112±0.014±0.040	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^*(892)^0\rho^0\ (S\text{-wave}_{\text{Longitud.}}))/\Gamma_{\text{total}}$ $\sigma\Gamma_{46}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.019	90	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\sigma(e^+e^- \to \psi(3770)) \times \Gamma(\overline{K}^*(892)^0\rho^0\ (P\text{-wave}))/\Gamma_{\text{total}}$ $\sigma\Gamma_{47}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.019	90	ADLER 90	MRK3	E^{ee}_{cm} = 3.77 GeV

$\Gamma(\overline{K}^0\omega)/\Gamma(K^-\pi^+)$ — Γ_{51}/Γ_{12}

VALUE	DOCUMENT ID	TECN	COMMENT
1.00±0.36±0.20	ALBRECHT 89D	ARG	E^{ee}_{cm} = 10 GeV

$\Gamma(\overline{K}^0\eta)/\Gamma(K^-\pi^+)$ — Γ_{52}/Γ_{12}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.64	90	ALBRECHT 89D	ARG	E^{ee}_{cm} = 10 GeV

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+)$ — Γ_{53}/Γ_{12}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.70	90	ALBRECHT 89D	ARG	E^{ee}_{cm} = 10 GeV

$\Gamma(\overline{K}^0\phi)/\Gamma_{total}$ — Γ_{54}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0080±0.0016 OUR FIT				
0.016 ±0.008	6	[53] BARLAG 89B	CCD	π^- Cu 230 GeV

[53] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(\overline{K}^0\phi)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — $\Gamma_{54}/(\Gamma_{14}+\Gamma_{16}+\frac{2}{3}\Gamma_{39})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.151±0.026 OUR FIT				
0.150±0.028 OUR AVERAGE				
0.155±0.033		[54] ALBRECHT 87E	ARG	E^{ee}_{cm} = 10 GeV
0.14 ±0.05	29	BEBEK 86	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.186±0.052	26	ALBRECHT 85B	ARG	Repl. by ALBRECHT 87E

[54] ALBRECHT 87E also report $\Gamma(\overline{K}^0K^+K^-$ non-$\phi) = 0.0064 \pm 0.0015 \pm 0.0009$ where they used $B(D^0 \rightarrow \overline{K}^0\pi^+\pi^-) = 0.076 \pm 0.007 \pm 0.008$.

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{55}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.00114± 0.00031 OUR FIT				
(9 ± 6) × 10^{-4} OUR AVERAGE				
(8 ± 6) × 10^{-4}	3	[55] BARLAG 89B	CCD	π^- Cu 230 GeV
$(50\ ^{+120}_{-20} \pm 40) \times 10^{-4}$	1	[56] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV

[55] BARLAG 89B computed the branching ratio using topological normalization.

[56] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.

$\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{55}/Γ_{12}

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.031±0.008 OUR FIT					
0.033±0.009 OUR AVERAGE					
0.033±0.010±0.006		39	BALTRUSAIT..85E	MRK3	E^{ee}_{cm} = 3.77 GeV
0.033±0.015			ABRAMS 79D	MRK2	E^{ee}_{cm} = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.07	90		PICCOLO 77	MRK1	E^{ee}_{cm} = 4.03 GeV

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{56}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.012±0.004 OUR AVERAGE				
$0.036^{+0.033}_{-0.021} \pm 0.001$	2	[57] BARLAG 89B	CCD	π^- Cu 230 GeV
0.011±0.004±0.002	10	[58] BALTRUSAIT..85E	MRK3	E^{ee}_{cm} = 3.77 GeV

[57] BARLAG 89B computed the branching ratio using topological normalization.

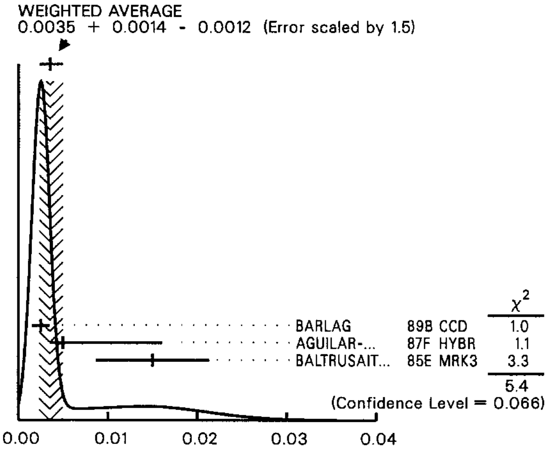
[58] All events consistent with $\rho^0\pi^0$.

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{57}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0035^{+0.0014}_{-0.0012}$ OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
0.0025±0.0010	10	[59] BARLAG 89B	CCD	π^- Cu 230 GeV
$0.005\ ^{+0.011}_{-0.001} \pm 0.001$	1	[60] AGUILAR-... 87F	HYBR	πp, pp 360,400 GeV
0.015 ±0.006 ±0.002	9	BALTRUSAIT..85E	MRK3	E^{ee}_{cm} = 3.77 GeV

[59] BARLAG 89B computed the branching ratio using topological normalization.

[60] AGUILAR-BENITEZ 87F computed the branching ratio by topological normalization.



$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{57}/Γ_{22}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.21	90	SCHINDLER 81	MRK2	E^{ee}_{cm} = 3.771 GeV

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{58}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.048^{+0.028}_{-0.020}$	4	[61] BARLAG 89B	CCD	π^- Cu 230 GeV

[61] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{total}$ — Γ_{59}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
(4±3) × 10^{-4}	2	[62] BARLAG 89B	CCD	π^- Cu 230 GeV

[62] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_{60}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0045±0.0007 OUR FIT				
$0.0049^{+0.0015}_{-0.0014}$	15	[63] BARLAG 89B	CCD	π^- Cu 230 GeV

[63] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ — Γ_{60}/Γ_{12}

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.121±0.016 OUR FIT					
0.119±0.018 OUR AVERAGE					
0.122±0.018±0.012		118	BALTRUSAIT..85E	MRK3	E^{ee}_{cm} = 3.77 GeV
0.113±0.030			ABRAMS 79D	MRK2	E^{ee}_{cm} = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.07	90		PICCOLO 77	MRK1	E^{ee}_{cm} = 4.03 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(\overline{K}^0K^0)/\Gamma_{total}$ — $\sigma\Gamma_{61}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.025	90	BALTRUSAIT..86C	MRK3	E^{ee}_{cm} = 3.77 GeV

$\Gamma(\overline{K}^0_SK^0_S)/\Gamma(K^+K^-)$ — Γ_{62}/Γ_{60}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.12±0.08	4	[64] CUMALAT 88	SPEC	nN 0–800 GeV

[64] Includes a correction communicated to us by the authors of CUMALAT 88.

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^0K^-\pi^+$ (non-res.)+c.c.$)/\Gamma_{total}$ — $\sigma\Gamma_{66}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID	TECN	COMMENT
<0.079	90	[65] BALTRUSAIT..86C	MRK3	E^{ee}_{cm} = 3.77 GeV

[65] Excludes contributions from $D^0 \rightarrow K^*(892)K$.

$\Gamma(K^0K^-\pi^+$ (non-res.)+c.c.$)/\Gamma_{total}$ — Γ_{66}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	1	AGUILAR-... 86B	HYBR	π^-p 360 GeV

$\Gamma(K^+K^-\pi^0\pi^0)/\Gamma_{total}$ — Γ_{67}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	1	AGUILAR-... 86B	HYBR	π^-p 360 GeV

$\Gamma((K^+K^-)\pi^+\pi^-$ non-res.$)/\Gamma_{\rm total}$ $\quad\Gamma_{68}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0017±0.0006	10	[66] BARLAG	89B	CCD	π^- Cu 230 GeV

[66] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(K^0K^-\pi^+\pi^0)/\Gamma_{\rm total}$ $\quad\Gamma_{70}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	1	AGUILAR-...	86B	HYBR	π^- p 360 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(\overline{K}^*(892)^0K^0$ + c.c.$)/\Gamma_{\rm total}$ $\quad\sigma\Gamma_{71}/\Gamma$

VALUE (nanobarns)	CL%	DOCUMENT ID		TECN	COMMENT
<0.036	90	BALTRUSAIT..	86C	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\sigma(e^+e^- \rightarrow \psi(3770)) \times \Gamma(K^*(892)^+K^-$ + c.c.$)/\Gamma_{\rm total}$ $\quad\sigma\Gamma_{72}/\Gamma$

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
0.050±0.024 OUR FIT				
0.050±0.023±0.010	BALTRUSAIT..	86C	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(\phi\pi^+\pi^-)/\Gamma_{\rm total}$ $\quad\Gamma_{73}/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0030±0.0010	10	[67] BARLAG	89B	CCD	π^- Cu 230 GeV

[67] BARLAG 89B computed the branching ratio using topological normalization.

$\Gamma(K^+\pi^-)/\Gamma(K^-\pi^+)$ $\quad\Gamma_{74}/\Gamma_{12}$

Doubly Cabibbo suppressed

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.015	90	2	ANJOS	88C	SILI	Photoproduction

$\Gamma(K^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+)$ $\quad\Gamma_{75}/\Gamma_{12}$

This is a D^0-$\overline{D}^0$ mixing limit.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0037	90	1	[68] ANJOS	88C	SILI	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.014	90		ALBRECHT	87K	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
<0.04	90		ABACHI	86D	HRS	$E^{ee}_{\rm cm}$ = 29 GeV
<0.07	90	0	[68] BAILEY	86	SILI	π^- Be fixed target
<0.11	90	2	ALBRECHT	85F	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
<0.081	90		[69] YAMAMOTO	85	DLCO	$E^{ee}_{\rm cm}$ = 29 GeV
<0.23	90		[69] ALTHOFF	84B	TASS	$E^{ee}_{\rm cm}$ = 34.4 GeV
<0.11	90		[69] AVERY	80	SPEC	$\gamma N \rightarrow D^{*+}$
<0.16	90		[69] FELDMAN	77B	MRK1	$D^{*+} \rightarrow D^0\pi^+$
<0.18	90		[69] GOLDHABER	77	MRK1	

[68] This measurement also uses $K^-\pi^+\pi^+\pi^-$ as well as $K^-\pi^+$.

[69] Results given as $\Gamma(K^+\pi^-)/[\Gamma(K^-\pi^+)+\Gamma(K^+\pi^-)]$ but do not change significantly for our denominator.

$\Gamma(K^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ $\quad\Gamma_{76}/\Gamma_{22}$

doubly Cabibbo suppressed

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.018	90	5	ANJOS	88C	SILI	Photoproduction

$\Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ $\quad\Gamma_{77}/\Gamma$

Test for $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.1 \times 10^{-5}$	90		LOUIS	86	SPEC	π^- W 225 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<7.0 \times 10^{-5}$	90	3	[70] ALBRECHT	88G	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
$<3.4 \times 10^{-4}$	90		AUBERT	85	EMC	Deep inelast. μ^- N

[70] The branching ratios are normalized to B($D^0 \rightarrow K^-\pi^+$), using ADLER 88C.

$\Gamma(e^+e^-)/\Gamma_{\rm total}$ $\quad\Gamma_{78}/\Gamma$

Test for $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.3 \times 10^{-4}$	90		ADLER	88	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.7 \times 10^{-4}$	90	7	[71] ALBRECHT	88G	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
$<2.2 \times 10^{-4}$	90	8	[72] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[71] The branching ratios are normalized to B($D^0 \rightarrow K^-\pi^+$) using ADLER 88C.

[72] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$ $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

$\Gamma(\mu^\pm e^\mp)/\Gamma_{\rm total}$ $\quad\Gamma_{79}/\Gamma$

Test of lepton family number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$< 1.0 \times 10^{-4}$	90	4	[73] ALBRECHT	88G	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 2.7 \times 10^{-4}$	90	9	[74] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV
$< 1.2 \times 10^{-4}$	90		BECKER	87C	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV
$< 9 \times 10^{-4}$	90		PALKA	87	SILI	200 GeV πp
$<21 \times 10^{-4}$	90	0	[75] RILES	87	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV

[73] The branching ratios are normalized to B($D^0 \rightarrow K^-\pi^+$) using ADLER 88C.

[74] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

[75] RILES 87 assumes B($D \rightarrow K\pi$) = 3.0% and has production model dependency.

$\Gamma(\overline{K}^0e^+e^-)/\Gamma_{\rm total}$ $\quad\Gamma_{80}/\Gamma$

Test for $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0017	90	ADLER	89C	MRK3	$E^{ee}_{\rm cm}$ = 3.77 GeV

$\Gamma(\rho^0e^+e^-)/\Gamma_{\rm total}$ $\quad\Gamma_{81}/\Gamma$

Test for $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<4.5 \times 10^{-4}$	90	2	[76] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[76] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

$\Gamma(\rho^0\mu^+\mu^-)/\Gamma_{\rm total}$ $\quad\Gamma_{82}/\Gamma$

Test for $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<8.1 \times 10^{-4}$	90	5	[77] HAAS	88	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

[77] The branching ratios are normalized to $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, and $D^{*+} \rightarrow D^0\pi^+$ using ADLER 88C.

$\Gamma(\mu^-$ anything (via $\overline{D}^0))/\Gamma(\mu^+$ anything$)$ $\quad\Gamma_{83}/\Gamma_2$

This is a D^0-$\overline{D}^0$ mixing limit. See the somewhat better limit in the section above on $D^0 \rightarrow K^+\pi^-$ (via $\overline{D}^0$).

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5.6 \times 10^{-3}$	90	LOUIS	86	SPEC	π^- W 225 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.012	90	BENVENUTI	85	CNTR	μC, 200 GeV
<0.044	90	BODEK	82	SPEC	π^-, pFe $\rightarrow D^0$

D^0 PRODUCTION CROSS SECTION AT ψ(3770)

A compilation of the cross sections for the direct production of D^0 mesons at or near the ψ(3770) peak in e^+e^- production. These cross sections are used for normalization of product branching fractions.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
6.6 ±0.4 OUR FIT				
6.5 ±0.6 OUR AVERAGE				
5.8 ±0.5 ±0.6	[78] ADLER	88C	MRK3	$E^{ee}_{\rm cm}$ = 3.768 GeV
7.3 ±1.3	[79] PARTRIDGE	84	CBAL	$E^{ee}_{\rm cm}$ = 3.771 GeV
8.00±0.95±1.21	[80] SCHINDLER	80	MRK2	$E^{ee}_{\rm cm}$ = 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11.5 ±2.5	[81] PERUZZI	77	MRK1	$E^{ee}_{\rm cm}$ = 3.774 GeV

[78] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C find the ratio of cross sections (neutral to charged) to be 1.36 ± 0.23 ± 0.14.

[79] This measurement comes from a scan of the ψ(3770) resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in ψ(3770) decay to be 1.33, and we assume that the ψ(3770) is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the ψ(3770) are included in this measurement and may amount to a few percent correction.

[80] This measurement comes from a scan of the ψ(3770) resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in ψ(3770) decay to be 1.33, and that the ψ(3770) is an isosinglet. The noncharm decays (e.g. radiative) of the ψ(3770) are included in this measurement and may amount to a few percent correction.

[81] This measurement comes from a scan of the ψ(3770) resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in ψ(3770) decay is taken to be 1.33, and ψ(3770) is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the ψ(3770) are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

REFERENCES FOR D^0

ADLER	90	SLAC-PUB-5130 (PRL)	+Blaylock, Bolton+	(Mark III Collab.)
BARLAG	90C	ZPHY C (to be pub.)	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ADLER	89	PRL 62 1821	+Becker, Blaylock, Bolton+	(Mark III Collab.)
ADLER	89C	PR D40 906	+Bai, Becker, Blaylock, Bolton+	(Mark III Collab.)
ALBRECHT	89D	ZPHY C43 181	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ANJOS	89F	PRL 62 1587	+Appel, Bean, Bracker, Browder+	(TPS Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
BARLAG	89B	PL B232 561	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ABACHI	88	PL B205 411	+Akerlof, Baringer+	(HRS Collab.)
ADLER	88	PR D37 2023	+Becker, Blaylock+	(Mark III Collab.)
ADLER	88C	PRL 60 89	+Becker, Blaylock+	(Mark III Collab.)
ALBRECHT	88G	PL B209 380	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
AMENDOLIA	88	EPL 5 407	+Bagliesi, Batignani+	(NA1 Collab.)
ANJOS	88C	PRL 60 1239	+Appel+	(Tagged Photon Spectrometer Collab.)
BORTOLETTO	88	PR D37 1719	+Goldberg, Horwitz, Mestayer, Moneti+	(CLEO Collab.)
Also	89D	PR D39 1471 erratum		
CUMALAT	88	PL B210 253	+Shipbaugh, Binkley+	(E-400 Collab.)
HAAS	88	PRL 60 1614	+Hempstead, Jensen+	(CLEO Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL TPS Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
ADLER	87	PL B196 107	+Becker, Blaylock, Bolton+	(Mark III Collab.)
AGUILAR-...	87C	ZPHY C34 143	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
AGUILAR-...	87D	PL B193 140	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88C	ZPHY C40 321	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
AGUILAR-...	87E	ZPHY C36 551	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)
Also	88C	ZPHY C40 321	Aguilar-Benitez, Allison+	(LEBC-EHS Collab.)

AGUILAR-... 87F ZPHY C36 559 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88 ZPHY C38 520 erratum
ALBRECHT 87E ZPHY C33 359 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87K PL B199 447 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALTHOFF 87 ZPHY C32 343 +Braunschweig, Gerhards+ (TASSO Collab.)
ANJOS 87 PRL 58 311 +Appel, Bracker, Browder+ (FNAL TPS Collab.)
BARLAG 87B ZPHY C37 17 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BECKER 87C PL B193 147 +Blaylock, Bolton, Brown+ (Mark III Collab.)
Also 87D PL B198 590 Becker, Blaylock, Bolton+ (Mark III Collab.)
Erratum.
CSORNA 87 PL B191 318 +Mestayer, Panvini, Word+ (CLEO Collab.)
PALKA 87 PL B189 238 +Bailey, Becker, Belau+ (ACCMOR Collab.)
RILES 87 PR D35 2914 +Dorfan, Abrams, Amidei+ (Mark II Collab.)
WAGNER 87 PR D36 2850 +Hinshaw, Ong, Abrams+ (Mark II Collab.)
ABACHI 86D PL B182 101 +Akerlof, Baringer, Ballam+ (HRS Collab.)
ABE 86 PR D33 1 + (SLAC Hybrid Facility Photon Collab.)
AGUILAR-... 86 PL 168B 170 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
AGUILAR-... 86B ZPHY C31 491 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
BAILEY 86 ZPHY C30 51 +Belau, Boehringer, Bosman+ (ACCMOR Collab.)
BALTRUSAIT... 86C PRL 56 2136 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 86E PRL 56 2140 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BEBEK 86 PRL 56 1893 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
GLADNEY 86 PR D34 2601 +Jaros, Ong, Barklow+ (Mark II Collab.)
LOUIS 86 PRL 56 1027 +Adolphsen, Alexander+ (PRIN, CHIC, ISU)
SCHINDLER 86B SLAC-PUB-4248 (SLAC)
SLAC Summer Institute
USHIDA 86B PRL 56 1771 +Kondo+ (AICH, FNAL, KOBE, SEOU, MCGI+)
ALBRECHT 85B PL 158B 525 +Binder, Harder, Philipp+ (ARGUS Collab.)
ALBRECHT 85F PL 150B 235 +Binder, Harder, Philipp+ (ARGUS Collab.)
AUBERT 85 PL 155B 461 +Bassompierre, Becks, Benchouk+ (EMC Collab.)
BAILEY 85 ZPHY C28 357 +Belau, Boehringer, Bosman+ (ABCCMR Collab.)
BALTRUSAIT... 85B PRL 54 1976 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 85E PRL 55 150 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BENVENUTI 85 PL 158B 531 +Bollini, Bruni, Camporesi+ (BCDMS Collab.)
YAMAMOTO 85 PRL 54 522 +Yamamoto, Atwood, Baillon+ (DELCO Collab.)
YAMAMOTO 85B PR D32 2901 +Yamamoto, Atwood, Baillon+ (DELCO Collab.)
ABE 84 PR D30 1 + (SLAC Hybrid Facility Photon Collab.)
ADAMOVICH 84B PL 140B 123 +Alexandrov, Bravo, Cartacci+ (WA58 Collab.)
AGUILAR-... 84 PL 135B 237 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
AGUILAR-... 84B PL 146B 266 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
ALTHOFF 84B PL 138B 317 +Braunschweig, Kirschfink+ (TASSO Collab.)
DERRICK 84 PRL 53 1971 +Fernandez, Fries, Hyman+ (HRS Collab.)
PARTRIDGE 84 Cal Tech 1984 Thesis (Crystal Ball Collab.)
SUMMERS 84 PRL 52 410 + (UCSB, CARL, COLO, FNAL, TNTO, OKLA, CNRC)
YELTON 84 PRL 52 2019 +Gladney, Goldhaber, Abrams+ (Mark II Collab.)
AGUILAR-... 83 PL 122B 312 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
BADERT... 83 PL 123B 471 Badertscher, Hahn, Hugentobler+ (BERN, MPIM)
BAILEY 83B PL 132B 237 +Bardsley, Becker, Blanar+ (ACCMOR Collab.)
BODEK 82 PL 113B 82 +Breedon+ (ROCH, CIT, CHIC, FNAL, STAN)
USHIDA 82 PRL 48 844 + (AICH, FNAL, KOBE, SEOU, MCGI, NAGO, OSU+)
ADEVA 81 PL 102B 285 +Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
BALLAGH 81 PR D24 7 +Bingham+ (LBL, UCB, FNAL, HAWA, WASH, WISC)
Also 80 PL 89B 423 Ballagh+ (LBL, UCB, FNAL, HAWA, WASH, WISC)
FIORINO 81 LNC 30 166 + (Photon-Emulsion and Omega-Photon Collab.)
FUCHI 81 LNC 31 199 +Hoshino, Miyanishi+ (NAGO, AICH, TOKY, YOKO)
SCHINDLER 81 PR D24 78 +Alam, Boyarski, Breidenbach+ (Mark II Collab.)
TRILLING 81 PRPL 75 57 (LBL, UCB) J
ALLASIA 80 NP B176 13 + (ANKA, LIBH, CERN, DUUC, LOUC, KEYN+)
ASTON 80E PL 94B 113 + (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
AVERY 80 PRL 44 1309 +Wiss, Butler, Gladding+ (ILL, FNAL, COLU)
BACINO 80 PRL 45 329 +Ferguson+ (UCLA, SLAC, STAN, UCI, STON)
SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
ABRAMS 79D PRL 43 481 +Alam, Blocker, Boyarski+ (SLAC, LBL)
ARMENISE 79 PL 86B 115 +Erriquez+ (BARI, CERN, EPOL, MILA, ORSA)
ATIYA 79 PRL 43 414 +Holmes, Knapp, Lee+ (COLU, ILL, FNAL)
BALTAY 78C PRL 41 73 +Caroumbalis, French, Hibbs, Hylton+ (COLU, BNL)
SCHARRE 78 PRL 40 74 +Barbaro-Galtieri+ (SLAC, LBL, NWES, HAWA)
VUILLEMIN 78 PRL 41 1149 +Feldman, Feller+ (LBL, SLAC, NWES, HAWA)
FELDMAN 77B PRL 38 1313 +Peruzzi, Piccolo, Abrams, Alam+ (SLAC, LBL)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (SLAC, LBL, NWES, HAWA)
PICCOLO 77 PL 70B 260 +Peruzzi, Luth, Nguyen, Wiss, Abrams+ (SLAC, LBL)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)
GOLDHABER 76 PRL 37 255 +Pierre, Abrams, Alam+ (LBL, SLAC)

OTHER RELATED PAPERS

SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
GRAB 87 SLAC-PUB-4372 (SLAC)
EPS Conference – Uppsala
SCHUBERT 87 IHEP-HD/87-7 (HEID)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791
SNYDER 87 IUHEEE-87-11 (IND)
Symp. on Prod. and Decay of Heavy Flavors, Stanford
SCHINDLER 86 SLAC-PUB-4136 (SLAC)
World Press International
SCHINDLER 86B SLAC-PUB-4248 (SLAC)
SLAC Summer Institute
KIRKBY 79 SLAC-PUB-2419 (SLAC)
Batavia Lepton Photon Conference.
BARBARO-... 78 LBL-8537 Erice 1978 Barbaro-Galtieri (LBL)
WOJCICKI 78 SLAC-PUB-2232 (SLAC)
SLAC Summer Institute. SLAC Summer Institute.
NGUYEN 77 PRL 39 262 +Wiss, Abrams, Alam, Boyarski+ (LBL, SLAC) J

$D^*(2010)^\pm$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

$D^*(2010)^\pm$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2010.1±0.6 OUR EVALUATION	From D^0 mass and mass difference below.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2008 ±3	[1] GOLDHABER	77	MRK1	±	e^+e^-
2008.6±1.0	[2] PERUZZI	77	MRK1	±	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2010)^0$, D^+, and D^0; not independent of FELDMAN 77B mass difference below.

[2] PERUZZI 77 mass not independent of FELDMAN 77B mass difference below and PERUZZI 77 D^0 mass value.

$D^*(2010)^+ - D^0$ MASS DIFFERENCE

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
145.44±0.06 OUR AVERAGE					
145.40±0.05±0.10		ABACHI	88B	HRS	$D^{*\pm} \to D^0\pi^\pm$
145.46±0.07±0.03		ALBRECHT	85F	ARG	$D^{*\pm} \to D^0\pi^+$
145.8 ±1.5	16	AHLEN	83	HRS	$D^{*+} \to D^0\pi^+$
145.1 ±1.8	12	BAILEY	83	SPEC	$D^{*\pm} \to D^0\pi^\pm$
145.5 ±0.3	28	BAILEY	83	SPEC	$D^{*\pm} \to D^0\pi^\pm$
145.1 ±0.5	14	BAILEY	83	SPEC	$D^{*\pm} \to D^0\pi^\pm$
145.5 ±0.5	14	YELTON	82	MRK2	29 $e^+e^- \to K^-\pi^+$
145.5 ±0.3	60	FITCH	81	SPEC	π^- A
145.2 ±0.6	2	BLIETSCHAU	79	BEBC	νp
145.3 ±0.5	30	FELDMAN	77B	MRK1	$D^{*+} \to D^0\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 145.5		AVERY	80	SPEC	γA

$D^*(2010)^+ - D^*(2010)^0$ MASS DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2.9±1.3 OUR EVALUATION	From D^{*+}-D^0 and D^{*0}-D^0 mass differences.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.6±1.8	[3] PERUZZI	77	MRK1	±	e^+e^-

[3] Not independent of FELDMAN 77B mass difference above, PERUZZI 77 D^0 mass, and GOLDHABER 77 $D^*(2010)^0$ mass.

$D^*(2010)^\pm$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.1	90		ABACHI	88B	HRS	$D^{*\pm} \to D^0\pi^\pm$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.2			YELTON	82	MRK2	$e^+e^- \to K^-\pi^+\pi^-$
<2.0	90	30	FELDMAN	77B	MRK1	$D^{*+} \to D^0\pi^+$

$D^*(2010)^+$ DECAY MODES

$D^*(2010)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	(55 ±4) %
Γ_2	$D^+\pi^0$	(27.2±2.5) %
Γ_3	$D^+\gamma$	(18 ±4) %

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 6 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 2.6 for 4 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ccc} x_2 & -19 & \\ x_3 & -82 & -41 \\ & x_1 & x_2 \end{array}$$

$D^*(2010)^+$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.55±0.04 OUR FIT				
0.54±0.05 OUR AVERAGE				
0.57±0.04±0.04	ADLER 88D	MRK3		e^+e^-
0.44±0.10	COLES 82	MRK2		e^+e^-
0.6 ±0.15	[4] GOLDHABER 77	MRK1	+	e^+e^-

[4] Assuming that isospin is conserved in the decay.

$\Gamma(D^+\pi^0)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.272±0.025 OUR FIT			
0.271±0.028 OUR AVERAGE Error includes scale factor of 1.1.			
0.26 ±0.02 ±0.02	ADLER 88D	MRK3	e^+e^-
0.34 ±0.07	COLES 82	MRK2	e^+e^-

$\Gamma(D^+\gamma)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.18±0.04 OUR FIT			
0.17±0.05±0.05	ADLER 88D	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.22±0.12	[5] COLES 82	MRK2	e^+e^-

[5] Not independent of $\Gamma(D^0\pi^+)/\Gamma_{\text{total}}$ and $\Gamma(D^+\pi^0)/\Gamma_{\text{total}}$ measurement.

$D^*(2010)^\pm$ REFERENCES

ABACHI 88B PL B212 533 +Akerlof+ (ANL, IND, MICH, PURD, LBL)
ADLER 88D PL B208 152 +Becker+ (Mark III Collab.)
ALBRECHT 85F PL 150B 235 +Binder, Harder, Philipp+ (ARGUS Collab.)
AHLEN 83 PRL 51 1147 +Akerlof+ (ANL, IND, LBL, MICH, PURD, SLAC)
BAILEY 83 PL 132B 230 +Bardsley+ (AMST, BRIS, CERN, CRAC, MPIM+)
COLES 82 PR D26 2190 +Abrams, Blocker, Blondel+ (LBL, SLAC)
YELTON 82 PRL 49 430 +Feldman, Goldhaber+ (SLAC, LBL, UCB, HARV)
FITCH 81 PRL 46 761 +Devaux, Cavaglia, May+ (PRIN, SACL, TORI, BNL)
AVERY 80 PRL 44 1309 +Wiss, Butler, Gladding+ (ILL, FNAL, COLU)
BLIETSCHAU 79 PL 86B 108 + (AACH, BONN, CERN, MPIM, OXF)
FELDMAN 77B PRL 38 1313 +Peruzzi, Piccolo, Abrams, Alam+ (SLAC, LBL)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (SLAC, LBL, NWES, HAWA)

OTHER RELATED PAPERS

ALTHOFF 83C PL 126B 493 +Fischer, Burkhardt+ (TASSO Collab.)
BEBEK 82 PRL 49 610 + (HARV, OSU, ROCH, RUTG, SYRA, VAND+)
TRILLING 81 PRPL 75 57 (LBL, UCB)
PERUZZI 76 PRL 37 569 +Piccolo, Feldman, Nguyen, Wiss+ (SLAC, LBL)

$D^*(2010)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

J consistent with 1, value 0 ruled out (NGUYEN 77).

$D^*(2010)^0$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2007.1±1.4 OUR EVALUATION From D^0 mass and mass difference below.			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2006 ±1.5	[1] GOLDHABER 77	MRK1	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2010)^0$, D^+, and D^0.

$D^*(2010)^0$ – D^0 MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
142.5±1.3 OUR AVERAGE				
142.2±2.0	SADROZINSKI 80	CBAL	0	$D^{*0} \to D^0\pi^0$
142.7±1.7	[2] GOLDHABER 77	MRK1	0	e^+e^-

[2] From simultaneous fit to $D^*(2010)^+$, $D^*(2010)^0$, D^+, and D^0.

$D^*(2010)^0$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
<2.1	90	[3] ABACHI 88B	HRS	$D^{*0} \to D^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5		GOLDHABER 76B	MRK1	$e^+e^- \to D^*D^*$

[3] Assuming $m(D^{*0}) = 2007.2 \pm 2.1$ MeV/c^2.

$D^*(2010)^0$ DECAY MODES

$\overline{D}{}^*(2010)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^0$	(55±6) %
Γ_2	$D^0\gamma$	(45±6) %

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 5 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 0.9 for 4 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ll} x_2 & -100 \\ & x_1 \end{array}$$

$D^*(2010)^0$ BRANCHING RATIOS

$\Gamma(D^0\gamma)/[\Gamma(D^0\pi^0) + \Gamma(D^0\gamma)]$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.45±0.06 OUR FIT			
0.45±0.06 OUR AVERAGE			
0.37±0.08±0.08	ADLER 88D	MRK3	e^+e^-
0.47±0.23	LOW 87	HRS	29 GeV e^+e^-
0.53±0.13	BARTEL 85G	JADE	e^+e^-, hadrons
0.47±0.12	COLES 82	MRK2	e^+e^-
0.45±0.15	[4] GOLDHABER 77	MRK1	e^+e^-

[4] We quote the normal fit value from table 1. The isospin-constrained fit is now known to give a $D^0\gamma$ fraction which is too large. See details in footnote 21 of FELDMAN 77C review.

$D^*(2010)^0$ REFERENCES

ABACHI 88B PL B212 533 +Akerlof+ (ANL, IND, MICH, PURD, LBL)
ADLER 88D PL B208 152 +Becker+ (Mark III Collab.)
LOW 87 PL B183 232 +Abachi, Akerlof, Baringer+ (HRS Collab.)
BARTEL 85G PL 161B 197 +Dietrich, Ambrus+ (JADE Collab.)
COLES 82 PR D26 2190 +Abrams, Blocker, Blondel+ (LBL, SLAC)
SADROZINSKI 80 Madison Conf. 681 + (PRIN, CIT, HARV, SLAC, STAN)
FELDMAN 77C Banff Sum. Inst. 75 (SLAC)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)
NGUYEN 77 PRL 39 262 +Wiss, Abrams, Alam, Boyarski+ (LBL, SLAC) J
GOLDHABER 76B SLAC Conf. 379 (LBL, SLAC)
Available as LBL-5534.

OTHER RELATED PAPERS

TRILLING 81 PRPL 75 57 (LBL, UCB)
FELDMAN 77C Banff Sum. Inst. 75 (SLAC)
GOLDHABER 76 PRL 37 255 +Pierre, Abrams, Alam+ (LBL, SLAC)

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+\pi^-$. $J^P = 1^+$ according to ALBRECHT 89B and ALBRECHT 89H. The $D_J(2420)^0$ entry of 1988 is a superposition of $D_1(2420)^0$ and $D_2^*(2460)^0$ according to ALBRECHT 89H and AVERY 90.

$D_1(2420)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2424±6 OUR AVERAGE Error includes scale factor of 2.2.				
2428±3±2	279 ± 34	AVERY 90	CLEO	$e^+e^- \to D^{*+}\pi^- X$
2414±2±5	171+-22	ALBRECHT 89H	ARG	$e^+e^- \to D^{*+}\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2428±8±5	171^{+43}_{-58}	ANJOS 89C	TPS	$\gamma N \to D^{*+}\pi^- X$
2421±5		[1] PRENTICE 87	ARG	$e^+e^- \to D^{*+}\pi^- X$

[1] Includes data of ALBRECHT 86E.

$D_1(2420)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
20^{+9}_{-5} OUR AVERAGE					
23^{+8+10}_{-6-3}	279 ± 34	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
$13 \pm 6^{+10}_{-5}$	171+-22	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^{*+}\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$58 \pm 14 \pm 10$	171^{+43}_{-58}	ANJOS	89C	TPS	$\gamma N \rightarrow D^{*+}\pi^- X$
62 ± 14		[2] PRENTICE	87	ARG	$e^+e^- \rightarrow D^{*+}\pi^- X$

[2] Includes data of ALBRECHT 86E.

$D_1(2420)^0$ DECAY MODES

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+\pi^-$	seen
Γ_2	$D^+\pi^-$	

$D_1(2420)^0$ BRANCHING RATIOS

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
seen	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^*\pi^- X$
seen	ANJOS	89C	TPS	$\gamma N \rightarrow D^{*+}\pi^- X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.24	90	AVERY	90	CLEO	$e^+e^- \rightarrow D^+\pi^- X$

$D_1(2420)^0$ REFERENCES

AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89B	PL B221 422	+Boeckmann+	(ARGUS Collab.)
ALBRECHT	89H	PL 232 398	+Glaser, Harder+	(ARGUS Collab.) JP
ANJOS	89C	PRL 62 1717	+Appel+	(TPS Collab.)
PRENTICE	87	Uppsala Conf. p. 910	+	(ARGUS Collab.)
ALBRECHT	86E	PRL 56 549	+Binder, Harder+	(ARGUS Collab.)

$D_J(2440)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE

Possibly seen in $D^*(2010)^0\pi^+$. $J^P = 0^+$ ruled out.

$D_J(2440)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$2443 \pm 7 \pm 5$	190^{+77}_{-44}	ANJOS	89C	TPS	$\gamma N \rightarrow D^0\pi^+ X^0$

$D_J(2440)^\pm$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$41 \pm 19 \pm 8$	190^{+77}_{-44}	ANJOS	89C	TPS	$\gamma N \rightarrow D^0\pi^+ X^0$

$D_J(2440)^\pm$ DECAY MODES

$D_J^*(2440)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^0\pi^+$	seen

$D_J(2440)^\pm$ BRANCHING RATIOS

$\Gamma(D^*(2010)^0\pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ANJOS	89C	TPS	$\gamma N \rightarrow D^0\pi^+ X^0$

$D_J(2440)^\pm$ REFERENCES

ANJOS	89C	PRL 62 1717	+Appel+	(TPS Collab.)

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$
I, J, P need confirmation.

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

$D_2^*(2460)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2459.4 ± 2.2 OUR AVERAGE					
$2461 \pm 3 \pm 1$	440 ± 97	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
$2455 \pm 3 \pm 5$	337 ± 100	ALBRECHT	89B	ARG	$e^+e^- \rightarrow D^+\pi^-$
$2459 \pm 3 \pm 2$	153^{+42}_{-37}	ANJOS	89C	TPS	$\gamma N \rightarrow D^+\pi^-$

$D_2^*(2460)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
19 ± 7 OUR AVERAGE					
20^{+9+9}_{-12-10}	440 ± 97	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
15^{+13+5}_{-10-10}	337 ± 100	ALBRECHT	89B	ARG	$e^+e^- \rightarrow D^+\pi^-$
$20 \pm 10 \pm 5$	153^{+42}_{-37}	ANJOS	89C	TPS	$\gamma N \rightarrow D^+\pi^-$

$D_2^*(2460)^0$ DECAY MODES

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^+\pi^-$	seen
Γ_2	$D^*(2010)^+\pi^-$	seen

$D_2^*(2460)^0$ BRANCHING RATIOS

$\Gamma(D^+\pi^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	337 ± 100	ALBRECHT	89B	ARG	$e^+e^- \rightarrow D^+\pi^-$
seen		ANJOS	89C	TPS	$\gamma N \rightarrow D^+\pi^-$

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
seen	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^*\pi^- X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
2.4 ± 0.7 OUR AVERAGE				
2.3 ± 0.8	AVERY	90	CLEO	e^+e^-
$3.0 \pm 1.1 \pm 1.5$	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^*\pi^- X$

$D_2^*(2460)^0$ REFERENCES

AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89B	PL B221 422	+Boeckmann+	(ARGUS Collab.) JP
ALBRECHT	89H	PL 232 398	+Glaser, Harder+	(ARGUS Collab.) JP
ANJOS	89C	PRL 62 1717	+Appel+	(TPS Collab.)

$D_J^*(2470)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE

Seen in $D^0\pi^+$.

$D_J^*(2470)^\pm$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2469±4±6	ALBRECHT	89F	ARG	$e^+e^- \to D^0\pi^+X$

$D_J^*(2470)^\pm - D_2^*(2460)^0$ MASS DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
14±5±8	ALBRECHT	89F	ARG	$e^+e^- \to D^0\pi^+X$

$D_J^*(2470)^+$ DECAY MODES

$D_J^*(2470)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	seen

$D_J^*(2470)^+$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	ALBRECHT	89F	ARG	$e^+e^- \to D^0\pi^+X$

$D_J^*(2470)^\pm$ REFERENCES

ALBRECHT 89F PL B231 208 +Glaeser+ (ARGUS Collab.)

CHARMED STRANGE MESONS
$(C = S = \pm 1)$

$D_s^+ = c\overline{s}$, $D_s^- = \overline{c}s$, similarly for D_s^*'s

$D_s^\pm$
was $F^\pm$

$I(J^P) = 0(0^-)$

Quantum numbers not measured. Values are assigned here assuming charmed-strange ground state D_S meson. CHEN 83B observations are consistent with $J = 0$. BLAYLOCK 87 observations are consistent with $J^P = 0^-$.

NOTE ON THE D_s DECAYS

(by W.H. Toki, SLAC)

New data on D_s decays in this edition come from the CLEO, ACCMOR, NA14$'$, Mark III, and ARGUS groups. This brief note discusses new results in hadronic decays, the absolute branching ratios, and the P-wave D_s candidates, obtained from recent publications, preprints, and summaries.[1]

The new D_s hadronic modes and recent measurements which differ substantially from previous measurements are listed in Table 1 by mode. The mode $K^0K^*(892)^+$ is analogous to the K^0K^+ and $K^*(892)^0K^+$ modes previously observed and is seen at a comparable rate to that of $\phi\pi$. The existence of these $K\overline{K}$ decays indicates that the strength of the internal W emission diagrams is sizeable. The $\phi\pi^+\pi^0$ mode is seen only in one experiment, and due to the limited statistics, it is not possible to determine if the decay is through the quasi-two body mode $\phi\rho^0$. The $f^0\pi$ mode has now been seen in the three-pion Dalitz plot by E691 and confirmed by Mark III. The $f^0\pi$ mode is predicted by the weak spectator decay as the f^0 is believed to be the scalar with hidden strangeness below $K\overline{K}$ threshold. The evidence for the $\eta\pi$ and $\eta'\pi$ modes is still controversial. A previous Mark II measurement reported a rate relative to $\phi\pi$ of 3.0 ± 1.1 and 4.8 ± 2.1[10] for these modes respectively. Recently E691 and Mark III have set upper limits whereas NA14$'$ has now seen a very large signal in $\eta'\pi$. The final answer may lie somewhere in between and will have to await more experimental data.

Table 1. D_s Hadronic Decay Modes

Decay Mode	$\Gamma(\text{Mode})/\Gamma(D_s^\pm \to \phi\pi^\pm)$	Group
$K^0K^*(892)^+$	0.89 ± 0.32	ACCOR[2]
$K^0K^*(892)^+$	1.20 ± 2.1	CLEO[3]
$\phi\pi^+\pi^0$	< 3.5 at 90%CL	NA14$'$[4]
$\phi\pi^+\pi^0$	$2.4\pm1.0\pm0.5$	TPS[5]
$\pi^+\pi^-\pi^+\pi^0$	< 3.3 at 90%CL	TPS[5]
$\omega\pi^+$	< 0.5 at 90%CL	TPS[5]
$f^0\pi$	$0.28 \pm 0.21 \pm 0.28$	TPS[6]
$f^0\pi$	$0.58 \pm 0.21 \pm 0.28$	Mark III[7]
$\eta\pi^+$	< 1.5 at 90%CL	TPS[5]
$\eta\pi^+$	< 2.5 at 90%CL	Mark III[8]
$\eta'\pi^-$	< 1.9 at 90%CL	Mark III[8]
$\eta'\pi^+$	$6.9 \pm 2.4 \pm 1.4$	NA14$'$[9]

All branching ratios of the D_s are currently normalized to that of the $\phi\pi$ mode. Therefore knowledge of $B(\phi\pi)$ is required to derive the absolute branching ratios of the other modes. There are three different approaches to estimate this ratio, all from e^+e^- production:

The first method experimentally measures the inclusive rate of $\sigma_{\text{exp}}(e^+e^- \to D_s,\ D_s \to \phi\pi)$ and theoretically determines the total D_s cross section, $\sigma_{\text{th}}(e^+e^- \to D_s)$, from estimates of the total charm content in R and estimates of the strange sea. The absolute branching ratio is then

$$B(D_s \to \phi\pi) = \frac{\sigma_{\text{exp}}(e^+e^- \to D_s,\ D_s \to \phi\pi)}{\sigma_{\text{th}}(e^+e^- \to D_s)} .$$

The second method from the CLEO group attempts a more precise estimate of $\sigma_{\text{th}}(e^+e^- \to D_s)$ by again estimating the total charm content in R and by measuring all the charm baryons and mesons (except the D_s) and attributing the remaining missing charm from e^+e^- production to the D_s.

The third method searches for associated production of exclusive D_s pairs in e^+e^- production into various decay modes near threshold and compares the rate to the inclusive D_s production in the same decay modes. Thus the branching ratio for the $\phi\pi$ mode is equal to

$$B(D_s \to \phi\pi) = \frac{\sigma_{\text{exp}}(e^+e^- \to D_s^+D_s^-,\ D_s^+ \to \phi\pi^+,\ D_s^- \to \phi\pi^-)}{\sigma_{\text{exp}}(e^+e^- \to D_s^\pm,\ D_s^\pm \to \phi\pi^\pm)} .$$

This technique, often called the double-tag method, was attempted by the Mark III for the D_s but because of limited statistics no events were found and an upper limit was set.

The first two approaches are model dependent and require several theoretical estimates. The last approach is model independent but will require more data to obtain a measurement. As the $\phi\pi$ branching ratio drops, we expect that there exist many more decays that have not been measured. These missing decay modes should contain hidden strangeness and are probably attributed to states with high-charged multiplicities and/or many neutral secondaries.

Table 2. Absolute $D_s \to \phi\pi$ Branching Ratio Estimates

Method	Absolute $B(D_s \to \phi\pi)$	Group
Charm continuum estimate	1.7 – 13%	Many groups[11]
All inclusive measurement	2 ± 1%	CLEO[12]
Associated production	< 4.1 at 90%CL	Mark III[13]

Table 3. Excited P-Wave D_s Candidate

Decay Mode	Mass	Width	Group
$D^{*+}K^0$	$2535.9 \pm 0.6 \pm 2.0$ MeV/c^2	< 4.6 MeV/c^2	ARGUS[14]
$D^{*+}K^0$	$2535.6 \pm 0.7 \pm 0.4$ MeV/c^2	< 5.44 MeV/c^2	CLEO[15]

Both ARGUS and CLEO observe a narrow resonance in the mode $D_{sJ}(2536)^+ \to D^*(2010)^+K^0$ as shown in Table 3. This can be identified as the P-wave $c\bar{s}$ state that strongly decays into charmed and strange mesons. The lack of evidence of the mode D^+K^0 suggests that the state is not the lowest-lying P-wave scalar but possibly the $^1P_1$ or $^3P_1$ state. The mass is roughly 100 MeV/c^2 above the P-wave $c\bar{u}$ candidate at 2428 MeV/c^2. This is where the P-wave $c\bar{s}$ candidate is expected since the P-wave mass splittings between charm-strange and charm-nonstrange mesons should follow the S-wave splittings, $M(c\bar{s}, {}^1S_0) - M(c\bar{u}, {}^1S_0) \approx M(c\bar{s}, {}^3S_1) - M(c\bar{u}, {}^3S_1) \approx$ 100 MeV/c^2. The width is surprisingly narrow but may be a consequence of mixing between the two 1^+ states.

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$D_s^{\pm}$ MASS

The fit includes the $D^{\pm}$, D^0, $D_s^{\pm}$, and $D_s^{*\pm}$ masses and the $D^0 - D^{\pm}$, $D_s^{\pm} - D^{\pm}$, and $D_s^{*\pm} - D_s^{\pm}$ mass differences.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1968.8 ± 0.7 OUR FIT	Error includes scale factor of 1.1.				
1969.1 ± 1.2 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
1967.0 ± 1.0 ± 1.0	54	[1] BARLAG	90C CCD		π^- Cu 230 GeV
1969.3 ± 1.4 ± 1.4		[2] ALBRECHT	88 ARG		$E^{ee}_{\rm cm}$ = 9.4–10.6 GeV
	290	[3] ANJOS	88 SILI		Photoproduction
1972.7 ± 1.5 ± 1.0	21	BECKER	87B SILI		200 GeV π,K,p
1972.4 ± 3.7 ± 3.7	27	BLAYLOCK	87 MRK3		$E^{ee}_{\rm cm}$ = 4.14 GeV
1980.0 ± 15.0	6	USHIDA	86 EMUL		ν wideband
1963 ± 3 ± 3	30	DERRICK	85B HRS		$E^{ee}_{\rm cm}$ = 29 GeV
1948 ± 28 ± 10	65	AIHARA	84D TPC		$E^{ee}_{\rm cm}$ = 29 GeV
1975 ± 9 ± 10	49	ALTHOFF	84 TASS	±	$E^{ee}_{\rm cm}$ = 14–25 GeV
1970 ± 5 ± 5	104	CHEN	83C CLEO	±	$E^{ee}_{\rm cm}$ = 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1973.6 ± 2.6 ± 3.0	163	ALBRECHT	85D ARG		$E^{ee}_{\rm cm}$ = 10 GeV
1975.0 ± 4.0	3	BAILEY	84 SILI		hadron$^+$ Be $\to \phi\pi^+X$
2017 ± 13	17	[4] ATKINSON	83 OMEG	±	γp
2020 ± 10 ± 20	460	[5] ASTON	81 OMEG	±	γp
2049 ± 15	30	ASTON	81B OMEG	±	γp
2017 ± 25	1	AMMAR	80 HYBR	+	ν wideband
2026 ± 56	1	USHIDA	80B EMUL	−	FNAL ν wideband
2089 ± 121	1	USHIDA	80B EMUL	+	FNAL ν wideband
2030 ± 60	6	BRANDELIK	79 DASP	±	$E^{ee}_{\rm cm}$ = 4.42 GeV
2030 ± 60	4	BRANDELIK	77B DASP	±	In BRANDELIK 79

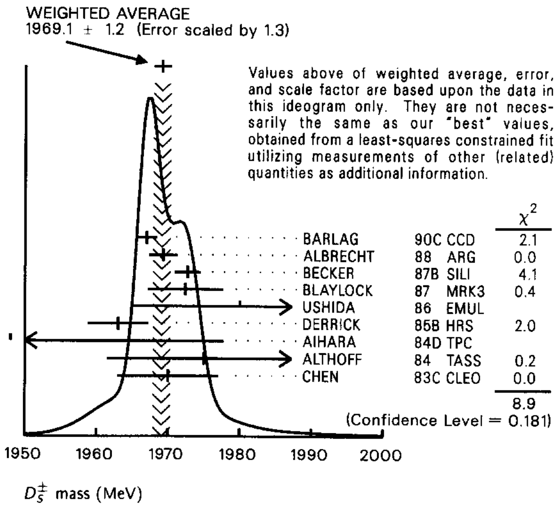
[1] BARLAG 90C use 54 $D_s^+ \to K^+K^-\pi^+$ decays.

[2] ALBRECHT 88 calculate their mass using the ARGUS value of $m(D^0) = 1864.1 \pm 1.4$ MeV which is 0.5 MeV lower than the world average.

[3] ANJOS 88 enters fit via the $D_s^{\pm} - D^{\pm}$ mass difference (see below). Their mass value is $1968.3 \pm 0.7 \pm 0.7$ MeV.

[4] ATKINSON 83 mass error includes systematic uncertainties.

[5] Error quoted by ASTON 81 is 10 MeV statistical and <20 MeV systematic average of three modes listed in sections $\Gamma(\eta\pi^+)/\Gamma(\phi\pi^+)$, $\Gamma(\eta\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$, and $\Gamma(\eta'(958)\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ below.



$D_s^\pm$ – $D^\pm$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
99.5±0.6 OUR FIT Error includes scale factor of 1.1.				
99.5±0.7 OUR AVERAGE				
98.5±1.5	555	CHEN 89	CLEO	$E^{ee}_{\rm cm}$ = 10.5 GeV
99.8±0.8	290	ANJOS 88	SILI	Photoproduction

$D_s^\pm$ MEAN LIFE

VALUE (10^{-13} s)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$\mathbf{4.45^{+0.35}_{-0.29}}$ **OUR AVERAGE**					
$4.69^{+1.02}_{-0.86}$	54	[6] BARLAG 90C	CCD		π^- Cu 230 GeV
$3.1\ ^{+2.4}_{-2.0}\ \pm0.5$		AVERILL 89	HRS		$E^{ee}_{\rm cm}$ = 29 GeV
$5.6\ ^{+1.3}_{-1.2}\ \pm0.8$		ALBRECHT 88I	ARG		$E^{ee}_{\rm cm}$ = 10 GeV
$4.7\ \pm0.4\ \pm0.2$	230	RAAB 88	SILI		Photoproduction
$3.3\ ^{+1.0}_{-0.6}$	21	[7] BECKER 87B	SILI		200 GeV π,K,p
$5.7\ ^{+3.6}_{-2.6}\ \pm0.9$	9	BRAUNSCH... 87	TASS		$E^{ee}_{\rm cm}$ = 35–44 GeV
$4.7\ \pm2.2\ \pm0.5$	141	CSORNA 87	CLEO		$E^{ee}_{\rm cm}$ = 10 GeV
$3.5\ ^{+2.4}_{-1.8}\ \pm0.9$	17	JUNG 86	HRS	+	$e^+e^-\to\phi\pi^+X$
$2.6\ ^{+1.6}_{-0.9}$	6	USHIDA 86	EMUL		ν wideband
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$4.8\ ^{+0.6}_{-0.5}\ \pm0.2$	99	ANJOS 87B	SILI		Repl. by RAAB 88
$3.2\ ^{+3.0}_{-1.3}$	3	BAILEY 84	SILI		hadron$^+$ Be $\to\phi\pi^+X$
$1.9\ ^{+1.3}_{-0.7}$	4	USHIDA 83	EMUL		Repl. by USHIDA 86
1.4	1	AMMAR 80	HYBR	+	ν wideband
$2.24^{+2.78}_{-1.05}$	2	USHIDA 80B	EMUL		ν wideband

[6] BARLAG 90C estimate systematic error to be negligible.
[7] BECKER 87B say systematic error was negligible.

D_s^+ DECAY MODES

D_s^- modes are charge conjugates of the modes below.

Values are all based on rough estimate of $D_s^\pm$ to total charm production. Only ratios of each fraction to the $\phi\pi^+$ mode are well known.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\phi\pi^+$	(2.7±0.7) %	
Γ_2	$\phi\pi^+\pi^+\pi^-$	(1.3±0.6) %	
Γ_3	$\rho^0\pi^+$	< 2.1 × 10^{-3}	90%
Γ_4	$K^0\pi^+$	< 6 × 10^{-3}	90%
Γ_5	$\overline{K}^0K^+$	(2.6±0.8) %	
Γ_6	$\overline{K}^*(892)^0K^+$	(2.6±0.7) %	
Γ_7	$K^*(892)^+\overline{K}^0$	(3.2±1.1) %	
Γ_8	$K^+K^-\pi^+$ (non-resonant)	(6.7±2.9) × 10^{-3}	
Γ_9	$K^+K^-\pi^+\pi^-\pi^+$ (non-res.)	< 9 × 10^{-3}	90%
Γ_{10}	$\mu^+\nu$	< 3 %	
Γ_{11}	$\eta\pi^+$	< 4 %	90%
Γ_{12}	$\eta\pi^+\pi^+\pi^-$	possibly seen	
Γ_{13}	$\eta'(958)\pi^+\pi^+\pi^-$	possibly seen	
Γ_{14}	$\phi\rho^+$	possibly seen	
Γ_{15}	$\eta'(958)\pi^+$	seen	
Γ_{16}	$f_0(975)\pi^+$	(7.5±3.4) × 10^{-3}	
Γ_{17}	$\pi^+\pi^-\pi^+$	(1.2±0.4) %	
Γ_{18}	$\pi^+\pi^-\pi^+$ (non-resonant)	(7.8±3.2) × 10^{-3}	
Γ_{19}	$\pi^+\pi^-\pi^+\pi^-\pi^+$	< 8 × 10^{-3}	90%
Γ_{20}	$\pi^+\pi^-\pi^+\pi^0$	< 9 %	90%
Γ_{21}	$\omega\pi^+$	< 1.3 %	90%
Γ_{22}	$\phi\pi^+\pi^0$	(6.4±3.4) %	
Γ_{23}	$K^+K^-\pi^+\pi^0$ (non-ϕ)	< 6 %	90%
Γ_{24}	η anything		

D_s^+ BRANCHING RATIOS

$\Gamma(\phi\pi^+)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.027±0.007 OUR AVERAGE					
<0.041	90	0	[8] ADLER 90B	MRK3	$E^{ee}_{\rm cm}$ = 4.14 GeV
0.02 ±0.01		405	[9] CHEN 89	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV
0.033±0.016±0.010		9	[9] BRAUNSCH... 87	TASS	$E^{ee}_{\rm cm}$ = 35–44 GeV
0.033±0.011		30	[9] DERRICK 85B	HRS	$E^{ee}_{\rm cm}$ = 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen		64	SHIPBAUGH 88	SPEC	$nN\to D_S$ +anything 0–800 GeV
		100	ALBRECHT 85D	ARG	$E^{ee}_{\rm cm}$ = 10 GeV
$0.13\ \pm0.03\ ^{+0.04}_{-0.07}$		49	[9] ALTHOFF 84	TASS	$E^{ee}_{\rm cm}$ = 14–25 GeV
seen			ARGUS 83	ARG	Preliminary
0.044		104	[9] CHEN 83C	CLEO	$E^{ee}_{\rm cm}$ = 10.5 GeV

[8] ADLER 90 used a technique based on full reconstruction of $D_s^+\ D_s^-$ pairs (double tags) to obtain branching ratio limit without $\sigma(D_S)$ assumptions.
[9] Values based on crude estimate of $D_s^\pm$ production level. ALTHOFF 84 errors have additional negative error for $D_s^\pm$ from primary B-meson. For DERRICK 85B the errors are statistical only.

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.48±0.20 OUR AVERAGE Error includes scale factor of 1.4.				
0.42±0.13±0.07	19	ANJOS 88	SILI	Photoproduction
1.11±0.37±0.28	62	ALBRECHT 85D	ARG	$E^{ee}_{\rm cm}$ = 10 GeV

$\Gamma(\rho^0\pi^+)/\Gamma(\phi\pi^+)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.08	90	ANJOS 89	TPS	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.22	90	ALBRECHT 87G	ARG	$E^{ee}_{\rm cm}$ = 10 GeV

$\Gamma(K^0\pi^+)/\Gamma(\phi\pi^+)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.21	90	ADLER 89B	MRK3	$E^{ee}_{\rm cm}$ = 4.14 GeV

$\Gamma(\overline{K}^0K^+)/\Gamma(\phi\pi^+)$ Γ_5/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.97±0.17 OUR AVERAGE			
0.92±0.32±0.20	ADLER 89B	MRK3	$E^{ee}_{\rm cm}$ = 4.14 GeV
0.99±0.17±0.10	CHEN 89	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

$\Gamma(\overline{K}^*(892)^0K^+)/\Gamma(\phi\pi^+)$ Γ_6/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.96±0.11 OUR AVERAGE				
0.84±0.30±0.22		ADLER 89B	MRK3	$E^{ee}_{\rm cm}$ = 4.14 GeV
1.05±0.17±0.12		CHEN 89	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV
0.87±0.13±0.05	117	ANJOS 88	SILI	Photoproduction
1.44±0.37	87	ALBRECHT 87F	ARG	$E^{ee}_{\rm cm}$ = 10 GeV

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(\phi\pi^+)$ Γ_7/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
1.20±0.21±0.13	CHEN 89	CLEO	$E^{ee}_{\rm cm}$ = 10 GeV

$\Gamma(K^+K^-\pi^+$ (non-resonant)$)/\Gamma(\phi\pi^+)$ Γ_8/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.25±0.07±0.05	48	ANJOS 88	SILI	Photoproduction

$\Gamma(K^+K^-\pi^+\pi^-\pi^+$ (non-res.)$)/\Gamma(\phi\pi^+)$ Γ_9/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.32	90	10	ANJOS 88	SILI	Photoproduction

$\Gamma(\mu^+\nu)/\Gamma_{\rm total}$ Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<0.03	0	[10] AUBERT 83	SPEC	μ^+ Fe, 250 GeV

[10] AUBERT 83 obtain this limit assuming that $D_s^\pm$ production rate is 20% of total charm production rate.

$\Gamma(\eta\pi^+)/\Gamma(\eta$ anything$)$ Γ_{11}/Γ_{24}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
possibly seen OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.09±0.06	6	[11] BRANDELIK 79	DASP	$E^{ee}_{\rm cm}$ = 4.42 GeV

[11] Denominator is inconsistent with PARTRIDGE 81 (Crystal Ball).

$\Gamma(\eta\pi^+)/\Gamma(\phi\pi^+)$ Γ_{11}/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.5	90		ANJOS 89E	TPS	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen			[12] WORMSER 88	MRK2	$E^{ee}_{\rm cm}$ = 29 GeV
		17	ATKINSON 83	OMEG	γp
		40	ASTON 81	OMEG	γp

[12] The $\eta\pi^+$ decay mode is observed with a branching ratio of about 3 times B($D_S\to\phi\pi^+$).

$\Gamma(\eta\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
possibly seen OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	360	ASTON 81	OMEG	γp

$\Gamma(\eta'(958)\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
possibly seen OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	60	ASTON 81	OMEG	γp

$\Gamma(\phi\rho^+)/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
possibly seen OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	83	ASTON 81B	OMEG	γp

$\Gamma(\eta'(958)\pi^+)/\Gamma(\phi\pi^+)$ Γ_{15}/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
seen	[13] WORMSER 88	MRK2	E^{ee}_{cm} = 29 GeV

[13] The $\eta'\pi^+$ decay mode is observed with a branching ratio of about 5 times B($D_s \to \phi\pi^+$).

$\Gamma(\pi^+\pi^-\pi^+)/\Gamma(\phi\pi^+)$ Γ_{17}/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.44±0.10±0.04	ANJOS 89	TPS	Photoproduction

$\Gamma(\pi^+\pi^-\pi^+ \text{ (non-resonant)})/\Gamma(\phi\pi^+)$ Γ_{18}/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.29±0.09±0.03	ANJOS 89	TPS	Photoproduction

$\Gamma(f_0(975)\pi^+)/\Gamma(\phi\pi^+)$ Γ_{16}/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.28±0.10±0.03	ANJOS 89	TPS	Photoproduction

$\Gamma(\pi^+\pi^-\pi^+\pi^-\pi^+)/\Gamma(\phi\pi^+)$ Γ_{19}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.29	90	ANJOS 89	TPS	Photoproduction

$\Gamma(\pi^+\pi^-\pi^+\pi^0)/\Gamma(\phi\pi^+)$ Γ_{20}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.3	90	ANJOS 89E	TPS	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(\phi\pi^+)$ Γ_{21}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.5	90	ANJOS 89E	TPS	Photoproduction

$\Gamma(\phi\pi^+\pi^0)/\Gamma(\phi\pi^+)$ Γ_{22}/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.4±1.0±0.5	11	ANJOS 89E	TPS	Photoproduction

$\Gamma(K^+K^-\pi^+\pi^0 \text{ (non-}\phi))/\Gamma(\phi\pi^+)$ Γ_{23}/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.4	90	[14] ANJOS 89E	TPS	Photoproduction

[14] Total minus ϕ component.

REFERENCES FOR $D_s^{\pm}$

ADLER	90	SLAC-PUB-5130 (PRL)	+Blaylock, Bolton+	(Mark III Collab.)
ADLER	90B	PRL 64 169	+Bai, Blaylock, Bolton+	(Mark III Collab.)
BARLAG	90C	ZPHY C (to be pub.)	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ADLER	89B	PRL 63 1211	+Bai, Becker, Blaylock, Bolton+	(Mark III Collab.)
ANJOS	89	PRL 62 125	+Appel, Bean, Bracker+	(TPS Collab.)
ANJOS	89E	PL B223 267	+Appel, Bean, Bracker+	(TPS Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
CHEN	89	PL B226 192	+McIlwain, Miller, Ng, Shibata+	(CLEO Collab.)
ALBRECHT	88	PL B207 349	+Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88	PRL 60 897	+Appel+	(Tagged Photon Spectrometer Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL TPS Collab.)
SHIPBAUGH	88	PRL 60 2117	+Wiss, Binkley+	(E-400 Collab.)
WORMSER	88	PRL 61 1057	+Abrams, Amidei, Baden+	(Mark II Collab.)
ALBRECHT	87F	PL B179 398	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	87G	PL B195 102	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ANJOS	87B	PRL 58 1818	+Appel, Bracker, Browder+	(FNAL TPS Collab.)
BECKER	87B	PL B184 277	+Boehringer, Bosman+	(NA11 and NA32 Collab.)
BLAYLOCK	87	PRL 58 2171	+Bolton, Brown, Bunnell+	(Mark III Collab.)
BRAUNSCH...	87	ZPHY C35 317	Braunschweig, Gerhards+	(TASSO Collab.)
CSORNA	87	PL B191 318	+Mestayer, Panvini, Word+	(CLEO Collab.)
JUNG	86	PRL 56 1775	+Abachi+	(HRS Collab.)
USHIDA	86	PRL 56 1767	+Kondo+	(AICH, FNAL, GIFU, GYEO, KOBE, SEOU+)
ALBRECHT	85D	PL 153B 343	+Drescher, Binder, Drews+	(ARGUS Collab.)
DERRICK	85B	PRL 54 2568	+Fernandez, Fries, Hyman+	(HRS Collab.)
AIHARA	84D	PRL 53 2465	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
ALTHOFF	84	PL 136B 130	+Braunschweig, Kirschfink+	(TASSO Collab.)
BAILEY	84	PL 139B 320	+Belau, Bohringer, Bosman+	(ACCMOR Collab.)
ARGUS	83	CERN Cour. 23 423		(ARGUS Collab.)
Preliminary.				
ATKINSON	83	ZPHY C17 1	+	(BONN, CERN, GLAS, LANC, MCHS, LPNP, RL+)
AUBERT	83	NP B213 31	+Bassompierre, Becks, Best+	(EMC Collab.)
CHEN	83B	PR D28 2304	+Fenker+	(ARIZ, FNAL, FLOR, NDAM, TUFT+)
CHEN	83C	PRL 51 634	+Alam, Giles, Kagan+	(CLEO Collab.)
USHIDA	83	PRL 51 2362	+	(AICH, FNAL, KOBE, SEOU, MCGI, NAGO+)
ASTON	81	PL 100B 91	+	(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
ASTON	81B	NP B189 205	+	(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
PARTRIDGE	81	PRL 47 760	+Peck, Porter, Gu+	(Crystal Ball Collab.)
AMMAR	80	PL 94B 118	+	(KANS, FNAL, SERP, ITEP, CRAC, JINR, WASH+)
USHIDA	80B	PRL 45 1053	+	(AICH, FNAL, KOBE, SEOU, MCGI, NAGO, OSU+)
BRANDELIK	79	PL 80B 412	+Braunschweig, Martyn, Sander+	(DASP Collab.)
BRANDELIK	77B	PL 70B 132	+Braunschweig, Martyn, Sander+	(DASP Collab.)

OTHER RELATED PAPERS

SCHINDLER	88	High Energy Electron-Positron Physics 234 Editors: A. Ali and P. Soeding, World Scientific, Singapore	(SLAC)
GRAB	87	SLAC-PUB-4372 EPS Conference – Uppsala	(SLAC)
SCHUBERT	87	IHEP-HD/87-7 EPS Conference – Uppsala, Proc., Vol. 2, p. 791	(HEID)
SNYDER	87	IUHEEE-87-11 Symp. on Prod. and Decay of Heavy Flavors, Stanford	(IND)
SCHINDLER	86	SLAC-PUB-4136 World Press International	(SLAC)
SCHINDLER	86B	SLAC-PUB-4248 SLAC Summer Institute	(SLAC)
TRILLING	81	PRPL 75 57	(LBL, UCB)

D_s^* was F^*

$I(J^P) = ?(?^?)$

D_s^* MASS

The fit includes the $D^\pm$, D^0, $D_s^\pm$, and $D_s^{*\pm}$ masses and the $D^0 - D^\pm$, $D_s^\pm - D^\pm$, and $D_s^{*\pm} - D_s^\pm$ mass differences.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2110.3±2.0 OUR FIT Error includes scale factor of 1.3.			
2106.6±2.1±2.7	[1] BLAYLOCK 87	MRK3	$e^+e^- \to D_s X$

[1] Assuming D_s mass = 1968.7 ± 0.9 MeV.

$D_s^* - D_s$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
141.5± 1.9 OUR FIT Error includes scale factor of 1.3.				
142.4± 1.7 OUR AVERAGE				
142.5± 0.8±1.5		[2] ALBRECHT 88	ARG	$e^+e^- \to D_s\gamma$
143.0±18.0	8	ASRATYAN 85	HLBC	FNAL 15-ft, ν-^{2}H
139.5± 8.3±9.7	60	AIHARA 84D	TPC	$e^+e^- \to$ hadrons
110 ±46		BRANDELIK 79	DASP	$e^+e^- \to D_s\gamma$

[2] Result includes data of ALBRECHT 84B

D_s^* WIDTH

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
< 4.5	90	ALBRECHT 88	ARG	E^{ee}_{cm} = 10.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<22	90	BLAYLOCK 87	MRK3	$e^+e^- \to D_s X$

D_s^* DECAY MODES

$\overline{D}_s^*$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D_s\gamma$	dominant

D_s^* BRANCHING RATIOS

$\Gamma(D_s\gamma)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
dominant OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	ALBRECHT 88	ARG	$e^+e^- \to D_s\gamma$
seen	ASRATYAN 85		
seen	AIHARA 84D		
seen	ALBRECHT 84B		
seen	BRANDELIK 79		

D_s^* REFERENCES

ALBRECHT	88	PL B207 349	+Binder, Boeckmann+	(ARGUS Collab.)
BLAYLOCK	87	PRL 58 2171	+Bolton, Brown, Bunnell+	(Mark III Collab.)
ASRATYAN	85	PL 156B 441	+Fedotov, Ammosov, Burtovoy+	(ITEP, SERP)
AIHARA	84D	PRL 53 2465	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
ALBRECHT	84B	PL 146B 111	+Drescher, Heller+	(ARGUS Collab.)
BRANDELIK	79	PL 80B 412	+Braunschweig, Martyn, Sander+	(DASP Collab.)

OTHER RELATED PAPERS

BRANDELIK	78C	PL 76B 361	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
BRANDELIK	77B	PL 70B 132	+Braunschweig, Martyn, Sander+	(DASP Collab.)

$D_{s1}(2536)^\pm$

$I(J^P) = 0(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+ K^0$. Not seen in $D^+ K^0$. $J^P = 1^+$ assignment strongly favored.

$D_{s1}(2536)^\pm$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2536.5± 0.8 OUR AVERAGE			
2536.6± 0.7±0.4	AVERY 90	CLEO	$e^+ e^- \to D^{*+} K^0 X$
2535.9± 0.9±2.0	ALBRECHT 89E	ARG	$D^*_{s1} \to D^*(2010) K^0$
2535 ±28	[1] ASRATYAN 88	HLBC	$\nu N \to D_S \gamma\gamma X$

[1] Not seen in $D^* K$.

$D_{s1}(2536)^\pm$ – $D_S^*(2111)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
424±28	ASRATYAN 88	HLBC	$D_S^* \gamma$

$D_{s1}(2536)^\pm$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
<5.44	90	AVERY 90	CLEO	$e^+ e^- \to D^{*+} K^0 X$
<4.6	90	ALBRECHT 89E	ARG	$D^*_{s1} \to D^*(2010) K^0$

$D_{s1}(2536)^+$ DECAY MODES

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+ K^0$	seen
Γ_2	$D^+ K^0$	
Γ_3	$D_S^* \gamma$	possibly seen

$D_{s1}(2536)^+$ BRANCHING RATIOS

$\Gamma(D^+ K^0)/\Gamma(D^*(2010)^+ K^0)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.43	90	ALBRECHT 89E	ARG	$D^*_{s1} \to D^*(2010) K^0$

$\Gamma(D_S^* \gamma)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
possibly seen	ASRATYAN 88	HLBC	$\nu N \to D_S \gamma\gamma X$

$D_{s1}(2536)^\pm$ REFERENCES

AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89E	PL B230 162	+Glaser, Harder+	(ARGUS Collab.)
ASRATYAN	88	ZPHY C40 483	+Fedotov+	(ITEP, SERP)

$D_{sJ}(2564)^\pm$

$I(J^P) = ?(?^?)$

OMITTED FROM SUMMARY TABLE

$D_{sJ}(2564)^\pm$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2564.3±4.4	ASRATYAN 88	HLBC	$D^* K$

$D_{sJ}(2564)^\pm$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
<2.5	ASRATYAN 88	HLBC	$D^* K$

$D_{sJ}(2564)^+$ DECAY MODES

$D_{sJ}(2564)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^* K$	seen

$D_{sJ}(2564)^+$ BRANCHING RATIOS

$\Gamma(D^* K)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	ASRATYAN 88	HLBC	$D^* K$

$D_{sJ}(2564)^\pm$ REFERENCES

ASRATYAN	88	ZPHY C40 483	+Fedotov+	(ITEP, SERP)

BOTTOM MESONS

$(B = \pm 1)$

$B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $\overline{B}^0 = \bar{d}b$, $B^- = \bar{u}b$,

similarly for B^*'s

HIGHLIGHTS OF B MESON PHYSICS

(by R.H. Schindler, SLAC)

The results obtained since our last edition are based largely on samples of B decays from ARGUS and CLEO taken at the $\Upsilon(4S)$, the $\Upsilon(5S)$, and in the nearby continuum, and represent an approximate doubling of data over that available in our last edition. The data samples reported amount to 0.2–0.4 fb^{-1}. In 1990 the new CLEO-II detector started taking data at the CESR ring. CESR itself is approved for major upgrades, and thus we may anticipate significantly larger samples (1 10 fb^{-1}) over the next few years, resulting in marked improvements in all the areas discussed below.

Since our last edition, the discrepancy between ARGUS and CLEO on the open (D, D_s) and closed (ψ) charm content of B decays has largely been resolved, with both experiments obtaining for the average number of c-quarks per B decay the value 1.0 ± 0.1 (Ref. 1) under the same assumptions for D_s, Λ_c, and ψ inclusive branching ratios. This is about one standard deviation less than the predicted value of 1.15 c-quarks per B decay. While the so-called *charm deficit* has largely vanished, the small remaining discrepancy leaves open the possibilities: (a) that the assumed charmed branching ratios are too large, (b) that the number of B mesons in the $\Upsilon(4S)$ normalization is too high, or (c) both.

For the $\psi(3770)$, hadronic (e.g., $\psi(3770) \to J/\psi\pi\pi$) and electromagnetic transitions have been identified,[2] and some evidence exists for direct $\psi(3770)$ decays to light mesons.[3] For the $\Upsilon(4S)$, CLEO previously set model-dependent limits on non-$B\overline{B}$ decays, and now, with more data, has observed such events.[4] The evidence takes the form of $\Upsilon(4S)$ decays to J/ψ which are a) beyond the kinematic limit for decays via $B\overline{B}$ and b) beyond the rate expected from the continuum under the $\Upsilon(4S)$. While the measured branching fraction is small (about 0.2%), this is for a limited kinematic range $(x_{J/\psi} \geq 0.38)$ and for only one specific meson. The mechanism for this OZI forbidden process is unknown. It may be due to a complicated hadronic rescattering effect, or to the admixture of $b\bar{b}g$ and $b\bar{b}$ states at the $\Upsilon(4S)$, or perhaps even to the production of new four-quark states near the $B\overline{B}$ threshold. As in the case of the evidence from $\psi(3770)$ decays, the large partial width makes it unlikely to be ordinary bottomonium transitions, implying the total $\Upsilon(4S) \rightarrow$ non-$B\overline{B}$ width may be substantial. Because of theoretical uncertainties in the mechanism, the total width is indeterminate until at least one absolute B meson branching fraction can be established.

If the observation of substantial non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is confirmed, it will require rescaling (upward) of all B meson branching fractions, since they are not absolute measurements. New measurements of the B^0 and B^+ mass splitting, 0.4 ± 0.6 MeV from CLEO[5] and 0.0 ± 1.6 MeV from ARGUS[6], imply the production of B^0 and B^+ at the $\Upsilon(4S)$ is closer to equal than previously thought. However, large (18%) coulomb corrections are suggested by Atwood and Marciano[7] to the neutral and charged pair-production rates, once again clouding the issue of the branching ratio scale.

As in the D meson system, the data for exclusive semileptonic decays of B mesons have improved substantially. These decays provide a sensitive measure of the C-K-M parameter V_{bc}. In the past year, B^0 and $B^+ \rightarrow \overline{D}^* \ell \nu$ decays as well as $B^+ \rightarrow \overline{D}^0 \ell \nu$ decays have been measured. The ratio of vector to pseudoscalar rates are found to be about 1.5 while the ratio of B^+ to B^0 vector rates (approximating the ratio of their total widths, or lifetimes) is close to unity with an error of about 20%.[8] The D^* in these decays is found to be polarized, with the ratio of longitudinal to transverse polarization being about 0.6–0.9 when $p(\text{lepton}) \geq 1$ GeV, in good agreement with the prediction of models such as Korner-Schuler's.[9]

In addition to exclusive semileptonic decays, CLEO and subsequently ARGUS reported last year the first observations of excess leptons in the region of the inclusive spectrum populated predominantly by $b \rightarrow u$ transitions. The observation of a nonvanishing C-K-M parameter V_{bu} is a *necessary* requirement for CP violation arising in the C-K-M matrix phase. Using models to correct for acceptance both CLEO and ARGUS obtain values of $\mid V_{bu}/V_{bc} \mid \approx 0.1$ (see FULTON 90 and ALBRECHT 90).

While semileptonic decays provided the first evidence for the V_{bu} transition, there is no evidence yet for the analogous weak-hadronic decays. Evidence from ARGUS for charmless B decays to $p\overline{p}\pi$ and $p\overline{p}\pi^+\pi^-$ was confirmed neither by CLEO nor by subsequent data from ARGUS. Our Tables this edition contain limits from searches for many other charmless B decays, all about one order of magnitude above the levels predicted by models.

Evidence for $B^0 - \overline{B}^0$ mixing, first presented by ARGUS (ALBRECHT 87E), has been confirmed by CLEO (ARTUSO 89) and improved upon by subsequent ARGUS measurements. The large value of the mixing parameter $r_d \approx 0.2$ for the B^0 meson suggests the nearly complete mixing of the B_s^0 meson. Experimentally, this conclusion is consistent with observations in high energy e^+e^- and $p\overline{p}$ experiments, but has not been directly confirmed.

$B_s^0 - \overline{B}_s^0$ mixing would provide one avenue to measure the C-K-M matrix element V_{ts} directly. The alternate method is to observe $b \rightarrow s$ transitions in one loop radiative or hadronic Penguin decays. Our Tables this edition provide extensive sets of limits on these decays. As in the case of $b \rightarrow u$ transitions in hadronic decays, the experiments are still about one order of magnitude above the levels needed to observe these decays.

References

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2. R. Schindler, *Proceedings of the XXIV International Conference on High Energy Physics, Munich (August 1988)*, p. 484.
3. Y. Zhu, PhD thesis CALTECH 68-1513 (1988), unpublished.
4. J. Alexander et al., Cornell Preprint CLNS -90/975 (1990).
5. M. Danilov, *XIV International Symposium on Lepton and Photon Interactions, Stanford, CA August 1989.*
6. W.Y. Chen, *XIV International Symposium on Lepton and Photon Interactions, Stanford, CA August 1989.*
7. D. Atwood and W.J. Marciano, "Radiative Corrections and Semileptonic B Decays", BNL preprint (1989).
8. N. Katayama, Heavy Quark Physics, *AIP Conference Proceedings 196 (1989)*; H. Albrecht et al., Phys. Lett. **B232**, 554 (1989).
9. J. Korner and G. Schuler, Z. Phys. **C38**, 511 (1988).

$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

This section also includes measurements which do not identify the charge state of B.

$B^{\pm}$ MASS

The fit uses the $B^{\pm}$ and B^0 mass and mass difference measurements. These experiments actually measure the difference between half of E_{cm} and the B mass.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
5277.6±1.4 OUR FIT				
5277.8±1.6 OUR AVERAGE				
5275.8±1.3±3.0	32	ALBRECHT 87C	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$
5278.2±1.8±3.0	12	[1] ALBRECHT 87D	ARG	$e^+ e^- \rightarrow \Upsilon(4S)$
5278.6±0.8±2.0		BEBEK 87	CLEO	$e^+ e^- \rightarrow \Upsilon(4S)$

[1] Found using fully reconstructed decays with J/ψ. ALBRECHT 87D assume $m(\Upsilon(4S))$ = 10577 MeV.

B MEAN LIFE

Unless stated otherwise, the measurements of the B mean life do not distinguish the charge state ($B^{\pm}$ or B^0) and the lifetime is an average over bottom particles produced, weighted by their semileptonic branching ratios.

VALUE (10^{-13} s)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
11.8±1.1 OUR AVERAGE					
$12.0^{+5.2}_{-3.6}{}^{+1.6}_{-1.4}$		15	[2] WAGNER 90	MRK2	B^0, $E^{ee}_{cm} = 29$ GeV
13.5±1.0±2.4			BRAUNSCH... 89B	TASS	$E^{ee}_{cm} = 35$ GeV
9.8±1.2±1.3			ONG 89	MRK2	$E^{ee}_{cm} = 29$ GeV
$11.7^{+2.7}_{-2.2}{}^{+1.7}_{-1.6}$			KLEM 88	DLCO	$E^{ee}_{cm} = 29$ GeV
12.9±2.0±2.6			[3] ASH 87	MAC	$E^{ee}_{cm} = 29$ GeV
$10.2^{+4.2}_{-3.9}$		301	[4] BROM 87	HRS	$E^{ee}_{cm} = 29$ GeV
14.6±2.2±3.4			[5] WU 87	RVUE	JADE result
$18\ ^{+5}_{-4}\ \pm 4$		25	BARTEL 86B	JADE	$E^{ee}_{cm} = 35$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$8.2^{+5.7}_{-3.7}\pm2.7$			[6] AVERILL	89	HRS	$E^{ee}_{cm}=29$ GeV
		2	[7] ALBANESE	85	HYBR	350 GeV $\pi^- p$ emulsion
$18.3^{+3.8+3.7}_{-3.7-3.4}$			ALTHOFF	84H	TASS	$E^{ee}_{cm}=30$–46.8 GeV
$11.6^{+3.7}_{-3.4}\pm2.3$		46	KLEM	84	DLCO	Repl. by KLEM 88
$18\ \pm6\ \pm4$			FERNANDEZ	83B	MAC	$E^{ee}_{cm}=29$ GeV
$12.0^{+4.5}_{-3.6}\pm3.0$			[8] LOCKYER	83	MRK2	Repl. by ONG 89
$<14.$	95		BARTEL	82C	JADE	e^+e^-, average $E_{cm}=34$ GeV

[2] WAGNER 90 tagged B^0 mesons by their decays into $D^{*-}e^+\nu$ and $D^{*-}\mu^+\nu$ where the D^{*-} is tagged by its decay into $\pi^-\overline{D}^0$.

[3] We have added an overall scale error of 15% linearly to the systematic error of ±0.7 to obtain ±2.6 systematic error.

[4] Statistical and systematic errors were combined by BROM 87.

[5] The errors quoted here came from a private communication from the Jade collaboration. This result will be submitted to Zeit. Phys. in 1990, along with a different technique which yields $13.2^{+2.8}_{-2.5}$.

[6] This is an estimate of the B^0 mean lifetime assuming that $B^0 \to D^{*+} + X$ always.

[7] The mean flight time for the one B^0 was 5×10^{-13} s while the one B^- was 0.8×10^{-13} s. Possible evidence for difference in B^0 and $B^{\pm}$ lifetime.

[8] The lifetime is an average over bottom particles produced.

B^+ DECAY MODES

B^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$B^+ \to \overline{D}^0\pi^+$		$(2.9 \pm 1.4)\times10^{-3}$	S=1.5
Γ_2	$B^+ \to \overline{D}^0\rho^+$		(2.1 ± 1.2) %	
Γ_3	$B^+ \to D^-\pi^+\pi^+$		$(2.5\ ^{+4.8}_{-2.4})\times10^{-3}$	
Γ_4	$B^+ \to \overline{D}^*(2010)^0\pi^+$		$(3 \pm 4)\times10^{-3}$	
Γ_5	$B^+ \to D^*(2010)^-\pi^+\pi^+$		$(2.5\ ^{+1.5}_{-1.3})\times10^{-3}$	
Γ_6	$B^+ \to D^*(2010)^-\pi^+\pi^+\pi^0$		(4.3 ± 2.9) %	
Γ_7	$B^+ \to J/\psi(1S)K^+$		$(8.0 \pm 2.8)\times10^{-4}$	
Γ_8	$B^+ \to J/\psi(1S)K^+\pi^+\pi^-$		$(1.1 \pm 0.7)\times10^{-3}$	
Γ_9	$B^+ \to \psi(2S)K^+$		$(2.2 \pm 1.7)\times10^{-3}$	
Γ_{10}	$B^+ \to \pi^+\pi^0$		$< 2.3 \times10^{-3}$	CL=90%
Γ_{11}	$B^+ \to \pi^+\pi^+\pi^-$		$< 1.7 \times10^{-4}$	CL=90%
Γ_{12}	$B^+ \to \rho^0\pi^+$		$< 1.5 \times10^{-4}$	CL=90%
Γ_{13}	$B^+ \to \pi^+ f_0(975)$		$< 1.2 \times10^{-4}$	CL=90%
Γ_{14}	$B^+ \to \pi^+ f_2(1270)$		$< 2.1 \times10^{-4}$	CL=90%
Γ_{15}	$B^+ \to \rho^0 a_1(1260)^+$		$< 5.4 \times10^{-4}$	CL=90%
Γ_{16}	$B^+ \to \rho^0 a_2(1320)^+$		$< 6.3 \times10^{-4}$	CL=90%
Γ_{17}	$B^+ \to K^0\pi^+$		$< 9 \times10^{-5}$	CL=90%
Γ_{18}	$B^+ \to K^*(892)^0\pi^+$		$< 1.3 \times10^{-4}$	CL=90%
Γ_{19}	$B^+ \to K^+\pi^-\pi^+$ (no charm)		$< 1.7 \times10^{-4}$	CL=90%
Γ_{20}	$B^+ \to K^+\rho^0$		$< 7 \times10^{-5}$	CL=90%
Γ_{21}	$B^+ \to K^+\phi$		$< 8 \times10^{-5}$	CL=90%
Γ_{22}	$B^+ \to K^+ f_0(975)$		$< 7 \times10^{-5}$	CL=90%
Γ_{23}	$B^+ \to K^*(892)^+\gamma$		$< 5.5 \times10^{-4}$	CL=90%
Γ_{24}	$B^+ \to K_1(1270)^+\gamma$		$< 6.6 \times10^{-3}$	CL=90%
Γ_{25}	$B^+ \to K_1(1400)^+\gamma$		$< 2.0 \times10^{-3}$	CL=90%
Γ_{26}	$B^+ \to K_2^*(1430)^+\gamma$		$< 1.3 \times10^{-3}$	CL=90%
Γ_{27}	$B^+ \to K^*(1680)^+\gamma$		$< 1.7 \times10^{-3}$	CL=90%
Γ_{28}	$B^+ \to K_3^*(1780)^+\gamma$		$< 5 \times10^{-3}$	CL=90%
Γ_{29}	$B^+ \to K_4^*(2045)^+\gamma$		$< 9.0 \times10^{-3}$	CL=90%
Γ_{30}	$B^+ \to p\overline{p}\pi^+$		$< 1.4 \times10^{-4}$	CL=90%
Γ_{31}	$B^+ \to p\overline{p}\pi^+\pi^+\pi^-$		$< 4.7 \times10^{-4}$	CL=90%
Γ_{32}	$B^+ \to p\overline{\Lambda}$		$< 5 \times10^{-5}$	CL=90%
Γ_{33}	$B^+ \to p\overline{\Lambda}\pi^+\pi^-$		$< 1.8 \times10^{-4}$	CL=90%
Γ_{34}	$B^+ \to \overline{\Delta}^0 p$		$< 3.3 \times10^{-4}$	CL=90%
Γ_{35}	$B^+ \to \Delta^{++}\overline{p}$		$< 1.3 \times10^{-4}$	CL=90%

Flavor-Changing neutral current (*FC*) modes

Γ_{36}	$B^+ \to K^+\mu^+\mu^-$	*FC*	$< 1.5 \times10^{-4}$	CL=90%
Γ_{37}	$B^+ \to K^+e^+e^-$	*FC*	$< 5 \times10^{-5}$	CL=90%

For the following modes, the charge of *B* was not determined.

Γ_{38}	$B \to \ell^+$ anything			
Γ_{39}	$B \to \ell\nu$ hadrons		(23.1 ± 1.1) %	
Γ_{40}	$B \to e^{\pm}\nu_e$ hadrons	[a]	(12.1 ± 0.6) %	
Γ_{41}	$B \to \mu^{\pm}\nu_{\mu}$ hadrons	[a]	(11.0 ± 0.9) %	
Γ_{42}	$B \to \ell\nu$ noncharm-hadrons			
Γ_{43}	$B \to K^+\ell^+$ anything			
Γ_{44}	$B \to K^-\ell^+$ anything			
Γ_{45}	$B \to K^0/\overline{K}^0\ell^+$ anything			
Γ_{46}	$B \to D^{\pm}$ anything	[a]	(17 ± 6) %	
Γ_{47}	$B \to D^0/\overline{D}^0$ anything		(39 ± 6) %	
Γ_{48}	$B \to D^*(2010)^{\pm}$ anything	[a]	$(22\ ^{+8}_{-6})$ %	
Γ_{49}	$B \to D_s^{\pm}$ anything	[a]	(12.5 ± 3.5) %	
Γ_{50}	$B \to \overline{D}^0\pi^+$, $D^-\pi^+$, $\overline{D}^*(2010)^0\pi^+$, or $D^*(2010)^-\pi^+$			
Γ_{51}	$B \to$ Charmed-baryon anything		< 11.2 %	CL=90%
Γ_{52}	$B \to J/\psi(1S)$ anything		(1.12 ± 0.18) %	
Γ_{53}	$B \to \psi(2S)$ anything		$(4.6 \pm 2.0)\times10^{-3}$	
Γ_{54}	$B \to K^{\pm}$ anything		(85 ± 11) %	
Γ_{55}	$B \to K^+$ anything			
Γ_{56}	$B \to K^-$ anything			
Γ_{57}	$B \to K^0/\overline{K}^0$ anything		(63 ± 8) %	
Γ_{58}	$B \to \phi$ anything		(2.3 ± 0.8) %	
Γ_{59}	$B \to K^*(892)\gamma$		$< 2.4 \times10^{-4}$	CL=90%
Γ_{60}	$B \to K_1(1400)\gamma$		$< 4.1 \times10^{-4}$	CL=90%
Γ_{61}	$B \to K_2^*(1430)\gamma$		$< 8.3 \times10^{-4}$	CL=90%
Γ_{62}	$B \to K_3^*(1780)\gamma$		$< 3.0 \times10^{-3}$	CL=90%
Γ_{63}	$B \to p$ anything		$(8.2\ ^{+1.4}_{-1.1})$ %	
Γ_{64}	$B \to p$ (direct) anything		(5.5 ± 1.6) %	
Γ_{65}	$B \to \Lambda$ anything		(4.2 ± 0.8) %	
Γ_{66}	$B \to \Xi^-$ anything		$(2.8 \pm 1.4)\times10^{-3}$	
Γ_{67}	$B \to$ baryons anything		(7.6 ± 1.4) %	
Γ_{68}	$B \to p\overline{p}$ anything		(2.50 ± 0.28) %	
Γ_{69}	$B \to \Lambda\overline{p}$ anything		(2.3 ± 0.5) %	
Γ_{70}	$B \to \Lambda\overline{\Lambda}$ anything		$< 8.8 \times10^{-3}$	CL=90%

Flavor-Changing neutral current (*FC*) modes

Γ_{71}	$B \to e^+e^-$ any + $\mu^+\mu^-$ any	*FC*	$< 2.4 \times10^{-3}$	CL=90%

[a] Value is for the sum of the charge states indicated.

B^+ BRANCHING RATIOS

$\Gamma(\overline{D}^0\pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0029±0.0014 OUR AVERAGE	Error includes scale factor of 1.5.			
0.0019±0.0010±0.0006	7	[9] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0047^{+0.0016+0.0011}_{-0.0013-0.0008}$	14	[10] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[9] ALBRECHT 88K assumes $B^0\overline{B}^0{:}B^+B^-$ ratio is 45:55.

[10] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. B($D^0 \to K^-\pi^+$) = (4.2 ± 0.4 ± 0.4)% and B($D^0 \to K^-\pi^+\pi^+\pi^-$) = (9.1 ± 0.8 ± 0.8)% were used.

$\Gamma(\overline{D}^0\rho^+)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.021±0.008±0.009	10	[11] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[11] ALBRECHT 88K assumes $B^0\overline{B}^0{:}B^+B^-$ ratio is 45:55.

$\Gamma(D^-\pi^+\pi^+)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{0.0025^{+0.0041+0.0024}_{-0.0023-0.0008}}$	1	[12] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[12] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. B($D^- \to K^+\pi^-\pi^-$) = (9.1 ± 1.3 ± 0.4)% is assumed.

$\Gamma(\overline{D}^*(2010)^0\pi^+)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0027±0.0044	[13] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[13] This is a derived branching ratio, using the inclusive pion spectrum and other two-body *B* decays. BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(D^*(2010)^-\pi^+\pi^+)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0025^{+0.0015}_{-0.0013}$ OUR AVERAGE				
$0.005\pm0.002\pm0.003$	7	[14] ALBRECHT 87C	ARG	$e^+e^-\to\Upsilon(4S)$
$0.0020^{+0.0014+0.0008}_{-0.0013-0.0005}$	3	[15] BEBEK 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[14] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S)\to B^+B^-)=55\%$ and $B(\Upsilon(4S)\to B^0\overline{B}^0)=45\%$.

[15] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. $B(D^*(2010)^+\to\pi^+D^0)=(60^{+\ 8}_{-15})\%$, $B(D^0\to K^-\pi^+)=(4.2\pm0.4\pm0.4)\%$, and $B(D^0\to K^-\pi^+\pi^+\pi^-)=(9.1\pm0.8\pm0.8)\%$ were used.

$\Gamma(D^*(2010)^-\pi^+\pi^+\pi^0)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.043\pm0.013\pm0.026$	24	[16] ALBRECHT 87C	ARG	$e^+e^-\to\Upsilon(4S)$

[16] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S)\to B^+B^-)=55\%$ and $B(\Upsilon(4S)\to B^0\overline{B}^0)=45\%$.

$\Gamma(J/\psi(1S)K^+)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
8.0 ± 2.8 OUR AVERAGE				
7 ± 4	3	[17] ALBRECHT 87D	ARG	$e^+e^-\to\Upsilon(4S)$
$9\pm6\pm2$	3	[18] BEBEK 87	CLEO	$e^+e^-\to\Upsilon(4S)$
9 ± 5	3	[19] ALAM 86	CLEO	$e^+e^-\to\Upsilon(4S)$

[17] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45.

[18] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

[19] ALAM 86 assumes $B^\pm/B^0$ ratio is 60/40.

$\Gamma(J/\psi(1S)K^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0011 ± 0.0007	6	[20] ALBRECHT 87D	ARG	$e^+e^-\to\Upsilon(4S)$

[20] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Analysis explicitly removes $B^+\to\psi(2S)K^+$.

$\Gamma(\psi(2S)K^+)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0022 ± 0.0017	3	[21] ALBRECHT 87D	ARG	$e^+e^-\to\Upsilon(4S)$

[21] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45.

$\Gamma(\pi^+\pi^0)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0023	90	[22] BEBEK 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[22] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7\times10^{-4}$	90	[23] BORTOLETTO 89	CLEO	$e^+e^-\to\Upsilon(4S)$

[23] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\rho^0\pi^+)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.5\times10^{-4}$	90		[24] BORTOLETTO 89	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2\times10^{-4}$	90		[25] BEBEK 87	CLEO	$e^+e^-\to\Upsilon(4S)$
$<6\times10^{-4}$	90	0	GILES 84	CLEO	Repl. by BEBEK 87

[24] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

[25] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+f_0(975))/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.2\times10^{-4}$	90	[26] BORTOLETTO 89	CLEO	$e^+e^-\to\Upsilon(4S)$

[26] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+f_2(1270))/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.1\times10^{-4}$	90	[27] BORTOLETTO 89	CLEO	$e^+e^-\to\Upsilon(4S)$

[27] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\rho^0a_1(1260)^+)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.4\times10^{-4}$	90	[28] BORTOLETTO 89	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.2\times10^{-3}$	90	[29] BEBEK 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[28] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

[29] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\rho^0a_2(1320)^+)/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.3\times10^{-4}$	90	[30] BORTOLETTO 89	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.3\times10^{-3}$	90	[31] BEBEK 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[30] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

[31] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0\pi^+)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9\times10^{-5}$	90	[32] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6.8\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[32] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^0\pi^+)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3\times10^{-4}$	90	[33] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.6\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[33] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+\pi^-\pi^+\ \text{(no charm)})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.7\times10^{-4}$	90	[34] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$

[34] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+\rho^0)/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7\times10^{-5}$	90	[35] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.6\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[35] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+\phi)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8\times10^{-5}$	90	[36] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.1\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[36] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+f_0(975))/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<7\times10^{-5}$	90	[37] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$

[37] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^*(892)^+\gamma)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.5\times10^{-4}$	90	[38] ALBRECHT 89G	ARG	$e^+e^-\to\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5.5\times10^{-4}$	90	[39] AVERY 89B	CLEO	$e^+e^-\to\Upsilon(4S)$
$<1.8\times10^{-3}$	90	AVERY 87	CLEO	$e^+e^-\to\Upsilon(4S)$

[38] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

[39] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K_1(1270)^+\gamma)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0066	90	[40] ALBRECHT 89G	ARG	$e^+e^-\to\Upsilon(4S)$

[40] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_1(1400)^+\gamma)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0020	90	[41] ALBRECHT 89G	ARG	$e^+e^-\to\Upsilon(4S)$

[41] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_2^*(1430)^+\gamma)/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0013	90	[42] ALBRECHT 89G	ARG	$e^+e^-\to\Upsilon(4S)$

[42] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K^*(1680)^+\gamma)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0017	90	[43] ALBRECHT 89G	ARG	$e^+e^-\to\Upsilon(4S)$

[43] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_3^*(1780)^+\gamma)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.005	90	[44] ALBRECHT 89G	ARG	$e^+e^-\to\Upsilon(4S)$

[44] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.

$\Gamma(K_4^*(2045)^+\gamma)/\Gamma_{\rm total}$ Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0090	90	[44] ALBRECHT 89G	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{p}\pi^+)/\Gamma_{\rm total}$ Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 1.4 \times 10^{-4}$	90	BEBEK 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$(5.2\pm1.4\pm1.9)\times10^{-4}$		ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{p}\pi^+\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.7\times10^{-4}$	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{\Lambda})/\Gamma_{\rm total}$ Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5 \times10^{-5}$	90	[45] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<8.5\times10^{-5}$	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[45] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(p\overline{\Lambda}\pi^+\pi^-)/\Gamma_{\rm total}$ Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.8\times10^{-4}$	90	ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{\Delta}^0 p)/\Gamma_{\rm total}$ Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.3\times10^{-4}$	90	[46] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

[46] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\Delta^{++}\overline{p})/\Gamma_{\rm total}$ Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.3\times10^{-4}$	90	[47] BORTOLETTO89	CLEO	$e^+e^- \to \Upsilon(4S)$

[47] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+\mu^+\mu^-)/\Gamma_{\rm total}$ Γ_{36}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.5\times10^{-4}$	90	[48] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.2\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[48] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^+e^+e^-)/\Gamma_{\rm total}$ Γ_{37}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5 \times10^{-5}$	90	[49] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.1\times10^{-4}$	90	AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[49] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

For all of the decays below, the charge of the decaying B was not determined (B^0, $\overline{B}^0$, B^+, or B^-).

$\Gamma(e^{\pm}\nu_e \text{ hadrons})/\Gamma_{\rm total}$ Γ_{40}/Γ

Only the experiments at the $\Upsilon(4S)$ are used in the average.

VALUE	DOCUMENT ID	TECN	COMMENT
0.121±0.006 OUR AVERAGE			
$0.117\pm0.004\pm0.010$	[50] WACHS 89	CBAL	Direct e at $\Upsilon(4S)$
$0.120\pm0.007\pm0.005$	CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
$0.132\pm0.008\pm0.014$	[51] KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.112\pm0.009\pm0.011$	ONG 88	MRK2	$E^{ee}_{\rm cm} = 29$ GeV
$0.149^{+0.022}_{-0.019}$	PAL 86	DLCO	$E^{ee}_{\rm cm} = 29$ GeV
$0.110\pm0.018\pm0.010$	AIHARA 85	TPC	$E^{ee}_{\rm cm} = 29$ GeV
$0.111\pm0.034\pm0.040$	ALTHOFF 84J	TASS	$E^{ee}_{\rm cm} = 34.6$ GeV
0.146 ± 0.028	KOOP 84	DLCO	Repl. by PAL 86
$0.116\pm0.021\pm0.017$	NELSON 83	MRK2	$E^{ee}_{\rm cm} = 29$ GeV

[50] Using data above $p(e) = 2.4$ GeV, WACHS 89 determine $\sigma(B \to e\nu\ \text{up})/\sigma(B \to e\nu\ \text{charm}) < 0.065$ at 90% CL.

[51] Ratio $\sigma(b \to e\nu\ \text{up})/\sigma(b \to e\nu\ \text{charm}) < 0.055$ at CL = 90%.

$\Gamma(\mu^{\pm}\nu_\mu \text{ hadrons})/\Gamma_{\rm total}$ Γ_{41}/Γ

The average of the four high-energy results is 0.117 ± 0.013. These experiments produce other bottom particles in addition to the B meson.

VALUE	DOCUMENT ID	TECN	COMMENT
0.110±0.009 OUR AVERAGE			
$0.108\pm0.006\pm0.01$	CHEN 84	CLEO	Direct μ at $\Upsilon(4S)$
$0.112\pm0.009\pm0.01$	LEVMAN 84	CUSB	Direct μ at $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.118\pm0.012\pm0.010$	ONG 88	MRK2	$E^{ee}_{\rm cm} = 29$ GeV
$0.117\pm0.016\pm0.015$	BARTEL 87	JADE	$E^{ee}_{\rm cm} = 34.6$ GeV
$0.114\pm0.018\pm0.025$	BARTEL 85J	JADE	Repl. by BARTEL 87
$0.117\pm0.028\pm0.010$	ALTHOFF 84G	TASS	$E^{ee}_{\rm cm} = 34.5$ GeV
$0.105\pm0.015\pm0.013$	ADEVA 83B	MRKJ	$E^{ee}_{\rm cm} = 33$–38.5 GeV
$0.155^{+0.054}_{-0.029}$	FERNANDEZ 83D	MAC	$E^{ee}_{\rm cm} = 29$ GeV

$\Gamma(\ell\nu \text{ noncharm-hadrons})/\Gamma(\ell\nu \text{ hadrons})$ Γ_{42}/Γ_{39}

ℓ denotes e or μ but not the sum. These experiments measure this ratio in very limited momentum intervals.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		41	[52] ALBRECHT 90	ARG	$e^+e^- \to \Upsilon(4S)$
		76	[53] FULTON 90	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.04	90		[54] BEHRENDS 87	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.04	90		CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
<0.055	90		KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$

[52] ALBRECHT 90 observes 41 ± 10 excess e and μ (lepton) events in the momentum interval $p = 2.3$–2.6 GeV signaling the presence of the $b \to u$ transition. The events correspond to a model-dependent measurement of $|V_{bu}/V_{bc}$ = 0.10 ± 0.01.

[53] FULTON 90 observe 76 ± 20 excess e and μ (lepton) events in the momentum interval $p = 2.4$–2.6 GeV signaling the presence of the $b \to u$ transition. The average branching ratio, $(1.8 \pm 0.4 \pm 0.3) \times 10^{-4}$, corresponds to a model-dependent measurement of approximately $|V_{bu}/V_{bc}| = 0.1$ using $B(b \to c\ell\nu) = 10.2 \pm 0.2 \pm 0.7\%$.

[54] The quoted possible limits range from 0.018 to 0.04 for the ratio, depending on which model or momentum range is chosen. We select the most conservative limit they have calculated. This corresponds to a limit on $|V_{bu}|/|V_{bc}| < 0.20$. While the endpoint technique employed is more robust than their previous results in CHEN 84, these results do not provide a numerical improvement in the limit.

$\Gamma(K^+\ell^+ \text{ anything})/\Gamma(\ell^+ \text{ anything})$ Γ_{43}/Γ_{38}

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.54\pm0.07\pm0.06$	[55] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[55] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^-\ell^+ \text{ anything})/\Gamma(\ell^+ \text{ anything})$ Γ_{44}/Γ_{38}

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.10\pm0.05\pm0.02$	[56] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[56] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^0/\overline{K}^0\ell^+ \text{ anything})/\Gamma(\ell^+ \text{ anything})$ Γ_{45}/Γ_{38}

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.39\pm0.06\pm0.04$	[57] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[57] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(c/\overline{c})/\Gamma_{\rm total}$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.98\pm0.16\pm0.12$	[58] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[58] From the difference between K^- and K^+ widths. ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(D^{\pm} \text{ anything})/\Gamma_{\rm total}$ Γ_{46}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.17±0.04±0.04	20k	[59] BORTOLETTO87	CLEO	$e^+e^- \to \Upsilon(4S)$

[59] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratio for $K^-\pi^+\pi^+ = 0.116 \pm 0.014 \pm 0.007$. The product branching ratio for $B(B \to D^{\mp} X)$ $B(D^+ \to K^-\pi^+\pi^+)$ is $0.019 \pm 0.004 \pm 0.002$.

$\Gamma(D^0/\overline{D}^0\ \text{anything})/\Gamma_{\text{total}}$ Γ_{47}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.39\pm0.05\pm0.04$	21k	[60] BORTOLETTO 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.57\pm0.14\pm0.12$		[61] GREEN 83	CLEO	Repl. by BORTOLETTO 87

[60] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratio for $K^-\pi^+ = 0.056 \pm 0.004 \pm 0.003$. The product branching ratio for $B(B \to D^0 X)\ B(D^0 \to K^-\pi^+)$ is $0.0210 \pm 0.0015 \pm 0.0021$.

[61] Corrected by us using assumptions $B(D^0 \to K^-\pi^+) = (0.042 \pm 0.006)$. The product branching ratio is $B(B^0 \to D^0 X)B(D^0 \to K^-\pi^+) = 0.024 \pm 0.006 \pm 0.004$.

$\Gamma(D^*(2010)^{\pm}\ \text{anything})/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.22\pm0.04^{+0.07}_{-0.04}$	5200	[62] BORTOLETTO 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.27\pm0.06^{+0.08}_{-0.06}$	510	[63] CSORNA 85	CLEO	Repl. by BORTOLETTO 87

[62] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratios $B(D^0 \to K^-\pi^+) = 0.056 \pm 0.004 \pm 0.003$ and also assumes $B(D^*(2010)^+ \to D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. The product branching ratio for $B(B \to D^*(2010)^+)\ B(D^*(2010)^+ \to D^0\pi^+)$ is $0.13 \pm 0.02 \pm 0.012$.

[63] $V-A$ momentum spectrum used to extrapolate below $p = 1$ GeV. We correct the value assuming $B(D^0 \to K^-\pi^+) = 0.042 \pm 0.006$ and $B(D^{*+} \to D^0\pi^+) = 0.6^{+0.08}_{-0.15}$. The product branching fraction is $B(B \to D^{*+} X)B(D^{*+} \to \pi^+ D^0)B(D^0 \to K^-\pi^+) = (68 \pm 15 \pm 9) \times 10^{-4}$.

$\Gamma(D_s^{\pm}\ \text{anything})/\Gamma_{\text{total}}$ Γ_{49}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.125 ± 0.035 OUR AVERAGE			
$0.13\ \pm0.05$	[64] ALBRECHT 87H	ARG	$e^+e^- \to \Upsilon(4S)$
$0.12\ \pm0.05$	[65] HAAS 86	CLEO	$e^+e^- \to \Upsilon(4S)$

[64] ALBRECHT 87H measure $B(B \to D_s^+ X)\ B(D_s^+ \to \phi\pi^+) = 0.0042 \pm 0.0009 \pm 0.0006$ and we obtain the result shown by dividing by $B(D_s^+ \to \phi\pi^+) = 0.033 \pm 0.010$. $46 \pm 16\%$ of $B \to D_s X$ decays are 2-body.

[65] HAAS 86 measure $B(B \to D_s^+ X)B(D_s^+ \to \phi\pi^+) = 0.0038 \pm 0.001$ and we obtain the result shown by dividing by $B(D_s^+ \to \phi\pi^+) = 0.033 \pm 0.010$. $64 \pm 22\%$ decays are 2-body.

$\Gamma(\overline{D}^0\pi^+,\ D^-\pi^+,\ \overline{D}^*(2010)^0\pi^+,\ \text{or}\ D^*(2010)^-\pi^+)/\Gamma_{\text{total}}$ Γ_{50}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0162 ± 0.0032	[66] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.020\ \pm0.006\ \pm0.005$	[67] GILES 84	CLEO	Repl by BEBEK 87

[66] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. This measurement is independent of D and $D^*(2010)$ meson branching fractions.

[67] No dependence on D used fast-π momentum.

$\Gamma(\text{Charmed-baryon anything})/\Gamma_{\text{total}}$ Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.112	90	[68] ALAM 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.14\ \pm0.09$		[69] ALBRECHT 88E	ARG	$e^+e^- \to \Upsilon(4S)$

[68] Assuming all baryons result from charmed baryons, ALAM 86 conclude the branching fraction is $7.4 \pm 2.9\%$. The limit given above is model independent.

[69] ALBRECHT 88E measured $B(B \to \Lambda_c^+ X)B(\Lambda_c^+ \to pK^-\pi^+) = (0.30 \pm 0.12 \pm 0.06)\%$ and used $B(\Lambda_c^+ \to pK^-\pi^+) = (2.2 \pm 1.0)\%$ from ABRAMS 80 to obtain above number.

$\Gamma(J/\psi(1S)\ \text{anything})/\Gamma_{\text{total}}$ Γ_{52}/Γ

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
1.12 ± 0.18 OUR AVERAGE					
$1.07\pm0.16\pm0.22$		120	[70] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
$1.09\pm0.16\pm0.21$		52	ALAM 86	CLEO	$e^+e^- \to \Upsilon(4S)$
$1.4\ ^{+0.6}_{-0.5}$		7	[71] ALBRECHT 85H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.1\ \pm0.21\pm0.23$		46	[72] HAAS 85	CLEO	Repl. by ALAM 86
<4.9	90		MATTEUZZI 83	MRK2	$E^{ee}_{\text{cm}} = 29$ GeV

[70] ALBRECHT 87D find the branching ratio for J/ψ not from $\psi(2S)$ to be 0.0081 ± 0.0023.

[71] Statistical and systematic errors were added in quadrature. ALBRECHT 85H also report a CL = 90% limit of 0.007 for $B \to J/\psi(1S) + X$ where $m(X) < 1$ GeV.

[72] Dimuon and dielectron events used.

$\Gamma(\psi(2S)\ \text{anything})/\Gamma_{\text{total}}$ Γ_{53}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0046\pm0.0017\pm0.0011$	8	ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^{\pm}\ \text{anything})/\Gamma_{\text{total}}$ Γ_{54}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.85\pm0.07\pm0.09$	ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	[73] BRODY 82	CLEO	$e^+e^- \to \Upsilon(4S)$
seen	[74] GIANNINI 82	CUSB	$e^+e^- \to \Upsilon(4S)$

[73] Assuming $\Upsilon(4S) \to B\overline{B}$, a total of $3.38 \pm 0.34 \pm 0.68$ kaons per $\Upsilon(4S)$ decay is found (the second error is systematic). In the context of the standard B-decay model, this leads to a value for (b-quark → c-quark)/(b-quark → all) of $1.09 \pm 0.33 \pm 0.13$.

[74] GIANNINI 82 at CESR-CUSB observed 1.58 ± 0.35 K^0 per hadronic event much higher than 0.82 ± 0.10 below threshold. Consistent with predominant $b \to cX$ decay.

$\Gamma(K^+\ \text{anything})/\Gamma_{\text{total}}$ Γ_{55}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.66\pm0.05\pm0.07$	[75] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[75] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^-\ \text{anything})/\Gamma_{\text{total}}$ Γ_{56}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.19\pm0.05\pm0.02$	[76] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[76] ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(K^0/\overline{K}^0\ \text{anything})/\Gamma_{\text{total}}$ Γ_{57}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.63\pm0.06\pm0.06$	ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\phi\ \text{anything})/\Gamma_{\text{total}}$ Γ_{58}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.023\pm0.006\pm0.005$	BORTOLETTO 86	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)\gamma)/\Gamma_{\text{total}}$ Γ_{59}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.4 \times 10^{-4}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)\gamma)/\Gamma_{\text{total}}$ Γ_{60}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.1 \times 10^{-4}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)\gamma)/\Gamma_{\text{total}}$ Γ_{61}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<8.3 \times 10^{-4}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_3^*(1780)\gamma)/\Gamma_{\text{total}}$ Γ_{62}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-3}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\ \text{anything})/\Gamma_{\text{total}}$ Γ_{63}/Γ

Values are for $[B(B \to pX)+B(B \to \overline{p}X)]/2$ and include protons from Λ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.082\pm0.005^{+0.013}_{-0.010}$	2163	[77] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.021		[78] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[77] ALBRECHT 89K include direct and nondirect protons.

[78] ALAM 83B reported their result as $> 0.036 \pm 0.006 \pm 0.009$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to p + X) = 0.03$ not including protons from Λ decays.

$\Gamma(p\ (\text{direct})\ \text{anything})/\Gamma_{\text{total}}$ Γ_{64}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.055 ± 0.016	1220	[79] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[79] ALBRECHT 89K subtract contribution of Λ decay from the inclusive proton yield.

$\Gamma(\Lambda\ \text{anything})/\Gamma_{\text{total}}$ Γ_{65}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.042\pm0.005\pm0.006$	943	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.011		[80] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[80] ALAM 83B reported their result as $> 0.022 \pm 0.007 \pm 0.004$. Values are for $(B(\Lambda X)+B(\overline{\Lambda} X))/2$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to \Lambda X) = 0.03$.

$\Gamma(\Xi^-\ \text{anything})/\Gamma_{\text{total}}$ Γ_{66}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0028 ± 0.0014	54	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\text{baryons anything})/\Gamma_{\text{total}}$ Γ_{67}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.076 ± 0.014	[81] ALBRECHT 89K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[81] ALBRECHT 89K obtain this result by adding their their measurements $(5.5 \pm 1.6)\%$ for direct protons and $(4.2 \pm 0.5 \pm 0.6)\%$ for inclusive Λ production. They then assume $(5.5 \pm 1.6)\%$ for neutron production and add it in also. Since each B decay has two baryons, they divide by 2 to obtain $(7.6 \pm 1.4)\%$.

$\Gamma(p\overline{p}\text{ anything})/\Gamma_{\text{total}}$ Γ_{68}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.025 \pm0.002 \pm0.002$	918	ALBRECHT 89K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\Lambda\overline{p}\text{ anything})/\Gamma_{\text{total}}$ Γ_{69}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.023\pm0.004\pm0.003$	165	ALBRECHT 89K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\Lambda\overline{\Lambda}\text{ anything})/\Gamma_{\text{total}}$ Γ_{70}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.0088	90	12	ALBRECHT 89K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$[\Gamma(e^+e^-\text{ anything}) + \Gamma(\mu^+\mu^-\text{ anything})]/\Gamma_{\text{total}}$ Γ_{71}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0024	90	[82] BEAN 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0062	90	[83] AVERY 84	CLEO	Repl. by BEAN 87
<0.008	90	MATTEUZZI 83	MRK2	$E^{ee}_{cm} = 29$ GeV

[82] BEAN 87 reports $[(\mu^+\mu^-)+(e^+e^-)]/2$ and we converted it.

[83] Determine ratio of B^+ to B^0 semileptonic decays to be in the range 0.25–2.9.

$\Gamma(e^+e^-\text{ anything})/\Gamma_{\text{total}}$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0024 OUR LIMIT	Our 90% CL limit, using $[\Gamma(e^+e^-\text{ anything}) + \Gamma(\mu^+\mu^-\text{ anything})]/\Gamma_{\text{total}}$ above.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.05	90	BEBEK 81	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\mu^+\mu^-\text{ anything})/\Gamma_{\text{total}}$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0024 OUR LIMIT	Our 90% CL limit, using $[\Gamma(e^+e^-\text{ anything}) + \Gamma(\mu^+\mu^-\text{ anything})]/\Gamma_{\text{total}}$ above.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	95	ALTHOFF 84G	TASS	$E^{ee}_{cm} = 34.5$ GeV
<0.007	95	ADEVA 83	MRKJ	$E^{ee}_{cm} = 30$–38 GeV
<0.007	95	BARTEL 83B	JADE	$E^{ee}_{cm} = 33$–37 GeV
<0.017	90	CHADWICK 81	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

REFERENCES FOR $B^{\pm}$

ALBRECHT	90	PL B234 409	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
FULTON	90	PRL 64 16	+Hempstead, Jensen, Johnson+	(CLEO Collab.)
WAGNER	90	PRL 64 1095	+Hinshaw, Ong, Snyder+	(Mark II Collab.)
ALBRECHT	89G	PL B229 304	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	89K	ZPHY C42 519	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
AVERY	89B	PL B223 470	+Besson, Garren, Yelton+	(CLEO Collab.)
BEBEK	89	PRL 62 8	+Berkelman, Blucher+	(CLEO Collab.)
BORTOLETTO	89	PRL 62 2436	+Goldberg, Horwitz, Mestayer+	(CLEO Collab.)
BRAUNSCH...	89B	ZPHY C44 1	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ONG	89	PRL 62 1236	+Jaros, Abrams, Amidei, Baden+	(Mark II Collab.)
WACHS	89	ZPHY C42 33	+Antreasyan, Bartels, Bieler+	(Crystal Ball Collab.)
ALBRECHT	88E	PL B210 263	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88F	PL B209 119	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88H	PL B210 258	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88K	PL B215 424	+Boeckmann, Glaeser+	(ARGUS Collab.)
KLEM	88	PR D37 41	+Atwood, Barish+	(DELCO Collab.)
ONG	88	PRL 60 2587	+Weir, Abrams, Amidei+	(Mark II Collab.)
ALAM	87	PRL 59 22	+Kitukama, Kim, Li+	(CLEO Collab.)
ALAM	87B	PRL 58 1814	+Katayama, Kim, Sun+	(CLEO Collab.)
ALBRECHT	87C	PL B185 218	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ALBRECHT	87D	PL B199 451	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	87H	PL B187 425	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ASH	87	PRL 58 640	+Band, Bloom, Bosman+	(MAC Collab.)
AVERY	87	PL B183 429	+Besson, Bowcock, Giles+	(CLEO Collab.)
BARTEL	87	ZPHY C33 339	+Becker, Felst, Haidt+	(JADE Collab.)
BEAN	87	PR D35 3533	+Bobbink, Brock, Engler+	(CLEO Collab.)
BEBEK	87	PR D36 1289	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
BEHRENDS	87	PRL 59 407	+Morrow, Guida, Guida+	(CLEO Collab.)
BORTOLETTO	87	PR D35 19	+Chen, Garren, Goldberg+	(CLEO Collab.)
BROM	87	PL B195 301	+Abachi, Akerlof, Baringer+	(HRS Collab.)
WU	87	Lepton-Photon Conf. DESY 87/164 and CERN-EP/87-235		(WISC, DESY)
ALAM	86	PR D34 3279	+Katayama, Kim, Sun+	(CLEO Collab.)
BALTRUSAIT...	86E	PRL 56 2140	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BARTEL	86B	ZPHY C31 349	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
BORTOLETTO	86	PRL 56 800	+Chen, Garren, Goldberg+	(CLEO Collab.)
HAAS	86	PRL 56 2781	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
PAL	86	PR D33 2708	+Atwood, Barish, Bonneaud+	(DELCO Collab.)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	
AIHARA	85	ZPHY C27 39	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
ALBANESE	85	PL 158B 186 WA75 experiment.	+Alpe, Aoki+	(BARI, CERN, DUUC, LOUC, NAGO+)
ALBRECHT	85H	PL 162B 395	+Binder, Harder+	(ARGUS Collab.)
BARTEL	85J	PL 163B 277	+Becker, Cords, Felst+	(JADE Collab.)
CSORNA	85	PRL 54 1894	+Garren, Mestayer, Panvini+	(CLEO Collab.)
HAAS	85	PRL 55 1248	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
ALTHOFF	84G	ZPHY C22 219	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84H	PL 149B 524	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84J	PL 146B 443	+Branschweig, Kirschfink+	(TASSO Collab.)
AVERY	84	PRL 53 1309	+Bebek, Berkelman, Cassel+	(CLEO Collab.)
CHEN	84	PRL 52 1084	+Goldberg, Horwitz, Jawahery+	(CLEO Collab.)
GILES	84	PR D30 2279	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
KLEM	84	PRL 53 1873	+Dubois, Young, Atwood+	(DELCO Collab.)
KOOP	84	PRL 52 970	+Sakuda, Atwood, Baillon+	(DELCO Collab.)
LEVMAN	84	PL 141B 271	+Sreedhar, Han, Imlay+	(CUSB Collab.)
ADEVA	83	PRL 50 799	+Barber, Becker, Berdugo+	(Mark-J Collab.)
ADEVA	83B	PRL 51 443	+Barber, Becker, Berdugo+	(Mark-J Collab.)
ALAM	83B	PRL 51 1143	+Csorna, Garren, Mestayer+	(CLEO Collab.)
BARTEL	83B	PL 132B 241	+Becker, Bowdery, Cords+	(JADE Collab.)
FERNANDEZ	83B	PRL 51 1022	+Ford, Read, Smith+	(MAC Collab.)
FERNANDEZ	83D	PRL 50 2054	+Ford, Read, Smith+	(MAC Collab.)
GREEN	83	PRL 51 347	+Hicks, Sannes, Skubic+	(CLEO Collab.)
KLOPFEN...	83B	PL 130B 444	Klopfenstein, Horstkotte+	(CUSB Collab.)
LOCKYER	83	PRL 51 1316	+Jaros, Nelson, Abrams+	(Mark II Collab.)
MATTEUZZI	83	PL 129B 141	+Abrams, Amidei, Blocker+	(Mark II Collab.)
NELSON	83	PRL 50 1542	+Blondel, Trilling, Abrams+	(Mark II Collab.)
BARTEL	82C	PL 114B 71	+Cords, Dittmann, Eichler+	(JADE Collab.)
BRODY	82	PRL 48 1070	+Chen, Goldberg, Horwitz+	(CLEO Collab.)
GIANNINI	82	NP B206 1	+Finocchiaro, Franzini+	(CUSB Collab.)
BEBEK	81	PRL 46 84	+Haggerty, Izen, Longuemare+	(CLEO Collab.)
CHADWICK	81	PRL 46 88	+Ganci, Kagar, Kass+	(CLEO Collab.)
ABRAMS	80	PRL 44 10	+Alam, Blocker, Boyarski+	(SLAC, LBL)

OTHER RELATED PAPERS

SCHINDLER	88	High Energy Electron-Positron Physics 234 Editors: A. Ali and P. Soeding, World Scientific, Singapore	(SLAC)
SCHUBERT	87	IHEP-HD/87-7 EPS Conference – Uppsala, Proc., Vol. 2, p. 791	(HEID)

B^0 $\quad I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions. See also the Listings for the B (following this entry) for measurements which do not identify the charge state.

For measurements of the B mean life and for branching ratios in which the charge of the decaying B is not determined, see the $B^{\pm}$ section.

In this issue we have attempted to bring the oldest measurements of branching ratios up to date wherever possible, and to explicitly state the input assumptions that the author(s) have made. Our own best fits to the D branching fractions now differ somewhat from the ones that have been used to calculate the B branching fractions. Whenever possible, the product branching fractions (the measured quantities) have been given.

See the Note at the beginning of the $B^{\pm}$ section.

B^0 MASS

The fit uses the $B^{\pm}$ and B^0 mass and mass difference measurements. These experiments actually measure the difference between half of E_{cm} and the B mass.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
5279.4 ± 1.5 OUR FIT				
5278.8 ± 2.3 OUR AVERAGE				
$5278.2\pm1.0\pm3.0$	40	ALBRECHT 87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$5279.5\pm1.6\pm3.0$	7	[1] ALBRECHT 87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$5280.6\pm0.8\pm2.0$		[2] BEBEK 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[1] Found using fully reconstructed decays with J/ψ. ALBRECHT 87D assume $m(\Upsilon(4S)) = 10577$ MeV.

[2] Redundant with data in the mass difference listing below. Enters fit via the mass difference.

$|m_{B^0_1} - m_{B^0_2}|$, MASS DIFFERENCE

VALUE (10^{-10} MeV)	DOCUMENT ID	TECN	COMMENT
4.0 ± 0.8 OUR AVERAGE			
3.8 ± 1.1	[3] ARTUSO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
4.1 ± 1.1	[3] ALBRECHT 87I	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[3] Calculated by us using $\Delta m = (2r/(1-r))^{1/2}\hbar/\tau_{B^0}$ where $\tau_{B^0} = (11.8 \pm 1.1)\times10^{-13}$ s and r is the B^0–$\overline{B}^0$ mixing ratio $\Gamma(B^0 \rightarrow \overline{B}^0 \rightarrow \mu^-\text{ anything})/\Gamma(B^0 \rightarrow \mu^+\text{ anything})$.

$B^0 - B^+$ MASS DIFFERENCE

The fit uses the $B^\pm$ and B^0 mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1.9±1.1 OUR FIT			
2.0±1.1±0.3	[4] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[4] BEBEK 87 actually measure the difference between half of E_{cm} and the $B^\pm$ or B^0 mass, so the $B^0 - B^\pm$ mass difference is more accurate. Assume $m(\Upsilon(4S))$ = 10580 MeV.

MEAN LIFE RATIO $\tau(B^0)/\tau(B^+)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.44 to 2.05	90	[5] BEAN 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[5] BEAN 87B assume the fraction of $B^0\overline{B}^0$ events at the $\Upsilon(4S)$ is 0.41.

B^0 DECAY MODES

$\overline{B}^0$ modes are charge conjugates of the modes below. Decays in which the charge of the B is not determined are in the $B^\pm$ section.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	μ^+ anything			
Γ_2	$D^-\ell^+\nu$ ($\ell = e$ or μ)		(1.8 ± 0.8) %	
Γ_3	$D^*(2010)^-\ell^+\nu$ ($\ell = e$ or μ)		(9.8 ± 1.5) %	
Γ_4	$D^*(2010)^-e^+\nu_e$			
Γ_5	$D^*(2010)^-\mu^+\nu_\mu$			
Γ_6	$D^-\pi^+$		$(3.7\pm1.5)\times10^{-3}$	
Γ_7	$D^-\rho^+$		(2.2 ± 1.5) %	
Γ_8	$\overline{D}^0\pi^+\pi^-$		< 3.9 %	90%
Γ_9	$\overline{D}^0\rho^0$		$< 3 \times10^{-3}$	90%
Γ_{10}	$D^*(2010)^-\pi^+$		$(3.3^{+1.2}_{-1.0})\times10^{-3}$	
Γ_{11}	$D^*(2010)^-\pi^+\pi^0$		(1.5 ± 1.1) %	
Γ_{12}	$D^*(2010)^-\rho^+$		$(8\ ^{+7}_{-4})$ %	
Γ_{13}	$D^*(2010)^-\pi^+\pi^+\pi^-$		(3.3 ± 1.8) %	
Γ_{14}	$J/\psi(1S)K^0$		$< 5 \times10^{-3}$	90%
Γ_{15}	$J/\psi(1S)K^+\pi^-$		$< 1.3 \times10^{-3}$	90%
Γ_{16}	$J/\psi(1S)K^*(892)^0$		$(3.7\pm1.3)\times10^{-3}$	
Γ_{17}	$\pi^+\pi^-$		$< 9 \times10^{-5}$	90%
Γ_{18}	$\pi^\pm\rho^\mp$		[a] $< 6.1 \times10^{-3}$	90%
Γ_{19}	$\pi^\pm a_1(1260)^\mp$		[a] $< 5.7 \times10^{-4}$	90%
Γ_{20}	$\pi^\pm a_2(1320)^\mp$		[a] $< 3.5 \times10^{-4}$	90%
Γ_{21}	$\rho^0\rho^0$		$< 3.4 \times10^{-4}$	90%
Γ_{22}	$a_1(1260)^+a_1(1260)^-$		$< 3.2 \times10^{-3}$	90%
Γ_{23}	$K^+\pi^-$		$< 9 \times10^{-5}$	90%
Γ_{24}	$K^0\rho^0$		$< 5.8 \times10^{-4}$	90%
Γ_{25}	$K^0\phi$		$< 4.9 \times10^{-4}$	90%
Γ_{26}	$K^0f_0(975)$		$< 4.2 \times10^{-4}$	90%
Γ_{27}	$K^*(892)^+\pi^-$		$< 4.4 \times10^{-4}$	90%
Γ_{28}	$K^*(892)^0\rho^0$		$< 6.7 \times10^{-4}$	90%
Γ_{29}	$K^*(892)^0\phi$		$< 4.4 \times10^{-4}$	90%
Γ_{30}	$K^*(892)^0f_0(975)$		$< 2.0 \times10^{-4}$	90%
Γ_{31}	$K^*(892)^0\gamma$		$< 2.8 \times10^{-4}$	90%
Γ_{32}	$K_1(1270)^0\gamma$		$< 7.8 \times10^{-3}$	90%
Γ_{33}	$K_1(1400)^0\gamma$		$< 4.8 \times10^{-3}$	90%
Γ_{34}	$K_2^*(1430)^0\gamma$		$< 4.4 \times10^{-4}$	90%
Γ_{35}	$K^*(1680)^0\gamma$		$< 2.2 \times10^{-3}$	90%
Γ_{36}	$K_3^*(1780)^0\gamma$		< 1.1 %	90%
Γ_{37}	$K_4^*(2045)^0\gamma$		$< 4.8 \times10^{-3}$	90%
Γ_{38}	$p\overline{p}$		$< 4 \times10^{-5}$	90%
Γ_{39}	$p\overline{p}\pi^+\pi^-$		$(6.0\pm3.0)\times10^{-4}$	
Γ_{40}	$p\overline{\Lambda}\pi^-$		$< 2.0 \times10^{-4}$	90%
Γ_{41}	$\Delta^0\overline{\Delta}^0$		$< 1.8 \times10^{-3}$	90%
Γ_{42}	$\Delta^{++}\Delta^{--}$		$< 1.3 \times10^{-4}$	90%
	Lepton Family number (*LF*) violating, Flavor-Changing neutral current (*FC*), or decay via Mixing (*MX*) modes			
Γ_{43}	$\mu^+\mu^-$	*FC*	$< 5 \times10^{-5}$	90%
Γ_{44}	e^+e^-	*FC*	$< 3 \times10^{-5}$	90%
Γ_{45}	$K^0\mu^+\mu^-$	*FC*	$< 4.5 \times10^{-4}$	90%
Γ_{46}	$K^0e^+e^-$	*FC*	$< 6.5 \times10^{-4}$	90%
Γ_{47}	$e^\pm\mu^\mp$	*LF*	[a] $< 4 \times10^{-5}$	90%
Γ_{48}	μ^- anything (via $\overline{B}^0$)	*MX*		

Measurements which do not identify the charge state of B appear in the $B^\pm$ section.

[a] Value is for the sum of the charge states indicated.

B^0 BRANCHING RATIOS

For branching ratios in which the charge of the decaying B is not determined, see the $B^\pm$ section.

$\Gamma(D^-\ell^+\nu\ (\ell = e \text{ or } \mu))/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.018±0.006±0.005	[6] ALBRECHT 89J	ARG	$e^+e^- \to \Upsilon(4S)$

[6] ALBRECHT 89J assume e-μ universality, $B(D^{*+} \to D^0\pi^+) = 57\pm4\pm4\%$, the Mark III D^0 and D^+ branching fractions, and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. The measurement gives $V_{cd} = 0.044 \pm 0.009$ averaging different models.

$[\Gamma(D^*(2010)^-e^+\nu_e) + \Gamma(D^*(2010)^-\mu^+\nu_\mu)]/\Gamma_{\text{total}}$ $(\Gamma_4+\Gamma_5)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.098±0.015 OUR AVERAGE				
0.120±0.020±0.028		[7] ALBRECHT 89J	ARG	$e^+e^- \to \Upsilon(4S)$
0.092±0.010±0.014		[8] BORTOLETTO 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[9] ALBRECHT 89C	ARG	$e^+e^- \to \Upsilon(4S)$
0.140±0.024±0.038	47	[10] ALBRECHT 87J	ARG	Repl. by ALBRECHT 89J

[7] ALBRECHT 89J is ALBRECHT 87J value rescaled using $B(D^*(2010)^- \to D^0\pi^-) = 0.57 \pm 0.04 \pm 0.04$.

[8] We have taken 2 times the BORTOLETTO 89B value to get the sum for electrons and muons. The measurement suggests a D^* polarization parameter value $\alpha = 0.65 \pm 0.66 \pm 0.25$. Assumes the $\Upsilon(4S)$ decays 50% to $B^0\overline{B}^0$, $B(D^0 \to K^-\pi^+) = 4.2 \pm 0.4 \pm 0.4\%$, $B(D^0 \to K^-\pi^+\pi^-\pi^+) = 9.1 \pm 1.3 \pm 0.4\%$, and $B(D^{*+} \to D^0\pi^+) = 57 \pm 4 \pm 4\%$.

[9] The measurement of ALBRECHT 89C suggests a D^* polarization γ_L/γ_T of 0.85 ± 0.45. or $\alpha = 0.7 \pm 0.9$.

[10] ALBRECHT 87J assume μ-e universality, the $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.45$, the $B(D^0 \to K^-\pi^+) = (0.042 \pm 0.004 \pm 0.004)$, and the $B(D^*(2010)^- \to D^0\pi^-) = 0.49 \pm 0.08$.

$\Gamma(D^-\pi^+)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0037±0.0015 OUR AVERAGE				
0.0031±0.0013±0.0010	7	[11] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0059^{+0.0033}_{-0.0029}{}^{+0.0015}_{-0.0014}$	4	[12] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[11] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55.

[12] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$ and $B(D^- \to K^+\pi^-\pi^-) = (9.1 \pm 1.3 \pm 0.4)\%$.

$\Gamma(D^-\rho^+)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.022±0.012±0.009	6	[13] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[13] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55.

$\Gamma(\overline{D}^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.039	90		[14] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.09 ±0.06		5	[15] BEHRENDS 83	CLEO	$e^+e^- \to \Upsilon(4S)$

[14] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. $B(D^0 \to K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-) = (9.1 \pm 0.8 \pm 0.8)\%$ were used.

[15] Corrected by us using assumptions: $B(D^0 \to K^-\pi^+) = (0.042 \pm 0.006)$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.40 \pm 0.02$. The product branching ratio is $B(B^0 \to \overline{D}^0\pi^+\pi^-)B(\overline{D}^0 \to K^+\pi^-) = (0.39 \pm 0.26) \times 10^{-2}$

$\Gamma(\overline{D}^0\rho^0)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.003	90	4	[16] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[16] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55.

$\Gamma(D^*(2010)^-\pi^+)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.0033^{+0.0012}_{-0.0010}$ OUR AVERAGE				
0.0027±0.0014±0.0010	5	[17] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0031^{+0.0017}_{-0.0013}{}^{+0.0011}_{-0.0007}$	5	[18] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0035±0.002 ±0.002		[19] ALBRECHT 86F	ARG	$e^+e^- \to \Upsilon(4S)$
0.017 ±0.005 ±0.005	41	[20] GILES 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[17] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$.

[18] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. $B(D^*(2010)^+ \to \pi^+D^0) = (60^{+\ 8}_{-15})\%$, $B(D^0 \to K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$, and $B(D^0 \to K^-\pi^+\pi^+\pi^-) = (9.1 \pm 0.8 \pm 0.8)\%$ were used.

[19] ALBRECHT 86F uses pseudomass that is independent of D^0 and D^+ branching ratios.

[20] Assumes $B(D^*(2010)^+ \to D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. Assumes $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.40 \pm 0.02$ Does not depend on D branching ratios.

$\Gamma(D^*(2010)^- \pi^+ \pi^0)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.015 \pm 0.008 \pm 0.008$	8	[21] ALBRECHT 87C	ARG	$e^+ e^- \to \Upsilon(4S)$

[21] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+ B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0 \overline{B}^0) = 45\%$.

$\Gamma(D^*(2010)^- \rho^+)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.081 \pm 0.029^{+0.059}_{-0.024}$	19	[22] CHEN 85	CLEO	$e^+ e^- \to \Upsilon(4S)$

[22] Uses $B(D^* \to D^0 \pi^+) = 0.6 \pm 0.15$ and $B(\Upsilon(4S) \to B^0 \overline{B}^0) = 0.4$. Does not depend on D branching ratios.

$\Gamma(D^*(2010)^- \pi^+ \pi^+ \pi^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$0.033 \pm 0.009 \pm 0.016$		27	[23] ALBRECHT 87C	ARG	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.046	90		[24] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[23] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+ B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0 \overline{B}^0) = 45\%$.

[24] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$. $B(D^*(2010)^+ \to \pi^+ D^0) = (60^{+8}_{-15})\%$, $B(D^0 \to K^- \pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$, and $B(D^0 \to K^- \pi^+ \pi^+ \pi^-) = (9.1 \pm 0.8 \pm 0.8)\%$ were used.

$\Gamma(J/\psi(1S) K^0)/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.005	90	ALAM 86	CLEO	$e^+ e^- \to \Upsilon(4S)$

$\Gamma(J/\psi(1S) K^+ \pi^-)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.0013	90		[25] ALBRECHT 87D	ARG	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0063	90	2	GILES 84	CLEO	$e^+ e^- \to \Upsilon(4S)$

[25] ALBRECHT 87D assume $B^+ B^- / B^0 \overline{B}^0$ ratio is 55/45. $K\pi$ system is specifically selected as nonresonant.

$\Gamma(J/\psi(1S) K^*(892)^0)/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0037 ± 0.0013 OUR AVERAGE				
0.0033 ± 0.0018	5	[26] ALBRECHT 87D	ARG	$e^+ e^- \to \Upsilon(4S)$
$0.0041 \pm 0.0019 \pm 0.0003$	5	[27] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0041 ± 0.0018	5	[28] ALAM 86	CLEO	Repl. by BEBEK 87

[26] ALBRECHT 87D assume $B^+ B^- / B^0 \overline{B}^0$ ratio is 55/45.

[27] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

[28] ALAM 86 assumes $B^\pm / B^0$ ratio is 60/40. The observation of the decay $B^+ \to J/\psi K^*(892)^+$ (HAAS 85) has been retracted in this paper.

$\Gamma(\pi^+ \pi^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<9 \times 10^{-5}$	90		[29] BORTOLETTO89	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-4}$	90		[29] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$
$<5 \times 10^{-4}$	90	4	GILES 84	CLEO	$e^+ e^- \to \Upsilon(4S)$

[29] Assume the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(\pi^\pm \rho^\mp)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0061	90	[30] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[30] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(\pi^\pm a_1(1260)^\mp)/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.7 \times 10^{-4}$	90	[31] BORTOLETTO89	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.2 \times 10^{-3}$	90	[31] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[31] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(\pi^\pm a_2(1320)^\mp)/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.5 \times 10^{-4}$	90	[32] BORTOLETTO89	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-3}$	90	[32] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[32] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(\rho^0 \rho^0)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.4 \times 10^{-4}$	90	[33] BORTOLETTO89	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5 \times 10^{-4}$	90	[33] BEBEK 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[33] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(a_1(1260)^+ a_1(1260)^-)/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0032	90	[34] BORTOLETTO89	CLEO	$e^+ e^- \to \Upsilon(4S)$

[34] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^+ \pi^-)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<9 \times 10^{-5}$	90	[35] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.2 \times 10^{-4}$	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[35] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^0 \rho^0)/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.8 \times 10^{-4}$	90	[36] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[36] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^0 \phi)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.9 \times 10^{-4}$	90	[37] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.3 \times 10^{-3}$	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[37] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^0 f_0(975))/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.2 \times 10^{-4}$	90	[38] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$

[38] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^*(892)^+ \pi^-)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.4 \times 10^{-4}$	90	[39] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<7 \times 10^{-4}$	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[39] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^*(892)^0 \rho^0)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<6.7 \times 10^{-4}$	90	[40] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.2 \times 10^{-3}$	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[40] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^*(892)^0 \phi)/\Gamma_{\text{total}}$ Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.4 \times 10^{-4}$	90	[41] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.7 \times 10^{-4}$	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[41] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^*(892)^0 f_0(975))/\Gamma_{\text{total}}$ Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.0 \times 10^{-4}$	90	[42] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$

[42] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K^*(892)^0 \gamma)/\Gamma_{\text{total}}$ Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<2.8 \times 10^{-4}$	90	[43] AVERY 89B	CLEO	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.2 \times 10^{-4}$	90	ALBRECHT 89G	ARG	$e^+ e^- \to \Upsilon(4S)$
$<2.1 \times 10^{-3}$	90	AVERY 87	CLEO	$e^+ e^- \to \Upsilon(4S)$

[43] Assumes the $\Upsilon(4S)$ decays 43% to $B^0 \overline{B}^0$.

$\Gamma(K_1(1270)^0 \gamma)/\Gamma_{\text{total}}$ Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0078	90	ALBRECHT 89G	ARG	$e^+ e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^0 \gamma)/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0048	90	ALBRECHT 89G	ARG	$e^+ e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0 \gamma)/\Gamma_{\text{total}}$ Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<4.4 \times 10^{-4}$	90	ALBRECHT 89G	ARG	$e^+ e^- \to \Upsilon(4S)$

$\Gamma(K^*(1680)^0 \gamma)/\Gamma_{\text{total}}$ Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0022	90	ALBRECHT 89G	ARG	$e^+ e^- \to \Upsilon(4S)$

$\Gamma(K_3^*(1780)^0\gamma)/\Gamma_{\text{total}}$ Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_4^*(2045)^0\gamma)/\Gamma_{\text{total}}$ Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0048	90	ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4 \times 10^{-5}$	90	[44] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.3 \times 10^{-4}$	90	ALBRECHT	88F	ARG	$e^+e^- \to \Upsilon(4S)$
$<2 \times 10^{-4}$	90	[44] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[44] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{39}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
$6.0\pm2.0\pm2.2$	ALBRECHT	88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{\Lambda}\pi^-)/\Gamma_{\text{total}}$ Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.0 \times 10^{-4}$	90	ALBRECHT	88F	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Delta^0\overline{\Delta}^0)/\Gamma_{\text{total}}$ Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0018	90	[45] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

[45] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\Delta^{++}\Delta^{--})/\Gamma_{\text{total}}$ Γ_{42}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.3 \times 10^{-4}$	90	[46] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

[46] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{43}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5 \times 10^{-5}$	90	[47] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<5 \times 10^{-5}$	90	ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9 \times 10^{-5}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<2 \times 10^{-4}$	90	GILES	84	CLEO	Repl. by AVERY 87

[47] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_{44}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3 \times 10^{-5}$	90	[48] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8.5 \times 10^{-5}$	90	ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
$<8 \times 10^{-5}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<3 \times 10^{-4}$	90	GILES	84	CLEO	Repl. by AVERY 87

[48] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_{45}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.5 \times 10^{-4}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0e^+e^-)/\Gamma_{\text{total}}$ Γ_{46}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.5 \times 10^{-4}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(e^\pm\mu^\mp)/\Gamma_{\text{total}}$ Γ_{47}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4 \times 10^{-5}$	90	[49] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<5 \times 10^{-5}$	90	ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
$<9 \times 10^{-5}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$
$<3 \times 10^{-4}$	90	GILES	84	CLEO	Repl. by AVERY 87

[49] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\mu^- \text{ anything (via } \overline{B}^0))/\Gamma(\mu^\pm \text{ anything})$ $\Gamma_{48}/(\Gamma_1+\Gamma_{48})$

This is a B^0-$\overline{B}^0$ mixing measurement. Violates $\Delta B \neq 2$ rule. Two different variables, χ and r, are used. We have converted all results to χ.

$$\chi = \Gamma(B \to \mu^- X)/\Gamma(B \to \mu^\pm X)$$
$$= \Gamma(\overline{B} \to \mu^+ X)/\Gamma(\overline{B} \to \mu^\pm X)$$

or $r = \chi/(1-\chi)$.

Note that the experiments other than those at the $\Upsilon(4S)$ have not separated χ_d from χ_s where the subscripts indicate $B^0(\overline{b}d)$ or $B_s^0(\overline{b}s)$, so they are not included in the average.

The experiments at $\Upsilon(4S)$ make an assumption about the $B^0\overline{B}^0$ fraction and about the ratio of the $B^\pm$ and B^0 semileptonic branching ratios (usually that it equals one).

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.16 ± 0.04 OUR AVERAGE					
$0.158^{+0.052}_{-0.059}$		[50] ARTUSO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
0.17 ± 0.05		[51] ALBRECHT	87I	ARG	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$0.21^{+0.29}_{-0.15}$		[52] BAND	88	MAC	$E_{\text{cm}}^{ee} = 29$ GeV
>0.02	90	[52] BAND	88	MAC	$E_{\text{cm}}^{ee} = 29$ GeV
0.121 ± 0.047		[52,53] ALBAJAR	87C	UA1	$p\overline{p}$ 546–630 GeV
<0.19	90	[54] BEAN	87B	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.12	90	[52,55] SCHAAD	85	MRK2	$E_{\text{cm}}^{ee} = 29$ GeV
<0.27	90	[56] AVERY	84	CLEO	$e^+e^- \to \Upsilon(4S)$

[50] χ is calculated as $r/(1+r)$. They also give $\Delta m/\Gamma = 0.69 \pm 0.17$. The authors take the B^+B^- fraction as 55% of the $\Upsilon(4S)$. The measurement is an average of $\mu\mu$, μe, and ee events.

[51] Measured inclusively with like-sign dileptons, with tagged B decays plus leptons, and one fully reconstructed event. ALBRECHT 87I measured $r=0.21 \pm 0.08$. We converted to χ for comparison.

[52] These experiments see a combination of B_s and B_d mesons.

[53] ALBAJAR 87C measured $\chi = (\overline{B}^0 \to B^0 \to \mu^+ X)$ divided by the average production weighted semileptonic branching fraction for B hadrons at 546 and 630 GeV.

[54] BEAN 87B measured $r < 0.24$; we converted to χ.

[55] Limit is average probability for hadron containing B quark to produce a positive lepton.

[56] Same-sign dilepton events. Limit assumes semileptonic BR for B^+ and B^0 equal. If $B^0/B^\pm$ ratio <0.58, no limit exists. The limit was corrected in BEAN 87B from $r < 0.30$ to $r < 0.37$. We converted this limit to χ.

REFERENCES FOR B^0

ALBRECHT 89C PL B219 121 +Boeckmannn, Glaeser, Harder+ (ARGUS Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 89J PL B229 175 +Glaser, Harder+ (ARGUS Collab.)
ARTUSO 89 PRL 62 2233 +Bebek, Berkelman, Blucher+ (CLEO Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
BORTOLETTO 89B PRL 63 1667 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88K PL B215 424 +Boeckmann, Glaeser+ (ARGUS Collab.)
BAND 88 PL B200 221 +Camporesi, Chadwick+ (MAC Collab.)
ALBAJAR 87C PL B186 247 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87I PL B192 245 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
ALBRECHT 87J PL B197 452 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
ALBRECHT 86F PL B182 95 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+
CHEN 85 PR D31 2386 +Goldberg, Horwitz, Jawahery+ (CLEO Collab.)
HAAS 85 PRL 55 1248 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
SCHAAD 85 PL 160B 188 +Nelson, Abrams, Amidei+ (Mark II Collab.)
AVERY 84 PRL 53 1309 +Bebek, Berkelman, Cassel+ (CLEO Collab.)
GILES 84 PR D30 2279 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
BEHRENDS 83 PRL 50 881 +Chadwick, Chauveau, Ganci+ (CLEO Collab.)

OTHER RELATED PAPERS

SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
SCHUBERT 87 IHEP-HD/87-7 (HEID)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791

B^*

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

OMITTED FROM SUMMARY TABLE

B^* MASS

VALUE (MeV)	DOCUMENT ID
5331.3±4.7 OUR EVALUATION	From mass difference below and $B^\pm$ and B^0 masses 5279.3 ± 1.4 MeV.
5330 ±5 OUR FIT	

$B^* - B$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
52 ±4 OUR FIT					
52.0±2.±4.	1400	HAN	85	CUSB	$e^+ e^- \to \gamma e X$

B^* REFERENCES

HAN 85 PRL 55 36 -Klopfenstein, Mageras- (COLU, LSU, MPIM, STON)

$c\bar{c}$ MESONS

$\eta_c(1S)$ or $\eta_c(2980)$

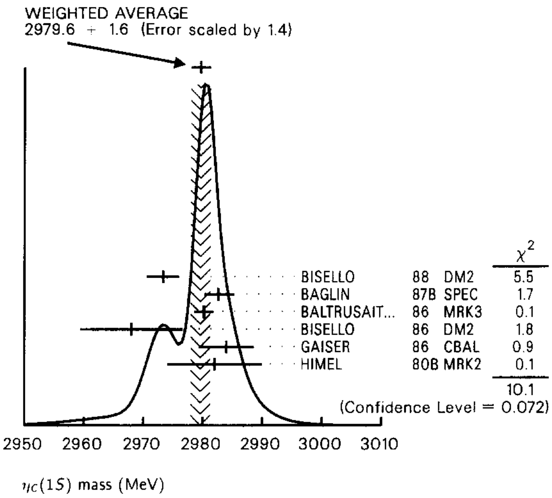
$I^G(J^{PC}) = 0^+(0^{-+})$

Observed in the inclusive γ spectrum generated from $\psi(2S)$ decay, therefore $C = +$. From the 4π decay $G = +$, therefore $I = 0$. From angular distribution in $J/\psi(1S) \to \eta_c\gamma$, $\eta_c \to \phi\phi$, $J^P = 0^-$ (BALTRUSAITIS 84).

$\eta_c(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2979.6±1.6 OUR AVERAGE		Error includes scale factor of 1.4.			See the ideogram below.
2973.3±2.7	137 ± 23	BISELLO	88	DM2	$J/\psi \to \gamma 2\pi^+ 2\pi^-$
$2982.6^{+2.7}_{-2.3}$	12	BAGLIN	87B	SPEC	$\bar{p}p \to \gamma\gamma$
2980.2±1.6		[1] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
2968.0±5 ±7	19	BISELLO	86	DM2	$J/\psi \to \gamma\phi\phi$
2984 ±2.3±4.0		GAISER	86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$
2982 ±8	18	[2] HIMEL	80B	MRK2	$e^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2976 ±8		[3] BALTRUSAIT..84		MRK3	$J/\psi \to 2\phi\gamma$
2980 ±9		[2] PARTRIDGE	80B	CBAL	$e^+ e^-$

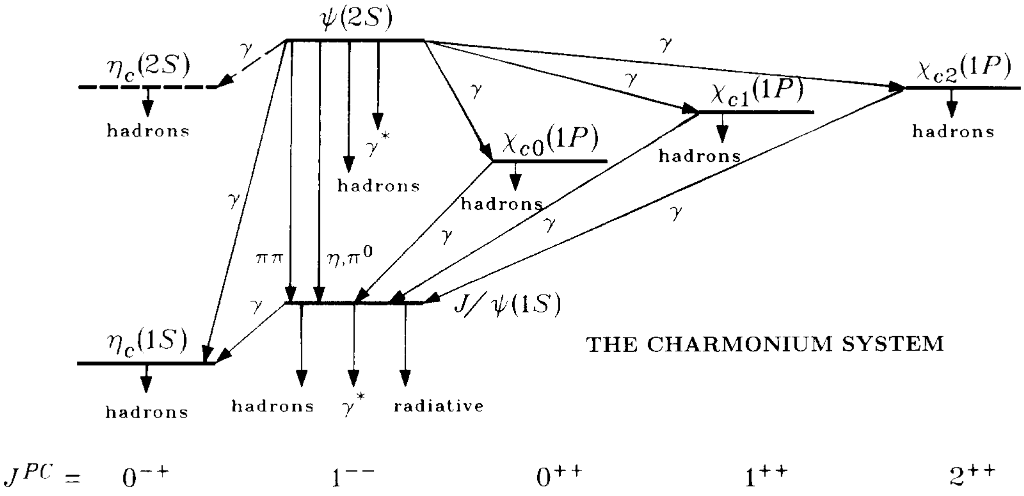
[1] Average of several decay modes.
[2] Mass adjusted by us to correspond to $J/\psi(1S)$ mass = 3097 MeV.
[3] $\eta_c \to \phi\phi$.



$\eta_c(1S)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$10.3^{+3.8}_{-3.4}$ OUR AVERAGE						
$7.0^{+7.5}_{-7.0}$		12	BAGLIN	87B	SPEC	$\bar{p}p \to \gamma\gamma$
$10.1^{+33.0}_{-8.2}$		23 ± 11	[4] BALTRUSAIT..86		MRK3	$J/\psi \to \gamma p\bar{p}$
11.5± 4.5			GAISER	86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<40	90	18	HIMEL	80B	MRK2	$e^+ e^-$
<20	90		PARTRIDGE	80B	CBAL	$e^+ e^-$

[4] Positive and negative errors correspond to 90% confidence level.



THE CHARMONIUM SYSTEM

The current state of knowledge of the charmonium system and transitions, as interpreted by the charmonium model. Uncertain states and transitions are indicated by dashed lines. The notation γ^* refers to decay processes involving intermediate virtual photons, including decays to e^+e^- and $\mu^+\mu^-$.

$\eta_c(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Decays involving hadronic resonances		
Γ_1	$\eta'(958)\pi\pi$	(4.1 ± 1.7) %	
Γ_2	$\rho\rho$	(2.6 ± 0.9) %	
Γ_3	$K^*(892)^0 K^- \pi^+$ + c.c.	(2.0 ± 0.7) %	
Γ_4	$K^*(892)\overline{K}^*(892)$	$(9 \pm 5) \times 10^{-3}$	
Γ_5	$\phi\phi$	$(3.4 \pm 1.2) \times 10^{-3}$	S=1.5
Γ_6	$a_0(980)\pi$	< 2 %	CL=90%
Γ_7	$a_2(1320)\pi$	< 2 %	CL=90%
Γ_8	$f_2(1270)\eta$	< 1.1 %	CL=90%
Γ_9	$\omega\omega$	$< 3.1 \times 10^{-3}$	CL=90%
	Decays into stable hadrons		
Γ_{10}	$K\overline{K}\pi$	(5.5 ± 0.8) %	
Γ_{11}	$\eta\pi\pi$	(5.0 ± 1.1) %	
Γ_{12}	$\pi^+\pi^- K^+ K^-$	(2.04 ± 0.28) %	
Γ_{13}	$2(\pi^+\pi^-)$	(1.17 ± 0.28) %	
Γ_{14}	$p\overline{p}$	$(1.04 \pm 0.19) \times 10^{-3}$	
Γ_{15}	$K\overline{K}\eta$	< 3.1 %	CL=90%
Γ_{16}	$\pi^+\pi^- p\overline{p}$	< 1.2 %	CL=90%
	Radiative decays		
Γ_{17}	$\gamma\gamma$	$(6 {}^{+6}_{-5}) \times 10^{-4}$	

$\eta_c(1S)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_{17}

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
$8 {}^{+7}_{-5}$ OUR AVERAGE Error includes scale factor of 1.4.			
$6.4 {}^{+5.0}_{-3.4}$	AIHARA 88D	TPC	$e^+e^- \to e^+e^- X$
28 ± 15	[5] BERGER 86	PLUT	$\gamma\gamma \to K\overline{K}\pi$

[5] Re-evaluated by AIHARA 88D.

$\eta_c(1S)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_{10}\Gamma_{17}/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
1.2 ± 0.4 OUR AVERAGE					
$1.06 \pm 0.41 \pm 0.27$		11 ± 4	BRAUNSCH... 89	TASS	$\gamma\gamma \to K\overline{K}\pi$
$1.5 {}^{+0.60}_{-0.45} \pm 0.3$		7	[6] BERGER 86	PLUT	$\gamma\gamma \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.63	95		[6] BEHREND 89	CELL	$\gamma\gamma \to K^0_S K^\pm \pi^\mp$
<4.4	95		ALTHOFF 85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[6] $K^\pm K^0_S \pi^\mp$ corrected to $K\overline{K}\pi$ by factor 3.

$\eta_c(1S)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(\eta'(958)\pi\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.041 ± 0.017	14 ± 4	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\rho\rho)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$26 \pm 8 \pm 5$		113	BISELLO 88	DM2	$J/\psi \to \eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<140	90		[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)^0 K^- \pi^+ + \text{c.c.})/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.02 ± 0.007	63 ± 10	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
90 ± 50	9 ± 4	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\phi\phi)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
34 ± 12 OUR AVERAGE Error includes scale factor of 1.5.				
$31 \pm 7 \pm 4$	19	[7] BISELLO 86	DM2	$J/\psi \to 2\phi\gamma$
$80 \pm 20 \pm 25$	16 ± 4	[7] BALTRUSAIT..84	MRK3	$J/\psi \to 2\phi\gamma$

$\Gamma(a_0(980)\pi)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	90	[7,8] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(a_2(1320)\pi)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	90	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(f_2(1270)\eta)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.011	90	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0031	90	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K\overline{K}\pi)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.055 ± 0.008 OUR AVERAGE					
0.0613 ± 0.0122			[7] AUGUSTIN 86	DM2	$J/\psi \to \eta_c\gamma$
0.048 ± 0.011		96 ± 18	[7,9] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$
$0.079 {}^{+0.042}_{-0.032}$			[10,11] HIMEL 80B	MRK2	$\psi(2S) \to \eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.107	90		[7] PARTRIDGE 80B	CBAL	$J/\psi \to \eta_c\gamma$

$\Gamma(\eta\pi\pi)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.050 ± 0.011 OUR AVERAGE				
0.054 ± 0.013	75 ± 11	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$
0.036 ± 0.024	18	[7] PARTRIDGE 80B	CBAL	$J/\psi \to \eta\pi^+\pi^-\gamma$

$\Gamma(\pi^+\pi^- K^+ K^-)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0204 ± 0.0028 OUR AVERAGE				
0.021 ± 0.003	110 ± 17	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$
$0.009 {}^{+0.014}_{-0.006}$		[10] HIMEL 80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0117 ± 0.0028 OUR AVERAGE				
0.0105 ± 0.0038	$137 \pm 23 \pm 7$	BISELLO 88	DM2	$J/\psi \to \eta_c\gamma$
0.013 ± 0.005	25 ± 9	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$
$0.013 {}^{+0.009}_{-0.006}$		[10] HIMEL 80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
10.4 ± 1.9 OUR AVERAGE				
10 ± 2		[7] AUGUSTIN 86	DM2	$J/\psi \to \eta_c\gamma$
11 ± 6	23 ± 11	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$
$20 {}^{+20}_{-10}$		[10] HIMEL 80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(K\overline{K}\eta)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.031	90	[7] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\pi^+\pi^- p\overline{p})/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.012	90	HIMEL 80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\overline{p} \to \eta_c(1S) \to \phi\phi$ — $\Gamma_{14}\Gamma_5/\Gamma^2$

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
$4.0 {}^{+3.5}_{-3.2}$	BAGLIN 89	SPEC	$\overline{p}p \to K^+K^-K^+K^-$

[7] The quoted branching ratios use $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$.

[8] We are assuming $B(a_0(980) \to \eta\pi) > 0.5$.

[9] Average from $K^+K^-\pi^0$ and $K^\pm K^0{}'\text{s}\,\pi^\mp$ decay channels.

[10] Estimated using $B(\psi(2S) \to \gamma\eta_c(1S)) = 0.0043$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

[11] Not seen by Partridge in $K^+K^-\pi^0$.

RADIATIVE DECAYS

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
$6 {}^{+4}_{-3} \pm 4$		BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<18	90	[12] BLOOM 83	CBAL	$J/\psi \to \eta_c\gamma$

[12] Using $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$.

$\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\overline{p} \to \eta_c(1S) \to \gamma\gamma$ — $\Gamma_{14}\Gamma_{17}/\Gamma^2$

VALUE (units 10^{-6})	EVTS	DOCUMENT ID	TECN	COMMENT
$0.68 {}^{+0.42}_{-0.31}$	12	BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$

$\eta_c(1S)$ REFERENCES

BAGLIN 89 PL B231 557 +Baird, Bassompierre (R704 Collab.)
BEHREND 89 ZPHY C42 367 +Criegee+ (CELLO Collab.)
BRAUNSCH... 89 ZPHY C41 533 Braunschweig, Bock+ (TASSO Collab.)
AIHARA 88D PRL 60 2355 +Alston-Garnjost+ (TPC Collab.)
BISELLO 88 PL B200 215 +Busetto+ (PADO, CLER, FRAS, LALO)
BAGLIN 87B PL B187 191 +Baird, Bassompierre, Borreani+ (R704 Collab.)
AUGUSTIN 86 Moriond XXI 421 +Ajaltouni, Bisello+ (LALO, CLER, PADO, FRAS)
BALTRUSAIT... 86 PR D33 629 Baltrusaitis, Coffman, Hauser+ (Mark III Collab.)
BERGER 86 PL 167B 120 +Genzel, Lackas, Pielorz+ (PLUTO Collab.)
BISELLO 86 PL B179 289 +Busetto, Castro, Limentani+ (DM2 Collab.)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
BALTRUSAIT... 84 PRL 52 2126 Baltrusaitis+ (CIT, UCSC, ILL, SLAC, WASH) JP
BLOOM 83 ARNS 33 143 +Peck (SLAC, CIT)
HIMEL 80B PRL 45 1146 +Trilling, Abrams, Alam+ (SLAC, LBL, UCB)
PARTRIDGE 80B PRL 45 1150 +Peck+ (CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

ARMSTRONG 89 PL B221 216 +Benayoun+ (CERN, CDEF, BIRM, BARI, ATHU, LPNP)
BLOOM 79 Fermilab Symp. 92 (CIT, HARV, PRIN, SLAC, STAN)

$J/\psi(1S)$
or $J/\psi(3097)$

$I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
3096.93±0.09 OUR AVERAGE				
3096.95±0.1 ±0.3	193	BAGLIN 87	SPEC	$\overline{p}p \to e^+e^- X$
3098.4 ±2.0	38k	LEMOIGNE 82	GOLI	190 GeV π^- Be $\to$ 2μ
3096.93±0.09	502	ZHOLENTZ 80	REDE	e^+e^-
3097.0 ±1		[1] BRANDELIK 79C	DASP	e^+e^-

[1] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$ and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

$J/\psi(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID
68±10 OUR EVALUATION	Uses $\Gamma(ee)$ from ALEXANDER 89 and $B(ee) = B(\mu\mu)$ from BOYARSKI 75.

$J/\psi(1S)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons		(86.0 ± 2.0) %	
Γ_2	virtual $\gamma \to$ hadrons		(17.0 ± 2.0) %	
Γ_3	e^+e^-		(6.9 ± 0.9) %	
Γ_4	$\mu^+\mu^-$		(6.9 ± 0.9) %	

Decays involving hadronic resonances

Γ_5	$\rho\pi$		(1.28 ± 0.10) %	
Γ_6	$\rho^0\pi^0$		$(4.2 \pm 0.5) \times 10^{-3}$	
Γ_7	$a_2(1320)\rho$		$(9.2 \pm 1.1) \times 10^{-3}$	
Γ_8	$\omega\pi^+\pi^+\pi^-\pi^-$		$(8.5 \pm 3.4) \times 10^{-3}$	
Γ_9	$\omega\pi^+\pi^-$		$(7.0 \pm 0.7) \times 10^{-3}$	
Γ_{10}	$K^*(892)^0\overline{K}_2^*(1430)^0$ + c.c.		$(6.7 \pm 2.6) \times 10^{-3}$	
Γ_{11}	$\omega K^*(892)\overline{K}$ + c.c.		$(5.3 \pm 2.0) \times 10^{-3}$	
Γ_{12}	$\omega f_2(1270)$		$(4.1 \pm 0.4) \times 10^{-3}$	
Γ_{13}	$K^+\overline{K}^*(892)^-$ + c.c.		$(3.8 \pm 0.7) \times 10^{-3}$	S=2.0
Γ_{14}	$K^0\overline{K}^*(892)^0$ + c.c.		$(3.7 \pm 0.8) \times 10^{-3}$	S=2.1
Γ_{15}	$\omega\pi^0\pi^0$		$(3.4 \pm 0.8) \times 10^{-3}$	
Γ_{16}	$b_1(1235)^\pm\pi^\mp$	[a]	$(3.0 \pm 0.5) \times 10^{-3}$	
Γ_{17}	$\omega K^\pm K_S^0\pi^\mp$	[a]	$(2.9 \pm 0.7) \times 10^{-3}$	
Γ_{18}	$b_1(1235)^0\pi^0$		$(2.3 \pm 0.6) \times 10^{-3}$	
Γ_{19}	$\phi K^*(892)\overline{K}$ + c.c.		$(2.04 \pm 0.28) \times 10^{-3}$	
Γ_{20}	$\omega K\overline{K}$		$(1.9 \pm 0.4) \times 10^{-3}$	
Γ_{21}	$\omega f_2(1720) \to \omega K\overline{K}$		$(4.8 \pm 1.1) \times 10^{-4}$	
Γ_{22}	$\omega\eta$		$(1.71 \pm 0.22) \times 10^{-3}$	
Γ_{23}	$\phi 2(\pi^+\pi^-)$		$(1.60 \pm 0.32) \times 10^{-3}$	
Γ_{24}	$\Delta(1232)^{++}\overline{p}\pi^-$		$(1.6 \pm 0.5) \times 10^{-3}$	
Γ_{25}	$\phi K\overline{K}$		$(1.48 \pm 0.22) \times 10^{-3}$	
Γ_{26}	$\phi f_2(1720) \to \phi K\overline{K}$		$(3.6 \pm 0.6) \times 10^{-4}$	
Γ_{27}	$p\overline{p}\omega$		$(1.30 \pm 0.25) \times 10^{-3}$	S=1.3
Γ_{28}	$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		$(1.10 \pm 0.29) \times 10^{-3}$	
Γ_{29}	$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[a]	$(1.03 \pm 0.13) \times 10^{-3}$	
Γ_{30}	$p\overline{p}\eta'(958)$		$(9 \pm 4) \times 10^{-4}$	S=1.7
Γ_{31}	$\phi f_2'(1525)$		$(8 \pm 4) \times 10^{-4}$	S=2.7
Γ_{32}	$\phi\pi^+\pi^-$		$(7.8 \pm 1.0) \times 10^{-4}$	
Γ_{33}	$\phi K^\pm K_S^0\pi^\mp$	[a]	$(7.2 \pm 0.9) \times 10^{-4}$	
Γ_{34}	$\phi\eta$		$(7.14 \pm 0.30) \times 10^{-4}$	
Γ_{35}	$\omega f_1(1420)$		$(6.8 \pm 2.4) \times 10^{-4}$	
Γ_{36}	$\Xi(1530)^-\overline{\Xi}^+$		$(5.9 \pm 1.5) \times 10^{-4}$	
Γ_{37}	$pK^-\overline{\Sigma}(1385)^0$		$(5.1 \pm 3.2) \times 10^{-4}$	
Γ_{38}	$\omega\pi^0$		$(4.8 \pm 0.7) \times 10^{-4}$	
Γ_{39}	$\phi\eta'(958)$		$(3.8 \pm 0.4) \times 10^{-4}$	S=1.6
Γ_{40}	$\phi f_0(975)$		$(3.2 \pm 0.5) \times 10^{-4}$	S=1.3
Γ_{41}	$\Xi(1530)^0\overline{\Xi}^0$		$(3.2 \pm 1.4) \times 10^{-4}$	
Γ_{42}	$\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)	[a]	$(3.1 \pm 0.5) \times 10^{-4}$	
Γ_{43}	$\rho\eta$		$(1.93 \pm 0.32) \times 10^{-4}$	
Γ_{44}	$\omega\eta'(958)$		$(1.66 \pm 0.25) \times 10^{-4}$	
Γ_{45}	$\omega f_0(975)$		$(1.41 \pm 0.34) \times 10^{-4}$	
Γ_{46}	$\rho\eta'(958)$		$(9.6 \pm 1.8) \times 10^{-5}$	S=1.2
Γ_{47}	$\phi f_1(1285)$		$(8 \pm 5) \times 10^{-5}$	S=2.2
Γ_{48}	$p\overline{p}\phi$		$(4.5 \pm 1.5) \times 10^{-5}$	
Γ_{49}	$a_2(1320)^\pm\pi^\mp$	[a]	$< 4.3 \times 10^{-3}$	CL=90%
Γ_{50}	$K\overline{K}_2^*(1430)$ + c.c.		$< 4.0 \times 10^{-3}$	CL=90%
Γ_{51}	$K_2^*(1430)^0\overline{K}_2^*(1430)^0$		$< 2.9 \times 10^{-3}$	CL=90%
Γ_{52}	$K^*(892)^0\overline{K}^*(892)^0$		$< 5 \times 10^{-4}$	CL=90%
Γ_{53}	$\phi f_2(1270)$		$< 3.7 \times 10^{-4}$	CL=90%
Γ_{54}	$p\overline{p}\rho$		$< 3.1 \times 10^{-4}$	CL=90%
Γ_{55}	$\phi\eta(1440) \to \phi\eta\pi\pi$		$< 2.5 \times 10^{-4}$	CL=90%
Γ_{56}	$\omega f_2'(1525)$		$< 2.2 \times 10^{-4}$	CL=90%
Γ_{57}	$\Sigma(1385)^0\overline{\Lambda}$		$< 2 \times 10^{-4}$	CL=90%
Γ_{58}	$\Delta(1232)^+\overline{p}$		$< 1 \times 10^{-4}$	CL=90%
Γ_{59}	$\Sigma^0\overline{\Lambda}$		$< 9 \times 10^{-5}$	CL=90%
Γ_{60}	$\phi\pi^0$		$< 6.8 \times 10^{-6}$	CL=90%

Decays into stable hadrons

Γ_{61}	$2(\pi^+\pi^-)\pi^0$		(3.42 ± 0.31) %	
Γ_{62}	$3(\pi^+\pi^-)\pi^0$		(2.9 ± 0.6) %	
Γ_{63}	$\pi^+\pi^-\pi^0$		(1.50 ± 0.15) %	
Γ_{64}	$\pi^+\pi^-\pi^0K^+K^-$		(1.20 ± 0.30) %	
Γ_{65}	$4(\pi^+\pi^-)\pi^0$		$(9.0 \pm 3.0) \times 10^{-3}$	
Γ_{66}	$\pi^+\pi^-K^+K^-$		$(7.2 \pm 2.3) \times 10^{-3}$	
Γ_{67}	$K\overline{K}\pi$		$(6.1 \pm 1.0) \times 10^{-3}$	
Γ_{68}	$p\overline{p}\pi^+\pi^-$		$(6.0 \pm 0.5) \times 10^{-3}$	S=1.3
Γ_{69}	$2(\pi^+\pi^-)$		$(4.0 \pm 1.0) \times 10^{-3}$	
Γ_{70}	$3(\pi^+\pi^-)$		$(4.0 \pm 2.0) \times 10^{-3}$	
Γ_{71}	$n\overline{n}\pi^+\pi^-$		$(4 \pm 4) \times 10^{-3}$	
Γ_{72}	$\Sigma\overline{\Sigma}$		$(3.8 \pm 0.5) \times 10^{-3}$	
Γ_{73}	$2(\pi^+\pi^-)K^+K^-$		$(3.1 \pm 1.3) \times 10^{-3}$	
Γ_{74}	$p\overline{p}\pi^+\pi^-\pi^0$	[b]	$(2.3 \pm 0.9) \times 10^{-3}$	S=1.9
Γ_{75}	$p\overline{p}$		$(2.16 \pm 0.11) \times 10^{-3}$	
Γ_{76}	$p\overline{p}\eta$		$(2.09 \pm 0.18) \times 10^{-3}$	
Γ_{77}	$p\overline{n}\pi^-$		$(2.00 \pm 0.10) \times 10^{-3}$	
Γ_{78}	$\Xi\overline{\Xi}$		$(1.8 \pm 0.4) \times 10^{-3}$	S=1.8
Γ_{79}	$n\overline{n}$		$(1.8 \pm 0.9) \times 10^{-3}$	
Γ_{80}	$\Lambda\overline{\Lambda}$		$(1.35 \pm 0.14) \times 10^{-3}$	S=1.2
Γ_{81}	$p\overline{p}\pi^0$		$(1.09 \pm 0.09) \times 10^{-3}$	
Γ_{82}	$\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)	[a]	$(1.06 \pm 0.12) \times 10^{-3}$	
Γ_{83}	$pK^-\overline{\Lambda}$		$(8.9 \pm 1.6) \times 10^{-4}$	
Γ_{84}	$2(K^+K^-)$		$(7.0 \pm 3.0) \times 10^{-4}$	
Γ_{85}	$pK^-\overline{\Sigma}^0$		$(2.9 \pm 0.8) \times 10^{-4}$	
Γ_{86}	K^+K^-		$(2.37 \pm 0.31) \times 10^{-4}$	
Γ_{87}	$\Lambda\overline{\Lambda}\pi^0$		$(2.2 \pm 0.7) \times 10^{-4}$	
Γ_{88}	$\pi^+\pi^-$		$(1.47 \pm 0.23) \times 10^{-4}$	
Γ_{89}	$K_S^0K_L^0$		$(1.01 \pm 0.18) \times 10^{-4}$	
Γ_{90}	$\Lambda\overline{\Sigma}$ + c.c.		$< 1.5 \times 10^{-4}$	CL=90%
Γ_{91}	$K_S^0K_S^0$		$< 5.2 \times 10^{-6}$	CL=90%

Radiative decays

Γ_{92}	$\gamma\eta_c(1S)$		(1.3 ± 0.4) %	
Γ_{93}	$\gamma\pi^+\pi^-2\pi^0$		$(8.3 \pm 3.1) \times 10^{-3}$	
Γ_{94}	$\gamma\eta\pi\pi$		$(6.1 \pm 1.0) \times 10^{-3}$	
Γ_{95}	$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	[c]	$(4.8 \pm 0.8) \times 10^{-3}$	
Γ_{96}	$\gamma\rho\rho$		$(4.5 \pm 0.8) \times 10^{-3}$	
Γ_{97}	$\gamma\eta'(958)$		$(4.2 \pm 0.4) \times 10^{-3}$	
Γ_{98}	$\gamma 2\pi^+2\pi^-$		$(2.8 \pm 0.5) \times 10^{-3}$	S=1.9
Γ_{99}	$\gamma f_4(2050)$		$(2.7 \pm 0.7) \times 10^{-3}$	
Γ_{100}	$\gamma\omega\omega$		$(1.59 \pm 0.33) \times 10^{-3}$	
Γ_{101}	$\gamma\eta(1490) \to \gamma\rho^0\rho^0$		$(1.4 \pm 0.4) \times 10^{-3}$	
Γ_{102}	$\gamma f_2(1270)$		$(1.38 \pm 0.14) \times 10^{-3}$	
Γ_{103}	$\gamma f_2(1720) \to \gamma K\overline{K}$		$(9.7 \pm 1.2) \times 10^{-4}$	
Γ_{104}	$\gamma\eta$		$(8.6 \pm 0.8) \times 10^{-4}$	

Γ_{105} $\gamma f'_2(1525)$		$(6.3 \pm 1.0) \times 10^{-4}$	
Γ_{106} $\gamma p\overline{p}$		$(3.8 \pm 1.0) \times 10^{-4}$	
Γ_{107} $\gamma\phi\phi$		$(3.1 \pm 0.8) \times 10^{-4}$	
Γ_{108} $\gamma\eta(2100) \rightarrow \gamma\rho^0\rho^0$		$(2.4 {}^{+1.5}_{-1.0}) \times 10^{-4}$	
Γ_{109} $\gamma\eta(1760) \rightarrow \gamma\rho^0\rho^0$		$(1.3 \pm 0.9) \times 10^{-4}$	
Γ_{110} $\gamma\pi^0$		$(3.9 \pm 1.3) \times 10^{-5}$	
Γ_{111} $\gamma f_1(1285)$	$<$	6×10^{-3}	CL=90%
Γ_{112} $\gamma p\overline{p}\pi^+\pi^-$	$<$	7.9×10^{-4}	CL=90%
Γ_{113} $\gamma\gamma$	$<$	5×10^{-4}	CL=90%
Γ_{114} $\gamma\Lambda\overline{\Lambda}$	$<$	1.3×10^{-4}	CL=90%
Γ_{115} 3γ	$<$	5.5×10^{-5}	CL=90%
Γ_{116} $\gamma X(2200)$			
Γ_{117} $\gamma f_4(2220)$			

[a] Value is for the sum of the charge states indicated.

[b] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[c] See $\eta(1440)$ mini-review.

$J/\psi(1S)$ PARTIAL WIDTHS

$\Gamma(\text{hadrons})$ — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
59±24	BALDINI-...	75	FRAG	e^+e^-
59±14	BOYARSKI	75	MRK1	e^+e^-
50±25	ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(\text{virtual } \gamma \rightarrow \text{hadrons})$ — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
12±2	[2] BOYARSKI	75	MRK1	e^+e^-

[2] Included in $\Gamma(\text{hadrons})$.

$\Gamma(e^+e^-)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
4.72±0.35	ALEXANDER	89	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.4 ±0.6	[3] BRANDELIK	79C	DASP	e^+e^-
4.6 ±0.8	[4] BALDINI-...	75	FRAG	e^+e^-
4.8 ±0.6	BOYARSKI	75	MRK1	e^+e^-
4.6 ±1.0	ESPOSITO	75B	FRAM	e^+e^-

[3] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

[4] Assuming equal partial widths for e^+e^- and $\mu^+\mu^-$.

$\Gamma(\mu^+\mu^-)$ — Γ_4

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.8±0.6	BOYARSKI	75	MRK1	e^+e^-
5.0±1.0	ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(\gamma\gamma)$ — Γ_{113}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<5.4	90	BRANDELIK	79C	DASP	e^+e^-

$J/\psi(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel in the e^+e^- annihilation.

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4 ±0.8	[5] BALDINI-...	75	FRAG	e^+e^-
3.9±0.8	[5] ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(e^+e^-) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_3\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.35±0.02	BRANDELIK	79C	DASP	e^+e^-
0.32±0.07	[5] BALDINI-...	75	FRAG	e^+e^-
0.34±0.14	BEMPORAD	75	FRAB	e^+e^-
0.34±0.09	[5] ESPOSITO	75B	FRAM	e^+e^-
0.36±0.10	[5] FORD	75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_4\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.31±0.09	BEMPORAD	75	FRAB	e^+e^-
0.51±0.09	DASP	75	DASP	e^+e^-
0.38±0.05	[5] ESPOSITO	75B	FRAM	e^+e^-
0.46±0.10	[5] LIBERMAN	75	SPEC	e^+e^-

[5] Data redundant with branching ratios or partial widths above.

$J/\psi(1S)$ BRANCHING RATIOS

For the first four branching ratios, see also the partial widths, and (partial widths)$\times\Gamma(e^+e^-)/\Gamma_{\text{total}}$ above.

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.86±0.02	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(\text{virtual } \gamma \rightarrow \text{hadrons})/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.17±0.02	[6] BOYARSKI	75	MRK1	e^+e^-

[6] Included in $\Gamma(\text{hadrons})/\Gamma_{\text{total}}$.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.069±0.009	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.069±0.009	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	COMMENT
0.98±0.04 OUR AVERAGE				
1.00±0.05	BOYARSKI	75	MRK1	e^+e^-
0.91±0.15	ESPOSITO	75B	FRAM	e^+e^-
0.93±0.10	FORD	75	SPEC	e^+e^-

HADRONIC DECAYS

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0128±0.0010 OUR AVERAGE					
0.0142±0.0001±0.0019		COFFMAN	88	MRK3	e^+e^-
0.013 ±0.003	150	FRANKLIN	83C	MRK2	e^+e^-
0.016 ±0.004	183	ALEXANDER	78	PLUT	e^+e^-
0.0133±0.0021		BRANDELIK	78B	DASP	e^+e^-
0.010 ±0.002	543	BARTEL	76	CNTR	e^+e^-
0.013 ±0.003	153	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\rho^0\pi^0)/\Gamma(\rho\pi)$ — Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
0.328±0.005±0.027	COFFMAN	88	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.36 ±0.03	SCHARRE	79B	MRK1	e^+e^-
0.35 ±0.08	ALEXANDER	78	PLUT	e^+e^-
0.32 ±0.08	BRANDELIK	78B	DASP	e^+e^-
0.39 ±0.11	BARTEL	76	CNTR	e^+e^-
0.37 ±0.09	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(a_2(1320)\rho)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
9.2±1.1 OUR AVERAGE					
11.7±0.7±2.5	7584	AUGUSTIN	89	DM2	e^+e^-
8.6±0.3±1.3		AUGUSTIN	86	DM2	$J/\psi \rightarrow$ hadrons
8.4±4.5	36	VANNUCCI	77	MRK1	$e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85±34	140	VANNUCCI	77	MRK1	$e^+e^- \rightarrow 3(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
7.0±0.7 OUR AVERAGE					
7.0±1.6	18058	AUGUSTIN	89	DM2	e^+e^-
6.6±1.0±0.6		AUGUSTIN	86	DM2	$J/\psi \rightarrow$ hadrons
7.8±1.6	215	BURMESTER	77D	PLUT	e^+e^-
6.8±1.9	348	VANNUCCI	77	MRK1	$e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-)\pi^0)$ — Γ_9/Γ_{61}

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.3	[7] JEAN-MARIE	76	MRK1	e^+e^-

[7] Final state $(\pi^+\pi^-)\pi^0$ under the assumption that $\pi\pi$ is isospin 0.

$\Gamma\left(K^*(892)^0\overline{K}{}^*_2(1430)^0 + \text{c.c.}\right)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
67±26	40	VANNUCCI 77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma\left(\omega K^*(892)\overline{K} + \text{c.c.}\right)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

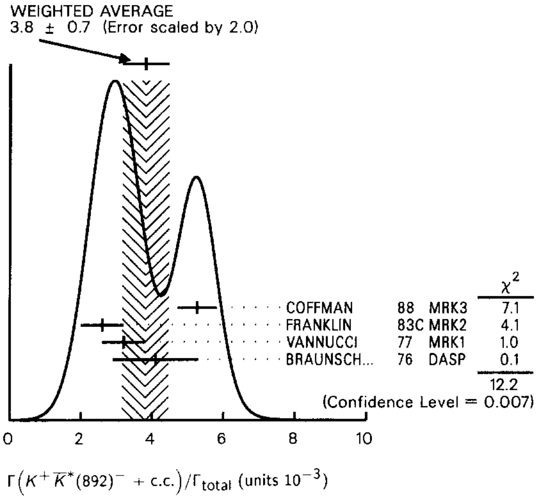
VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
53±14±14	530 ± 140	BECKER 87	MRK3	$e^+e^- \to$ hadrons

$\Gamma\left(\omega f_2(1270)\right)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
4.1±0.4 OUR AVERAGE				
4.3±0.2±0.6	5860	AUGUSTIN 89	DM2	e^+e^-
4.0±0.6		AUGUSTIN 86	DM2	$J/\psi \to$ hadrons
4.0±1.6	70	BURMESTER 77D	PLUT	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.9±0.8	81	VANNUCCI 77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma\left(K^+\overline{K}{}^*(892)^- + \text{c.c.}\right)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.8 ±0.7 OUR AVERAGE Error includes scale factor of 2.0. See the ideogram below.				
5.26±0.13±0.53		COFFMAN 88	MRK3	$J/\psi \to K^\pm K^0_S\pi^\mp$, $K^+K^-\pi^0$
2.6 ±0.6	24	FRANKLIN 83C	MRK2	$J/\psi \to K^+K^-\pi^0$
3.2 ±0.6	48	VANNUCCI 77	MRK1	$J/\psi \to K^\pm K^0_S\pi^\mp$
4.1 ±1.2	39	BRAUNSCH... 76	DASP	$J/\psi \to K^\pm X$



$\Gamma\left(K^0\overline{K}{}^*(892)^0 + \text{c.c.}\right)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.7 ±0.8 OUR AVERAGE Error includes scale factor of 2.1.				
4.33±0.12±0.45		COFFMAN 88	MRK3	$J/\psi \to K^\pm K^0_S\pi^\mp$
2.7 ±0.6	45	VANNUCCI 77	MRK1	$J/\psi \to K^\pm K^0_S\pi^\mp$

$\Gamma\left(K^0\overline{K}{}^*(892)^0 + \text{c.c.}\right)/\Gamma\left(K^+\overline{K}{}^*(892)^- + \text{c.c.}\right)$ — Γ_{14}/Γ_{13}

VALUE	DOCUMENT ID	TECN	COMMENT
0.82±0.05±0.09	COFFMAN 88	MRK3	$J/\psi \to K\overline{K}{}^*(892)$ +c.c.

$\Gamma\left(\omega\pi^0\pi^0\right)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.4±0.3±0.7	509	AUGUSTIN 89	DM2	e^+e^-

$\Gamma\left(b_1(1235)^\pm\pi^\mp\right)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
30±5 OUR AVERAGE				
31±6	4600	AUGUSTIN 89	DM2	e^+e^-
29±7	87	BURMESTER 77D	PLUT	e^+e^-

$\Gamma\left(\omega K^\pm K^0_S\pi^\mp\right)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
29.5±1.4±7.0	879 ± 41	BECKER 87	MRK3	$e^+e^- \to$ hadrons

$\Gamma\left(b_1(1235)^0\pi^0\right)/\Gamma_{\text{total}}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
23±3±5	229	AUGUSTIN 89	DM2	e^+e^-

$\Gamma\left(\phi K^*(892)\overline{K} + \text{c.c.}\right)/\Gamma_{\text{total}}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
20.4±2.8 OUR AVERAGE				
20.7±2.4±3.0		FALVARD 88	DM2	$J/\psi \to$ hadrons
20 ±3 ±3	155 ± 20	BECKER 87	MRK3	$e^+e^- \to$ hadrons

$\Gamma\left(\omega K\overline{K}\right)/\Gamma_{\text{total}}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
19 ± 4 OUR AVERAGE				
19.8± 2.1±3.9		[8] FALVARD 88	DM2	$J/\psi \to$ hadrons
16 ±10	22	FELDMAN 77	MRK1	e^+e^-

[8] Addition of ωK^+K^- and $\omega K^0\overline{K}{}^0$ branching ratios.

$\Gamma\left(\omega f_2(1720) \to \omega K\overline{K}\right)/\Gamma_{\text{total}}$ — Γ_{21}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
4.8±1.1±0.3	[9,10] FALVARD 88	DM2	$J/\psi \to$ hadrons

[9] Includes unknown branching fraction $f_2(1720) \to K\overline{K}$.

[10] Addition of $f_2(1720) \to K^+K^-$ and $f_2(1720) \to K^0\overline{K}{}^0$ branching ratios.

$\Gamma\left(\omega\eta\right)/\Gamma_{\text{total}}$ — Γ_{22}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
1.71±0.08±0.20	COFFMAN 88	MRK3	$e^+e^- \to 3\pi\eta$

$\Gamma\left(\phi 2(\pi^+\pi^-)\right)/\Gamma_{\text{total}}$ — Γ_{23}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
16.0±1.0±3.0	FALVARD 88	DM2	$J/\psi \to$ hadrons

$\Gamma\left(\Delta(1232)^{++}\overline{p}\pi^-\right)/\Gamma_{\text{total}}$ — Γ_{24}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.58±0.23±0.40	332	EATON 84	MRK2	e^+e^-

$\Gamma\left(\phi K\overline{K}\right)/\Gamma_{\text{total}}$ — Γ_{25}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
14.8±2.2 OUR AVERAGE				
14.6±0.8±2.1		[11] FALVARD 88	DM2	$J/\psi \to$ hadrons
18 ±8	14	FELDMAN 77	MRK1	e^+e^-

[11] Addition of ϕK^+K^- and $\phi K^0\overline{K}{}^0$ branching ratios.

$\Gamma\left(\phi f_2(1720) \to \phi K\overline{K}\right)/\Gamma_{\text{total}}$ — Γ_{26}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
3.6± .2±0.6	[12,13] FALVARD 88	DM2	$J/\psi \to$ hadrons

[12] Including interference with $f'_2(1525)$.

[13] Includes unknown branching fraction $f_2(1720) \to K\overline{K}$.

$\Gamma\left(p\overline{p}\omega\right)/\Gamma_{\text{total}}$ — Γ_{27}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.30±0.25 OUR AVERAGE Error includes scale factor of 1.3.				
1.10±0.17±0.18	486	EATON 84	MRK2	e^+e^-
1.6 ±0.3	77	PERUZZI 78	MRK1	e^+e^-

$\Gamma\left(\Delta(1232)^{++}\overline{\Delta}(1232)^{--}\right)/\Gamma_{\text{total}}$ — Γ_{28}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.10±0.09±0.28	233	EATON 84	MRK2	e^+e^-

$\Gamma\left(\Sigma(1385)^-\overline{\Sigma}(1385)^+ \text{ (or c.c.)}\right)/\Gamma_{\text{total}}$ — Γ_{29}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.03±0.13 OUR AVERAGE				
1.00±0.04±0.21	631 ± 25	HENRARD 87	DM2	$e^+e^- \to \Sigma^{*-}$
1.19±0.04±0.25	754 ± 27	HENRARD 87	DM2	$e^+e^- \to \Sigma^{*+}$
0.86±0.18±0.22	56	EATON 84	MRK2	$e^+e^- \to \Sigma^{*-}$
1.03±0.24±0.25	68	EATON 84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma\left(p\overline{p}\eta'(958)\right)/\Gamma_{\text{total}}$ — Γ_{30}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.9 ±0.4 OUR AVERAGE Error includes scale factor of 1.7.				
0.68±0.23±0.17	19	EATON 84	MRK2	e^+e^-
1.8 ±0.6	19	PERUZZI 78	MRK1	e^+e^-

$\Gamma\left(\phi f'_2(1525)\right)/\Gamma_{\text{total}}$ — Γ_{31}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
8 ±4 OUR AVERAGE Error includes scale factor of 2.7.				
12.3±0.6±2.0		[14,15] FALVARD 88	DM2	$J/\psi \to$ hadrons
4.8±1.8	46	[14] GIDAL 81	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.6±0.5		AUGUSTIN 86	DM2	$J/\psi \to$ hadrons

[14] Re-evaluated using $B(f'_2(1525) \to K\overline{K}) = 0.713$.

[15] Including interference with $f_2(1720)$.

$\Gamma\left(\phi\pi^+\pi^-\right)/\Gamma_{\text{total}}$ — Γ_{32}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.78±0.10 OUR AVERAGE				
0.78±0.03±0.12		FALVARD 88	DM2	$J/\psi \to$ hadrons
0.75±0.16		AUGUSTIN 86	DM2	$J/\psi \to$ hadrons
2.1 ±0.9	23	FELDMAN 77	MRK1	e^+e^-

$\Gamma(\phi K^{\pm} K^0_S \pi^{\mp})/\Gamma_{\rm total}$ Γ_{33}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.2±0.9 OUR AVERAGE					
7.4±0.9±1.1		FALVARD	88	DM2	$J/\psi \to$ hadrons
7 ±0.6±1.0	163 ± 15	BECKER	87	MRK3	$e^+ e^- \to$ hadrons

$\Gamma(\phi\eta)/\Gamma_{\rm total}$ Γ_{34}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.714±0.030 OUR AVERAGE					
0.661±0.045±0.078		COFFMAN	88	MRK3	$e^+ e^- \to K^+ K^- \eta$
0.72 ±0.03 ±0.01	330	AUGUSTIN	86	DM2	$J/\psi \to$ hadrons

$\Gamma(\omega f_1(1420))/\Gamma_{\rm total}$ Γ_{35}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$6.8^{+1.9}_{-1.6}\pm1.7$	111^{+31}_{-26}	BECKER	87	MRK3	$e^+ e^- \to$ hadrons

$\Gamma(\Xi(1530)^- \overline{\Xi}^+)/\Gamma_{\rm total}$ Γ_{36}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.59±0.09±0.12	75 ± 11	HENRARD	87	DM2	$e^+ e^-$

$\Gamma(p K^- \overline{\Sigma}(1385)^0)/\Gamma_{\rm total}$ Γ_{37}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.26±0.18	89	EATON	84	MRK2	$e^+ e^-$

$\Gamma(\omega\pi^0)/\Gamma_{\rm total}$ Γ_{38}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.482±0.019±0.064	COFFMAN	88	MRK3	$e^+ e^- \to \pi^0 \pi^+ \pi^- \pi^0$

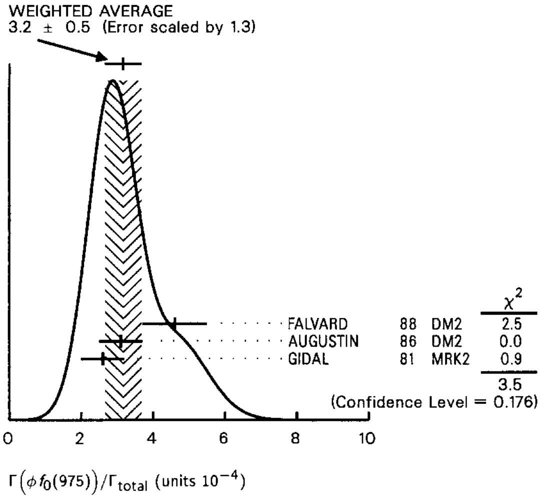
$\Gamma(\phi\eta'(958))/\Gamma_{\rm total}$ Γ_{39}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.38 ±0.04 OUR AVERAGE Error includes scale factor of 1.6.						
0.308±0.034±0.036			COFFMAN	88	MRK3	$e^+ e^- \to K^+ K^- \eta'$
0.40 ±0.025±0.01		177	AUGUSTIN	86	DM2	$J/\psi \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		VANNUCCI	77	MRK1	$e^+ e^-$

$\Gamma(\phi f_0(975))/\Gamma_{\rm total}$ Γ_{40}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
3.2±0.5 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
4.6±0.4±0.8		[16] FALVARD	88	DM2	$J/\psi \to$ hadrons
3.1±0.6		[16] AUGUSTIN	86	DM2	$J/\psi \to$ hadrons
2.6±0.6	50	[16] GIDAL	81	MRK2	$e^+ e^-$

[16] Assuming B($f_0(975) \to \pi\pi$) = 0.78.



$\Gamma(\Xi(1530)^0 \overline{\Xi}^0)/\Gamma_{\rm total}$ Γ_{41}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.12±0.07	24 ± 9	HENRARD	87	DM2	$e^+ e^-$

$\Gamma(\Sigma(1385)^- \overline{\Sigma}^+$ (or c.c.)$)/\Gamma_{\rm total}$ Γ_{42}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.31±0.05 OUR AVERAGE					
0.30±0.03±0.07	74 ± 8	HENRARD	87	DM2	$e^+ e^- \to \Sigma^{*-}$
0.34±0.04±0.07	77 ± 9	HENRARD	87	DM2	$e^+ e^- \to \Sigma^{*+}$
0.29±0.11±0.10	26	EATON	84	MRK2	$e^+ e^- \to \Sigma^{*-}$
0.31±0.11±0.11	28	EATON	84	MRK2	$e^+ e^- \to \Sigma^{*+}$

$\Gamma(\rho\eta)/\Gamma_{\rm total}$ Γ_{43}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.193±0.013±0.029	COFFMAN	88	MRK3	$e^+ e^- \to \pi^+ \pi^- \eta$

$\Gamma(\omega\eta'(958))/\Gamma_{\rm total}$ Γ_{44}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.166±0.017±0.019	COFFMAN	88	MRK3	$e^+ e^- \to 3\pi\eta'$

$\Gamma(\omega f_0(975))/\Gamma_{\rm total}$ Γ_{45}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
1.41±0.27±0.21	[17] AUGUSTIN	89	DM2	$e^+ e^-$

[17] Assuming B($f_0(975) \to \pi\pi$) = 0.78.

$\Gamma(\rho\eta'(958))/\Gamma_{\rm total}$ Γ_{46}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.096±0.018 OUR AVERAGE Error includes scale factor of 1.2.					
0.114±0.014±0.016		COFFMAN	88	MRK3	$J/\psi \to \pi^+ \pi^- \eta'$
0.078±0.017±0.012	18	AUGUSTIN	86	DM2	$J/\psi \to$ hadrons

$\Gamma(\phi f_1(1285))/\Gamma_{\rm total}$ Γ_{47}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.8 ±0.5 OUR AVERAGE Error includes scale factor of 2.2.					
0.6 ±0.2±0.1	16 ± 6	BECKER	87	MRK3	$e^+ e^- \to$ hadrons
1.77±0.4±0.25	10	AUGUSTIN	86	DM2	$J/\psi \to$ hadrons

$\Gamma(p\overline{p}\phi)/\Gamma_{\rm total}$ Γ_{48}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
0.45±0.13±0.07	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(a_2(1320)^{\pm}\pi^{\mp})/\Gamma_{\rm total}$ Γ_{49}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<43	90	BRAUNSCH...	76	DASP	$e^+ e^-$

$\Gamma(K\overline{K}^*_2(1430)$ + c.c.$)/\Gamma_{\rm total}$ Γ_{50}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<40	90	VANNUCCI	77	MRK1	$e^+ e^- \to K^0 \overline{K}^{*0}_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<66	90	BRAUNSCH...	76	DASP	$e^+ e^- \to K^{\pm} \overline{K}^{*\mp}_2$

$\Gamma(K^*_2(1430)^0 \overline{K}^*_2(1430)^0)/\Gamma_{\rm total}$ Γ_{51}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<29	90	VANNUCCI	77	MRK1	$e^+ e^- \to \pi^+ \pi^- K^+ K^-$

$\Gamma(K^*(892)^0 \overline{K}^*(892)^0)/\Gamma_{\rm total}$ Γ_{52}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	VANNUCCI	77	MRK1	$e^+ e^- \to \pi^+ \pi^- K^+ K^-$

$\Gamma(\phi f_2(1270))/\Gamma_{\rm total}$ Γ_{53}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.7	90	VANNUCCI	77	MRK1	$e^+ e^- \to \pi^+ \pi^- K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.5	90	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(p\overline{p}\rho)/\Gamma_{\rm total}$ Γ_{54}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.31	90	EATON	84	MRK2	$e^+ e^- \to$ hadrons γ

$\Gamma(\phi\eta(1440) \to \phi\eta\pi\pi)/\Gamma_{\rm total}$ Γ_{55}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.5	90	[18] FALVARD	88	DM2	$J/\psi \to$ hadrons

[18] Includes unknown branching fraction $\eta(1440) \to \eta\pi\pi$.

$\Gamma(\omega f'_2(1525))/\Gamma_{\rm total}$ Γ_{56}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	[19] VANNUCCI	77	MRK1	$e^+ e^- \to \pi^+ \pi^- \pi^0 K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.8	90	[19] FALVARD	88	DM2	$J/\psi \to$ hadrons

[19] Re-evaluated assuming B($f'_2(1525) \to K\overline{K}$) = 0.713.

$\Gamma(\Sigma(1385)^0 \overline{\Lambda})/\Gamma_{\rm total}$ Γ_{57}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.2	90	HENRARD	87	DM2	$e^+ e^-$

$\Gamma(\Delta(1232)^+ \overline{p})/\Gamma_{\rm total}$ Γ_{58}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	HENRARD	87	DM2	$e^+ e^-$

$\Gamma(\Sigma^0\overline{\Lambda})/\Gamma_{\text{total}}$ — Γ_{59}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.9	90	HENRARD 87	DM2	$e^+ e^-$

$\Gamma(\phi\pi^0)/\Gamma_{\text{total}}$ — Γ_{60}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.068	90	COFFMAN 88	MRK3	$e^+ e^- \rightarrow K^+ K^- \pi^0$

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{61}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0342±0.0031 OUR AVERAGE				
0.0325±0.049	46055	AUGUSTIN 89	DM2	$e^+ e^-$
0.0317±0.0042	147	FRANKLIN 83C	MRK2	$e^+ e^- \rightarrow$ hadrons
0.0364±0.0052	1500	BURMESTER 77D	PLUT	$e^+ e^-$
0.04 ±0.01	675	JEAN-MARIE 76	MRK1	$e^+ e^-$

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{62}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.029±0.006 OUR AVERAGE				
0.028±0.009	11	FRANKLIN 83C	MRK2	$e^+ e^- \rightarrow$ hadrons
0.029±0.007	181	JEAN-MARIE 76	MRK1	$e^+ e^-$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0150±0.0015 OUR AVERAGE				
0.0149±0.0022		EINSWEILER 83	MRK3	$e^+ e^-$
0.015 ±0.002	168	FRANKLIN 83C	MRK2	$e^+ e^-$

$\Gamma(\pi^+\pi^-\pi^0 K^+ K^-)/\Gamma_{\text{total}}$ — Γ_{64}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.012±0.003	309	VANNUCCI 77	MRK1	$e^+ e^-$

$\Gamma(4(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ — Γ_{65}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
90±30	13	JEAN-MARIE 76	MRK1	$e^+ e^-$

$\Gamma(\pi^+\pi^- K^+ K^-)/\Gamma_{\text{total}}$ — Γ_{66}/Γ

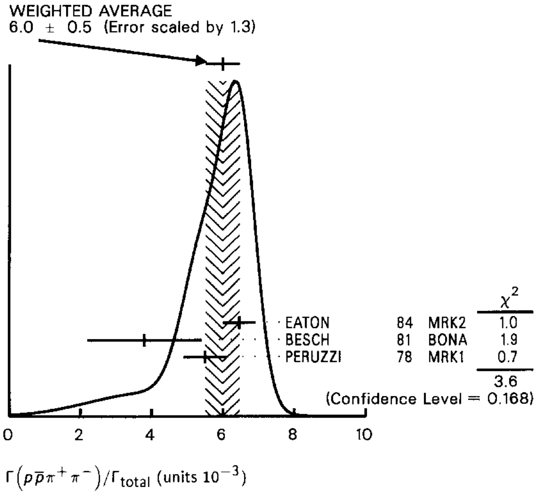
VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
72±23	205	VANNUCCI 77	MRK1	$e^+ e^-$

$\Gamma(K\overline{K}\pi)/\Gamma_{\text{total}}$ — Γ_{67}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
61 ±10 OUR AVERAGE				
55.2±12.0	25	FRANKLIN 83C	MRK2	$e^+ e^- \rightarrow K^+ K^- \pi^0$
78.0±21.0	126	VANNUCCI 77	MRK1	$e^+ e^- \rightarrow K^0_S K^\pm \pi^\mp$

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{68}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
6.0 ±0.5 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
6.46±0.17±0.43	1435	EATON 84	MRK2	$e^+ e^-$
3.8 ±1.6	48	BESCH 81	BONA	$e^+ e^-$
5.5 ±0.6	533	PERUZZI 78	MRK1	$e^+ e^-$



$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{69}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.004±0.001	76	JEAN-MARIE 76	MRK1	$e^+ e^-$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{70}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
40±20	32	JEAN-MARIE 76	MRK1	$e^+ e^-$

$\Gamma(n\overline{n}\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{71}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.8±3.6	5	BESCH 81	BONA	$e^+ e^-$

$\Gamma(\Sigma\overline{\Sigma})/\Gamma_{\text{total}}$ — Γ_{72}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.8 ±0.5 OUR AVERAGE				
3.18±0.12±0.69	884 ± 30	PALLIN 87	DM2	$e^+ e^-$
4.74±0.48±0.75	90	EATON 84	MRK2	$e^+ e^- \rightarrow \Sigma^0\overline{\Sigma}^0$
7.2 ±7.8	3	BESCH 81	BONA	$e^+ e^- \rightarrow \Sigma^+\overline{\Sigma}^-$
3.9 ±1.2	52	PERUZZI 78	MRK1	$e^+ e^- \rightarrow \Sigma^0\overline{\Sigma}^0$

$\Gamma(2(\pi^+\pi^-)K^+K^-)/\Gamma_{\text{total}}$ — Γ_{73}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
31±13	30	VANNUCCI 77	MRK1	$e^+ e^-$

$\Gamma(p\overline{p}\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{74}/Γ

Including $p\overline{p}\pi^+\pi^-\gamma$ and excluding ω, η, η'

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.3 ±0.9 OUR AVERAGE Error includes scale factor of 1.9.				
3.36±0.65±0.28	364	EATON 84	MRK2	$e^+ e^-$
1.6 ±0.6	39	PERUZZI 78	MRK1	$e^+ e^-$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ — Γ_{75}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.16±0.11 OUR AVERAGE				
1.91±0.04±0.30		PALLIN 87	DM2	$e^+ e^-$
2.16±0.07±0.15	1420	EATON 84	MRK2	$e^+ e^-$
2.5 ±0.4	133	BRANDELIK 79C	DASP	$e^+ e^-$
2.0 ±0.5		BESCH 78	BONA	$e^+ e^-$
2.2 ±0.2	331	[20] PERUZZI 78	MRK1	$e^+ e^-$

[20] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\overline{p})/\Gamma(\mu^+\mu^-)$ — Γ_{75}/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.051±0.02	20	[21] WIIK 75	PLUT	$e^+ e^-$

[21] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\overline{p}\eta)/\Gamma_{\text{total}}$ — Γ_{76}/Γ

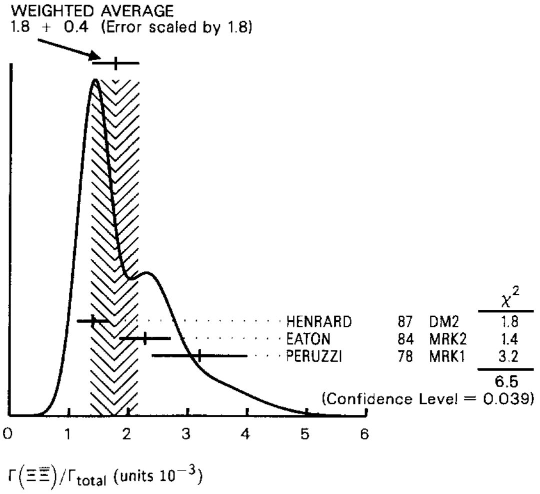
VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.09±0.18 OUR AVERAGE				
2.03±0.13±0.15	826	EATON 84	MRK2	$e^+ e^-$
2.5 ±1.2		BRANDELIK 79C	DASP	$e^+ e^-$
2.3 ±0.4	197	PERUZZI 78	MRK1	$e^+ e^-$

$\Gamma(p\overline{n}\pi^-)/\Gamma_{\text{total}}$ — Γ_{77}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.00±0.10 OUR AVERAGE				
2.02±0.07±0.16	1288	EATON 84	MRK2	$e^+ e^- \rightarrow p\pi^-$
1.93±0.07±0.16	1191	EATON 84	MRK2	$e^+ e^- \rightarrow \overline{p}\pi^+$
1.7 ±0.7	32	BESCH 81	BONA	$e^+ e^- \rightarrow p\pi^-$
1.6 ±1.2	5	BESCH 81	BONA	$e^+ e^- \rightarrow \overline{p}\pi^+$
2.16±0.29	194	PERUZZI 78	MRK1	$e^+ e^- \rightarrow p\pi^-$
2.04±0.27	204	PERUZZI 78	MRK1	$e^+ e^- \rightarrow \overline{p}\pi^+$

$\Gamma(\Xi\overline{\Xi})/\Gamma_{\text{total}}$ — Γ_{78}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.8 ±0.4 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.				
1.40±0.12±0.24	132 ± 11	HENRARD 87	DM2	$e^+ e^- \rightarrow \Xi^-\overline{\Xi}^+$
2.28±0.16±0.40	194	EATON 84	MRK2	$e^+ e^- \rightarrow \Xi^-\overline{\Xi}^+$
3.2 ±0.8	71	PERUZZI 78	MRK1	$e^+ e^-$



$\Gamma(n\overline{n})/\Gamma_{\text{total}}$ Γ_{79}/Γ

VALUE (units 10^{-2})	*DOCUMENT ID*	*TECN*	*COMMENT*
0.18±0.09	BESCH 78	BONA	$e^+ e^-$

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{\text{total}}$ Γ_{80}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.35±0.14 OUR AVERAGE Error includes scale factor of 1.2.				
1.38±0.05±0.20	1847	PALLIN 87	DM2	$e^+ e^-$
1.58±0.08±0.19	365	EATON 84	MRK2	$e^+ e^-$
2.6 ±1.6	5	BESCH 81	BONA	$e^+ e^-$
1.1 ±0.2	196	PERUZZI 78	MRK1	$e^+ e^-$

$\Gamma(p\overline{p}\pi^0)/\Gamma_{\text{total}}$ Γ_{81}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.09±0.09 OUR AVERAGE				
1.13±0.09±0.09	685	EATON 84	MRK2	$e^+ e^-$
1.4 ±0.4		BRANDELIK 79C	DASP	$e^+ e^-$
1.00±0.15	109	PERUZZI 78	MRK1	$e^+ e^-$

$\Gamma(\Lambda\overline{\Sigma}^- \pi^+ \text{ (or c.c.)})/\Gamma_{\text{total}}$ Γ_{82}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.06±0.12 OUR AVERAGE				
0.90±0.06±0.16	225 ± 15	HENRARD 87	DM2	$e^+ e^- \to \Lambda\overline{\Sigma}^+ \pi^-$
1.11±0.06±0.20	342 ± 18	HENRARD 87	DM2	$e^+ e^- \to \Lambda\overline{\Sigma}^- \pi^+$
1.53±0.17±0.38	135	EATON 84	MRK2	$e^+ e^- \to \Lambda\overline{\Sigma}^+ \pi^-$
1.38±0.21±0.35	118	EATON 84	MRK2	$e^+ e^- \to \Lambda\overline{\Sigma}^- \pi^+$

$\Gamma(pK^-\overline{\Lambda})/\Gamma_{\text{total}}$ Γ_{83}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.89±0.07±0.14	307	EATON 84	MRK2	$e^+ e^-$

$\Gamma(2(K^+K^-))/\Gamma_{\text{total}}$ Γ_{84}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*	*TECN*	*COMMENT*
7±3	VANNUCCI 77	MRK1	$e^+ e^-$

$\Gamma(pK^-\overline{\Sigma}^0)/\Gamma_{\text{total}}$ Γ_{85}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.29±0.06±0.05	90	EATON 84	MRK2	$e^+ e^-$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_{86}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2.37±0.31 OUR AVERAGE				
2.39±0.24±0.22	107	BALTRUSAIT..85D	MRK3	$e^+ e^-$
2.2 ±0.9	6	BRANDELIK 79C	DASP	$e^+ e^-$

$\Gamma(\Lambda\overline{\Lambda}\pi^0)/\Gamma_{\text{total}}$ Γ_{87}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.22±0.05±0.05	19 ± 4	HENRARD 87	DM2	$e^+ e^-$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{88}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.47±0.23 OUR AVERAGE				
1.58±0.20±0.15	84	BALTRUSAIT..85D	MRK3	$e^+ e^-$
1.0 ±0.5	5	BRANDELIK 78B	DASP	$e^+ e^-$
1.6 ±1.6	1	VANNUCCI 77	MRK1	$e^+ e^-$

$\Gamma(K^0_S K^0_L)/\Gamma_{\text{total}}$ Γ_{89}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.01±0.16±0.09	74	BALTRUSAIT..85D	MRK3	$e^+ e^-$

$\Gamma(\Lambda\overline{\Sigma} + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{90}/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.15	90	PERUZZI 78	MRK1	$e^+ e^- \to \Lambda X$

$\Gamma(K^0_S K^0_S)/\Gamma_{\text{total}}$ Γ_{91}/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.052	90	[22] BALTRUSAIT..85C	MRK3	$e^+ e^-$

[22] Forbidden by *CP*.

RADIATIVE DECAYS

$\Gamma(\gamma\eta_c(1S))/\Gamma_{\text{total}}$ Γ_{92}/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0127±0.0036		GAISER 86	CBAL	$J/\psi \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	16	BALTRUSAIT..84	MRK3	$J/\psi \to 2\phi\gamma$

$\Gamma(\gamma\pi^+\pi^- 2\pi^0)/\Gamma_{\text{total}}$ Γ_{93}/Γ

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*	*COMMENT*
8.3±0.2±3.1	[23] BALTRUSAIT..86B	MRK3	$J/\psi \to 4\pi\gamma$

[23] 4π mass less than 2.0 GeV.

$\Gamma(\gamma\eta\pi\pi)/\Gamma_{\text{total}}$ Γ_{94}/Γ

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*	*COMMENT*
6.1 ±1.0 OUR AVERAGE			
5.85±0.3±1.05	[24] EDWARDS 83B	CBAL	$J/\psi \to \eta\pi^+\pi^-$
7.8 ±1.2±2.4	[24] EDWARDS 83B	CBAL	$J/\psi \to \eta 2\pi^0$

[24] Broad enhancement at 1700 MeV.

$\Gamma(\gamma\eta(1440) \to \gamma K\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_{95}/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0048±0.0008 OUR AVERAGE			
0.0063±0.0014	[25] WISNIEWSKI 87	MRK3	$J/\psi \to K\overline{K}\pi\gamma$
0.0040±0.0007±0.001	[25] EDWARDS 82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$
0.0043±0.0017	[25,26] SCHARRE 80	MRK2	$e^+ e^-$

[25] Includes unknown branching fraction $\eta(1440) \to K\overline{K}\pi$.

[26] Corrected for spin-zero hypothesis for $\eta(1440)$.

$\Gamma(\gamma\rho\rho)/\Gamma_{\text{total}}$ Γ_{96}/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
4.5 ±0.8 OUR AVERAGE				
4.7 ±0.3 ±0.9		[27] BALTRUSAIT..86B	MRK3	$J/\psi \to 4\pi\gamma$
3.75±1.05±1.20		[28] BURKE 82	MRK2	$J/\psi \to 4\pi\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.09	90	[29] BISELLO 89B		$J/\psi \to 4\pi\gamma$

[27] 4π mass less than 2.0 GeV.

[28] 4π mass less than 2.0 GeV, $2\rho^0$ corrected to 2ρ by factor of 3.

[29] 4π mass in the range 2.0–25 GeV.

$\Gamma(\gamma\eta'(958))/\Gamma_{\text{total}}$ Γ_{97}/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
4.2±0.4 OUR AVERAGE				
4.1±0.3±0.6		BLOOM 83	CBAL	$e^+ e^- \to 3\gamma +$ hadrons γ
4.6±0.4±0.65		EINSWEILER 83	MRK3	$e^+ e^- \to \gamma\eta\pi^+\pi^-$
4.7±0.3±0.9		EINSWEILER 83	MRK3	$e^+ e^- \to \gamma\rho^0\gamma$
2.9±1.1	6	BRANDELIK 79C	DASP	$e^+ e^- \to 3\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.8±1.3		[30] SCHARRE 79B	MRK1	$e^+ e^- \to \gamma X$
3.4±0.7		SCHARRE 79B	MRK1	$e^+ e^- \to 2\pi 2\gamma$
2.4±0.7	57	BARTEL 76	CNTR	$e^+ e^- \to 2\gamma\rho$

[30] From the inclusive γ decay spectrum.

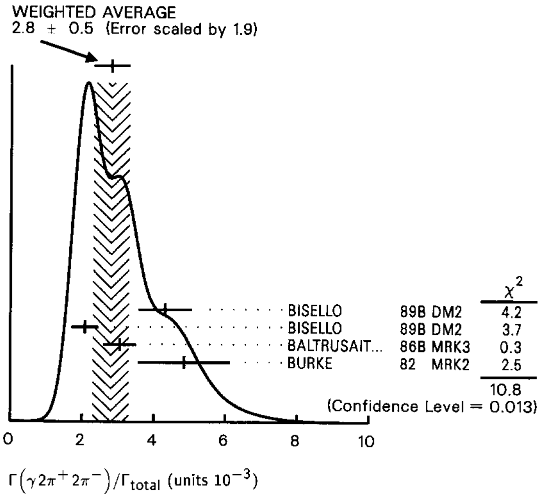
$\Gamma(\gamma 2\pi^+ 2\pi^-)/\Gamma_{\text{total}}$ Γ_{98}/Γ

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*	*COMMENT*
2.8 ±0.5 OUR AVERAGE Error includes scale factor of 1.9. See the ideogram below.			
4.32±0.14±0.73	[31] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$
2.08±0.13±0.35	[32] BISELLO 89B	DM2	$J/\psi \to 4\pi\gamma$
3.05±0.08±0.45	[32] BALTRUSAIT..86B	MRK3	$J/\psi \to 4\pi\gamma$
4.85±0.45±1.20	[33] BURKE 82	MRK2	$e^+ e^-$

[31] 4π mass less than 3.0 GeV.

[32] 4π mass less than 2.0 GeV.

[33] 4π mass less than 2.5 GeV.



$\Gamma(\gamma f_4(2050))/\Gamma_{\text{total}}$ Γ_{99}/Γ

VALUE (units 10^{-3})	*DOCUMENT ID*	*TECN*	*COMMENT*
2.7±0.5±0.5	[34] BALTRUSAIT..87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$

[34] Assuming branching fraction $f_4(2050) \to \pi\pi/$ total $= 0.167$.

$J/\psi(1S) = J/\psi(3097)$

$\Gamma(\gamma\omega\omega)/\Gamma_{\text{total}}$ Γ_{100}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.33 OUR AVERAGE					
1.41±0.2 ±0.42	120 ± 17	BISELLO	87	SPEC	e^+e^-, hadrons γ
1.76±0.09±0.45		BALTRUSAIT...	85C	MRK3	$e^+e^- \to$ hadrons γ

$\Gamma(\gamma\eta(1490) \to \gamma\rho^0\rho^0)/\Gamma_{\text{total}}$ Γ_{101}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
1.36±0.38	[35,36] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[35] Estimated by us from various fits.

[36] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma f_2(1270))/\Gamma_{\text{total}}$ Γ_{102}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.38±0.14 OUR AVERAGE						
1.33±0.05±0.20		[37] AUGUSTIN	87	DM2		$J/\psi \to \gamma\pi^+\pi^-$
1.36±0.09±0.23		[37] BALTRUSAIT...	87	MRK3		$J/\psi \to \gamma\pi^+\pi^-$
1.48±0.25±0.30	178	EDWARDS	82B	CBAL		$e^+e^- \to 2\pi^0\gamma$
2.0 ±0.7	35	ALEXANDER	78	PLUT	0	e^+e^-
1.2 ±0.6	30	[38] BRANDELIK	78B	DASP		$e^+e^- \to \pi^+\pi^-\gamma$

[37] Estimated using B($f_2(1270) \to \pi\pi$)=0.843 ± 0.012. The errors do not contain the uncertainty in the $f_2(1270)$ decay.

[38] Restated by us to take account of spread of E1, M2, E3 transitions.

$\Gamma(\gamma f_2(1720) \to \gamma K\overline{K})/\Gamma_{\text{total}}$ Γ_{103}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
9.7±1.2 OUR AVERAGE					
9.2±1.4±1.4		[39] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
10.4±1.2±1.6		[39] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
9.6±1.2±1.8		[39] BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.8	90	[40] BISELLO	89B		$J/\psi \to 4\pi\gamma$
1.6±0.4±0.3		[41] BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma\pi^+\pi^-$
3.8±1.6		[42] EDWARDS	82D	CBAL	$e^+e^- \to \eta\eta\gamma$

[39] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$. We have multiplied K^+K^- measurement by 2, and $K^0_S K^0_S$ by 4 to obtain $K\overline{K}$ result.

[40] Includes unknown branching fraction to $\rho^0\rho^0$.

[41] Includes unknown branching fraction to $\pi^+\pi^-$.

[42] Includes unknown branching fraction to $\eta\eta$.

$\Gamma(\gamma\eta)/\Gamma_{\text{total}}$ Γ_{104}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.86±0.08 OUR AVERAGE					
0.88±0.08±0.11		BLOOM	83	CBAL	e^+e^-
0.82±0.10		BRANDELIK	79C	DASP	e^+e^-
1.3 ±0.4	21	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma f'_2(1525))/\Gamma_{\text{total}}$ Γ_{105}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.63±0.10 OUR AVERAGE						
0.70±0.17±0.11			[43] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
0.56±0.06±0.11			[43] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
0.84±0.20±0.17			[43] BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.25±0.14			[43] FRANKLIN	83B	MRK2	$J/\psi \to \gamma K\overline{K}$
<0.34	90	4	[44] BRANDELIK	79C	DASP	$e^+e^- \to \pi^+\pi^-\gamma$
<0.23	90	3	ALEXANDER	78	PLUT	$e^+e^- \to K^+K^-\gamma$

[43] Using B($f'_2(1525) \to K\overline{K}$) = 0.713.

[44] Assuming isotropic production and decay of the $f'_2(1525)$ and isospin.

$\Gamma(\gamma p\overline{p})/\Gamma_{\text{total}}$ Γ_{106}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.38±0.07±0.07		49	EATON	84	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.11	90		PERUZZI	78	MRK1	e^+e^-

$\Gamma(\gamma\phi\phi)/\Gamma_{\text{total}}$ Γ_{107}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
3.1±0.7±0.4	[45] BISELLO	86B	DM2	$J/\psi \to \gamma\phi\phi$

[45] $\phi\phi$ mass less than 2.9 GeV, η_c excluded.

$\Gamma(\gamma\eta(2100) \to \gamma\rho^0\rho^0)/\Gamma_{\text{total}}$ Γ_{108}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
$0.24^{+0.15}_{-0.10}$	[46,47] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[46] Estimated by us from various fits.

[47] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\eta(1760) \to \gamma\rho^0\rho^0)/\Gamma_{\text{total}}$ Γ_{109}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.13±0.09	[48,49] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[48] Estimated by us from various fits.

[49] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\pi^0)/\Gamma_{\text{total}}$ Γ_{110}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.039±0.013 OUR AVERAGE					
0.036±0.011±0.007		BLOOM	83	CBAL	e^+e^-
0.073±0.047	10	BRANDELIK	79C	DASP	e^+e^-

$\Gamma(\gamma f_1(1285))/\Gamma_{\text{total}}$ Γ_{111}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	[50] SCHARRE	80	MRK2	e^+e^-

[50] Using B($f_1(1285) \to K\overline{K}\pi$) = 0.12.

$\Gamma(\gamma p\overline{p}\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{112}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.79	90	EATON	84	MRK2	e^+e^-

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{113}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma\Lambda\overline{\Lambda})/\Gamma_{\text{total}}$ Γ_{114}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.13	90	HENRARD	87	DM2	e^+e^-

$\Gamma(3\gamma)/\Gamma_{\text{total}}$ Γ_{115}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.055	90	PARTRIDGE	80	CBAL	e^+e^-

$\Gamma(\gamma X(2200))/\Gamma_{\text{total}}$ Γ_{116}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5	[51] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$

[51] Includes unknown branching fraction to $K^0_S K^0_S$

$\Gamma(\gamma f_4(2220))/\Gamma_{\text{total}}$ Γ_{117}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.3	95	[52] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
< 1.6	95	[52] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$12.4^{+6.4}_{-5.2}\pm 2.8$	23	[52] BALTRUSAIT...	86D	MRK3	$J/\psi \to \gamma K^0_S K^0_S$
$8.4^{+3.4}_{-2.8}\pm 1.6$	93	[52] BALTRUSAIT...	86D	MRK3	$J/\psi \to \gamma K^+K^-$

[52] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$.

$J/\psi(1S)$ REFERENCES

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
COFFMAN	88	PR D38 2695	+Dubois, Eigen, Hauser+	(Mark III Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BAGLIN	87	NP B286 592	+	(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)
BISELLO	87	PL B192 239	+Ajaltouni, Baldini+	(PADO, CLER, FRAS, LALO)
HENRARD	87	NP B292 670	+Ajaltouni, et al	(CLER, FRAS, LALO, PADO)
PALLIN	87	NP B292 653	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
WISNIEWSKI	87	CALT-68-1446		(Mark III Collab.)
AUGUSTIN	86	Moriond XXI 421	+Ajaltouni, Bisello+	(LALO, CLER, PADO, FRAS)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BALTRUSAIT...	86D	PRL 56 107	Baltrusaitis	(CIT, UCSC, ILL, SLAC, WASH)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
BALTRUSAIT...	85C	PRL 55 1723	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	85D	PR D32 566	Baltrusaitis, Coffman+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	84	PRL 52 2126	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
EATON	84	PR D29 804	+Goldhaber, Abrams, Alam, Boyarski+	(LBL, SLAC)
BLOOM	83	ARNS 33 143	+Peck	(SLAC, CIT)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EINSWEILER	83	Brighton Conf. 348		(Mark III Collab.)
FRANKLIN	83B	SLAC-254 Thesis		(STAN)
FRANKLIN	83C	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
BURKE	82	PRL 49 632	+Trilling, Abrams, Alam, Blocker+	(LBL, SLAC)
EDWARDS	82B	PR D25 3065	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EDWARDS	82D	PRL 48 458	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	ARNS 33 143	Bloom, Peck	(SLAC, CIT)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
BESCH	81	ZPHY C8 1	+Eisermann, Lohr, Kowalski+	(BONN, DESY, MANZ)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
PARTRIDGE	80	PRL 44 712	+Peck+	(CIT, HARV, PRIN, SLAC, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814 Translated from YAF 34 1471.	Zholentz, Kurdadze, Lelchuk+	(NOVO)

BRANDELIK	79C	ZPHY C1 233	+	(AACH, DESY, HAMB, MPIM, TOKY)
SCHARRE	79B	SLAC-PUB-2321		(SLAC, LBL)
Also	79	LBL-9502	Abrams, Alam, Blocker, Boyarski+	(SLAC, LBL)
ALEXANDER	78	PL 72B 493	+Criegee+	(DESY, HAMB, SIEG, WUPP)
BESCH	78	PL 78B 347	+Eisermann, Kowalski, Eyss+	(BONN, DESY, MANZ)
BRANDELIK	78B	PL 74B 292	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
PERUZZI	78	PR D17 2901	+Piccolo, Alam, Boyarski, Goldhaber+	(SLAC, LBL)
BARTEL	77	PL 66B 489	+Duinker, Olsson, Heintze+	(DESY, HEID)
BURMESTER	77D	PL 72B 135	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
VANNUCCI	77	PR D15 1814	+Abrams, Alam, Boyarski+	(SLAC, LBL)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEID)
BRAUNSCH...	76	PL 63B 487	Braunschweig+	(AACH, DESY, HAMB, MPIM+)
JEAN-MARIE	76	PRL 36 291	+Abrams, Boyarski, Breidenbach+	(SLAC, LBL) IG
BALDINI-...	75	PL 58B 471	Baldini-Celio, Bozzo, Capon+	(FRAS, ROMA)
BEMPORAD	75	Stanford Symp. 113		(PISA, FRAS)
BOYARSKI	75	PRL 34 1357	+Breidenbach, Bulos, Feldman+	(SLAC, LBL) JPC
DASP	75	PL 56B 491	Braunschweig+	(AACH, DESY, MPIM, TOKY)
ESPOSITO	75B	LNC 14 73	+Bartoli, Bisello+	(FRAS, NAPL, PADO, ROMA)
FORD	75	PRL 34 604	+Beron, Hilger, Hofstadter+	(SLAC, PENN)
LIBERMAN	75	Stanford Symp. 55		(STAN)
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

BAGLIN	85	SLAC Summer Inst. 609		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
KIRK	79	PRL 42 619	+Goodman+	(FNAL, HARV, ILL, OXF, TUFT)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
CORDEN	77	PL 68B 96	+Dowell+	(BIRM, CERN, MPIM, NEUC, EPOL+)
YAMADA	77	Hamburg Conf. 69		(DESY, TOKY)
ANTIPOV	76	Tbilisi Conf. N8	+Bessubov, Budanov, Bushnin, Denisov+	(SERP)
BUSSER	76	NP B113 189	+Blumenfeld, Banner+	(CERN, COLU, ROCK, SACL)
SNYDER	76	PRL 36 1415	+Hom, Lederman, Appel+	(COLU, FNAL, STON)
ANDREWS	75	PRL 34 231	+Harvey, Lobkowicz, May+	(ROCH, CORN)
AUBERT	75	NP B89 1	+Becker, Biggs, Burger, Glenn+	(MIT, BNL)
BACCI	75B	LNC 12 269	+Penso, Stella, Baldini-Celio+	(ROMA, FRAS)
BALDINI-...	75B	PL 58B 475	Baldini-Celio, Capon, DelFabbro+	(FRAS, ROMA)
BLANAR	75	PRL 35 346	+Boyer, Faissler, Garelick, Gettner+	(NEAS)
BRAUNSCH...	75	PL 53B 491	Braunschweig+	(AACH, HAMB, MUNI, TOKY)
BUSSER	75	PL 56B 482	+Blumenfeld, Banner+	(CERN, COLU, ROCK, SACL)
CAMERINI	75	PRL 35 483	+Learned, Prepost, Ash, Anderson+	(WISC, SLAC)
DAKIN	75	PL 56B 405	+Kreisler, Bolon, Heile+	(MASA, MIT, SLAC)
DASP	75B	PL 57B 297	Braunschweig+	(AACH, DESY, MPIM, TOKY)
GITTELMAN	75	PRL 35 1616	+Hanson, Larson, Loh+	(CORN)
GRECO	75	PL 56B 367	+Pancheri-Srivastava, Srivastava	(FRAS)
HEINTZE	75	Stanford Symp. 97		(HEID)
JACKSON	75	NIM 128 13	+Scharre	(LBL)
KNAPP	75	PRL 34 1040	+Lee, Bronstein+	(COLU, HAWA, CORN, ILL, FNAL)
KNAPP	75B	PRL 34 1044	+Lee, Bronstein+	(COLU, HAWA, CORN, ILL, FNAL)
MARTIN	75B	PRL 34 288	+Bolon, Dakin, Feldman+	(MIT, MASA, SLAC)
SIMPSON	75	PRL 35 699	+Beron, Ford, Hilger, Hofstadter+	(STAN, PENN)
YENNIE	75	PRL 34 239		(CORN)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)
ASH	74	LNC 11 705	+Zorn, Bartoli+	(FRAS, UMD, NAPL, PADO, ROMA)
AUBERT	74	PRL 33 1404	+Becker, Biggs, Burger, Chen, Everhart	(MIT, BNL)
AUGUSTIN	74	PRL 33 1406	+Boyarski, Abrams, Briggs+	(SLAC, LBL)
BACCI	74	PRL 33 1408	+Bartoli, Barbarino, Barbiellini+	(FRAS)
Also	74B	PRL 33 1649	Bacci	
BALDINI-...	74	LNC 11 711	Baldini-Celio, Bacci+	(FRAS, ROMA)
BARBIELLINI	74	LNC 11 718	+Bemporad+	(FRAS, NAPL, PISA, ROMA)
BRAUNSCH...	74	PL 53B 393	Braunschweig+	(AACH, HAMB, MUNI, TOKY)
CHRISTENSON	70	PRL 25 1523	+Hicks, Lederman+	(COLU, BNL, CERN)

$\chi_{c0}(1P)$

or $\chi_{c0}(3415)$ [was $\chi(3415)$]

$$I^G(J^{PC}) = 0^+(0^{++})$$

Observed in the radiative decay $\psi(2S) \rightarrow \chi_{c0}(1P)\gamma$. Therefore $C = +$. The observed decay into $\pi^+\pi^-$ or K^+K^- implies $G = +$, $J^P = 0^+, 2^+$, ... The angular distribution is consistent with $J = 0$. J^P abnormal excluded by $\pi^+\pi^-$ and K^+K^- decays. $J^P = 0^+$ preferred (FELDMAN 77).

$\chi_{c0}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3415.1± 1.0 OUR AVERAGE					
3417.8± 0.4±4		[1] GAISER	86	CBAL	$\psi(2S) \rightarrow \gamma X$
3414.8± 1.1		[2,3] HIMEL	79	MRK2	$e^+e^- \rightarrow$ hadrons
3422.0±10.0		[2] BARTEL	78B	CNTR	$e^+e^- \rightarrow J/\psi 2\gamma$
3416.0± 3 ±4		[2] TANENBAUM	78	MRK1	e^+e^-
3415.0± 9.0		[2] BIDDICK	77	CNTR	$e^+e^- \rightarrow \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3407.0± 8.0	2	[4] WIIK	75	DASP	$e^+e^- \rightarrow J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.

[2] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[3] Systematic error added linearly by us.

[4] Only two events; this mass apparently never published.

$\chi_{c0}(1P)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
13.5±3.3±4.2	GAISER	86	CBAL	$\psi(2S) \rightarrow \gamma X, \gamma\pi^0\pi^0$

$\chi_{c0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(3.7 ± 0.7) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(3.0 ± 0.7) %	
Γ_3	$\rho^0\pi^+\pi^-$	(1.6 ± 0.5) %	
Γ_4	$3(\pi^+\pi^-)$	(1.5 ± 0.5) %	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(1.2 ± 0.4) %	
Γ_6	$\pi^+\pi^-$	$(7.5\pm2.1)\times10^{-3}$	
Γ_7	K^+K^-	$(7.1\pm2.4)\times10^{-3}$	
Γ_8	$\pi^+\pi^-p\overline{p}$	$(5.0\pm2.0)\times10^{-3}$	
Γ_9	$p\overline{p}$	$< 9.0 \times10^{-4}$	90%
	Radiative decays		
Γ_{10}	$\gamma J/\psi(1S)$	$(6.6\pm1.8)\times10^{-3}$	
Γ_{11}	$\gamma\gamma$	$< 1.5 \times10^{-3}$	90%

$\chi_{c0}(1P)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_{11}

VALUE (KeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.0±2.8		LEE	85		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<17	95	AIHARA	88D	TPC	$e^+e^- \rightarrow e^+e^- X$

$\chi_{c0}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.037±0.007	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.030±0.007	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.016±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.015±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.012±0.004	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
75±21 OUR AVERAGE				
70±30	[5] BRANDELIK	79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c0}$
80±30	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
71±24 OUR AVERAGE				
60±30	[5] BRANDELIK	79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c0}$
90±40	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.005±0.002	[5] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<9.0	90	[5] BRANDELIK	79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c0}$

[5] Calculated using B($\psi(2S) \rightarrow \gamma\chi_{c0}(1P)$) = 0.094; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
66± 18 OUR AVERAGE				
60± 18	GAISER	86	CBAL	$\psi(2S) \rightarrow \gamma\chi_{c0}$
320±210	[6] BRANDELIK	79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c0}$
150±100	[6] BARTEL	78B	CNTR	$\psi(2S) \rightarrow \gamma\chi_{c0}$
210±210	[6] TANENBAUM	78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c0}$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<15	90	[6] YAMADA	77	DASP	$e^+e^- \to 3\gamma$

[6] Calculated using B($\psi(2S) \to \gamma\chi_{c0}(1P)$) = 0.094; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c0}(1P)$ REFERENCES

AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEE	85	SLAC 282		(SLAC)
BRANDELIK	79B	NP B160 426	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
HIMEL	79	SLAC-223 Thesis		(SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEID)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DESY, TOKY)
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
BRANDELIK	79C	ZPHY C1 233	+	(AACH, DESY, HAMB, MPIM, TOKY)
KIRK	79	PRL 42 619	+Goodman+	(FNAL, HARV, ILL, OXF, TUFT)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
Also Erratum.	75C	PRL 35 1189	Feldman	
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)

$\chi_{c1}(1P)$

or $\chi_{c1}(3510)$ [was $\chi(3510)$]

$$I^G(J^{PC}) = 0^+(1^{++})$$

Observed in the radiative sequential decay $\psi(2S) \to \chi_{c1}(1P)\gamma$, $\chi_{c1}(1P) \to J/\psi(1S)\gamma$. Therefore, $C = +$. The lack of decays into $\pi^+\pi^-$ or K^+K^- is suggestive of J^P=abnormal. The decays into 4π and 6π imply $G = +$, thus $I = 0$. J=0,2 excluded by angular distribution in the $J/\psi(1S)\gamma$ decay. $J^P = 1^+$ preferred (FELDMAN 77, OREGLIA 82).

$\chi_{c1}(1P)$ MASS

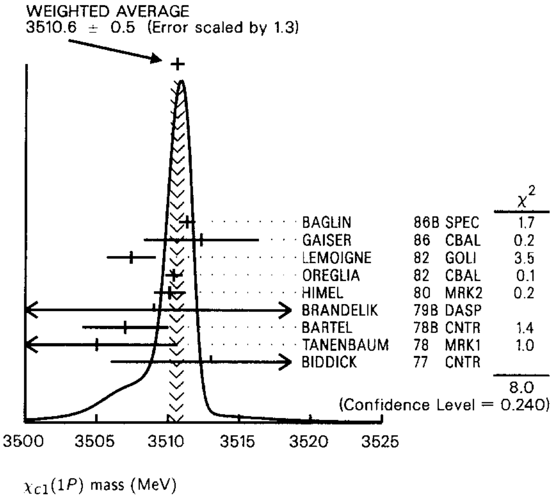
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3510.6± 0.5 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
3511.3± 0.4±0.4	30	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^-$
3512.3± 0.3±4.0		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3507.4± 1.7	91	[2] LEMOIGNE	82	GOLI	190 GeV π^- Be $\to \gamma 2\mu$
3510.4± 0.6		OREGLIA	82	CBAL	$e^+e^- \to J/\psi 2\gamma$
3510.1± 1.1	254	[3] HIMEL	80	MRK2	$e^+e^- \to J/\psi 2\gamma$
3509.0±11.0	21	BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
3507.0± 3.0		[3] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3505.0± 4 ±4		[3,4] TANENBAUM	78	MRK1	e^+e^-
3513.0± 7.0	367	[3] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3510.0±20.0		BARTEL	76B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3500 ±10	40	TANENBAUM	75	MRK1	Hadrons γ
3507.0± 7.0	7	WIIK	75	DASP	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.

[2] $J/\psi(1S)$ mass constrained to 3097 MeV.

[3] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[4] From a simultaneous fit to radiative and hadronic decay channels.



$\chi_{c1}(1P)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	95	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.8	90	GAISER	86	CBAL	$\psi(2S) \to \gamma X$

$\chi_{c1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$3(\pi^+\pi^-)$	(2.2±0.8) %	
Γ_2	$2(\pi^+\pi^-)$	(1.6±0.5) %	
Γ_3	$\pi^+\pi^-K^+K^-$	(9 ±4) × 10^{-3}	
Γ_4	$\rho^0\pi^+\pi^-$	(3.9±3.5) × 10^{-3}	
Γ_5	$K^+\bar{K}^*(892)^0\pi^-$ + c.c.	(3.2±2.1) × 10^{-3}	
Γ_6	$\pi^+\pi^-p\bar{p}$	(1.4±0.9) × 10^{-3}	
Γ_7	$p\bar{p}$	(5.4–120)×10^{-5}	
Γ_8	$\pi^+\pi^-$ + K^+K^-	< 1.7 × 10^{-3}	90%
Γ_9	$\pi^+\pi^-$		
Γ_{10}	K^+K^-		
	Radiative decays		
Γ_{11}	$\gamma J/\psi(1S)$	(27.3±1.6) %	
Γ_{12}	$\gamma\gamma$	< 1.5 × 10^{-3}	90%

$\chi_{c1}(1P)$ PARTIAL WIDTHS

$\Gamma(p\bar{p})$ Γ_7

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$57^{+13}_{-11}\pm11$	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^-$

$\chi_{c1}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.022±0.008	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ Γ_3/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
90±40	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
39±35	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c1}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
32±21	[5] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^- p\overline{p})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
14±9	[5] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
> 0.54	95	BAGLIN 86B	SPEC	$\overline{p}p \rightarrow \gamma e^+e^-$
<12.0	90	[5] BRANDELIK 79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{\text{total}}$ $(\Gamma_9+\Gamma_{10})/\Gamma$

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<21		[5] FELDMAN 77	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<38	90	[5] BRANDELIK 79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c1}$

[5] Estimated using $B(\psi(2S) \rightarrow \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.273±0.016 OUR AVERAGE				
0.284±0.021		GAISER 86	CBAL	$\psi(2S) \rightarrow \gamma X$
0.274±0.046	943	[6] OREGLIA 82	CBAL	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.28 ±0.07		[6] HIMEL 80	MRK2	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.19 ±0.05		[6] BRANDELIK 79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.29 ±0.05		[6] BARTEL 78B	CNTR	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.28 ±0.09		[6] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.57 ±0.17		[6] BIDDICK 77	CNTR	$\psi(2S) \rightarrow \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0015	90	[6] YAMADA 77	DASP	$e^+e^- \rightarrow 3\gamma$

[6] Estimated using $B(\psi(2S) \rightarrow \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c1}(1P)$ REFERENCES

BAGLIN 86B PL B172 455 (LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
LEMOIGNE 82 PL 113B 509 +Barate, Astbury+ (SACL, LOIC, SHMP, IND)
OREGLIA 82 PR D25 2259 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
Also 82B Private Comm. Oreglia (EFI)
HIMEL 80 PRL 44 920 +Abrams, Alam, Blocker+ (LBL, SLAC)
Also 82 Private Comm. Trilling (LBL, UCB)
BRANDELIK 79B NP B160 426 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEID)
TANENBAUM 78 PR D17 1731 +Alam, Boyarski+ (SLAC, LBL)
Also 82 Private Comm. Trilling (LBL, UCB)
BIDDICK 77 PRL 38 1324 +Burnett+ (UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN 77 PL 33C 285 +Perl (LBL, SLAC)
YAMADA 77 Hamburg Conf. 69 (DESY, TOKY)
BARTEL 76B Tbilisi Conf. N75 +Duinker, Olsson, Heintze+ (DESY, HEID)
TANENBAUM 75 PRL 35 1323 +Whitaker, Abrams+ (LBL, SLAC)
WIIK 75 Stanford Symp. 69 (DESY)

OTHER RELATED PAPERS

BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
BRANDELIK 79C ZPHY C1 233 + (AACH, DESY, HAMB, MPIM, TOKY)
KIRK 79 PRL 42 619 +Goodman+ (FNAL, HARV, ILL, OXF, TUFT)
BRAUNSCH... 75B PL 57B 407 Braunschweig+ (AACH, DESY, MPIM, TOKY)
FELDMAN 75 Stanford Symp. 39 (SLAC)
HEINTZE 75 Stanford Symp. 97 (HEID)
SIMPSON 75 PRL 35 699 +Beron, Ford, Hilger, Hofstadter+ (STAN, PENN)

$\chi_{c2}(1P)$

or $\chi_{c2}(3555)$ [was $\chi(3555)$]

$I^G(J^{PC}) = 0^+(2^{++})$

Observed in the radiative decay $\psi(2S) \rightarrow \chi_{c2}(1P)\gamma$. Therefore $C = +$. The observed decay into 4π and 6π imply $G = +$, thus $I = 0$. $J = 0$ is excluded by the angular distribution in the hadronic decays. J^P abnormal excluded by $\pi^+\pi^-$ and K^+K^- decays. $J^P = 2^+$ preferred (FELDMAN 77, OREGLIA 82).

$\chi_{c2}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
3556.3± 0.4 OUR AVERAGE				
3556.9± 0.4±0.5	50	BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-$
3557.8± 0.2±4		[1] GAISER 86	CBAL	$\psi(2S) \rightarrow \gamma X$
3553.4± 2.2	66	[2] LEMOIGNE 82	GOLI	190 GeV π^- Be $\rightarrow \gamma 2\mu$
3555.9± 0.7		[3] OREGLIA 82	CBAL	$e^+e^- \rightarrow J/\psi 2\gamma$
3557 ± 1.5	69	[4] HIMEL 80	MRK2	$e^+e^- \rightarrow J/\psi 2\gamma$
3551.0±11.0	15	BRANDELIK 79B	DASP	$e^+e^- \rightarrow J/\psi 2\gamma$
3553.0± 4.0		[4] BARTEL 78B	CNTR	$e^+e^- \rightarrow J/\psi 2\gamma$
3553.0± 4 ±4		[4,5] TANENBAUM 78	MRK1	e^+e^-
3563.0± 7.0	360	[4] BIDDICK 77	CNTR	$e^+e^- \rightarrow \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3550.0±10.0		TRILLING 76	MRK1	$e^+e^- \rightarrow$ hadrons γ
3543.0±10.0	4	WHITAKER 76	MRK1	$e^+e^- \rightarrow J/\psi 2\gamma$

[1] Using mass of $\psi(2S) = 3686.0$ MeV.

[2] $J/\psi(1S)$ mass constrained to 3097 MeV.

[3] Assuming $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[4] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.

[5] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c2}(1P)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$2.6^{+1.2}_{-0.9}$ OUR AVERAGE				
$2.6^{+1.4}_{-1.0}$	50	BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-$
$2.8^{+2.1}_{-2.0}$		[6] GAISER 86	CBAL	$\psi(2S) \rightarrow \gamma X$

[6] Errors correspond to 90% confidence level; authors give only width range.

$\chi_{c2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(2.2±0.5) %	
Γ_2	$\pi^+\pi^- K^+K^-$	(1.9±0.5) %	
Γ_3	$3(\pi^+\pi^-)$	(1.2±0.8) %	
Γ_4	$\rho^0\pi^+\pi^-$	(7 ±4) × 10^{-3}	
Γ_5	$K^+\overline{K}^*(892)^0\pi^- + \text{c.c.}$	(4.8±2.8) × 10^{-3}	
Γ_6	$\pi^+\pi^- p\overline{p}$	(3.3±1.3) × 10^{-3}	
Γ_7	$\pi^+\pi^-$	(1.9±1.0) × 10^{-3}	
Γ_8	K^+K^-	(1.5±1.1) × 10^{-3}	
Γ_9	$p\overline{p}$	($9.0^{+4.5}_{-3.2}$) × 10^{-5}	
Γ_{10}	$J/\psi(1S)\pi^+\pi^-\pi^0$	< 1.5 %	90%
	Radiative decays		
Γ_{11}	$\gamma J/\psi(1S)$	(13.5±1.1) %	
Γ_{12}	$\gamma\gamma$	(1.1±0.6) × 10^{-3}	

$\chi_{c2}(1P)$ PARTIAL WIDTHS

$\Gamma(p\overline{p})$ Γ_9

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
$233^{+51}_{-45}\pm48$	BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-$

$\Gamma(\gamma\gamma)$ Γ_{12}

VALUE (KeV)	CL%	DOCUMENT ID	TECN	COMMENT
2.8±2.0		LEE 85		
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.2	95	AIHARA 88D	TPC	$e^+e^- \rightarrow e^+e^- X$

$\chi_{c2}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.022±0.005	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.019±0.005	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.012±0.008	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
68±40	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
48±28	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
33±13	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.9±1.0	4	[7] BRANDELIK 79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{\text{total}}$ $(\Gamma_7+\Gamma_8)/\Gamma$

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
24±10	[7] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.5±1.1	2	[7] BRANDELIK 79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
$0.90^{+0.41}_{-0.26}\pm0.19$		BAGLIN 86B	SPEC	$\overline{p}p \to e^+e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<9.5	90	[7] BRANDELIK 79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(J/\psi(1S)\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	90	BARATE 81	SPEC	190 GeV π^- Be $\to 2\pi 2\mu$

$\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\overline{p} \to \chi_{c2}(1P) \to \gamma\gamma$ $\Gamma_9\Gamma_{12}/\Gamma^2$

VALUE (units 10^{-7})	EVTS	DOCUMENT ID	TECN	COMMENT
$0.99^{+0.46}_{-0.35}$	6	[8] BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$

[7] Estimated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

[8] Assuming isotropic $\chi_{c2}(1P) \to \gamma\gamma$ distribution.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.135±0.011 OUR AVERAGE				
0.124±0.015		GAISER 86	CBAL	$\psi(2S) \to \gamma X$
0.162±0.028	479	[9] OREGLIA 82	CBAL	$\psi(2S) \to \gamma\chi_{c2}$
0.14 ±0.04		[9] HIMEL 80	MRK2	$\psi(2S) \to \gamma\chi_{c2}$
0.18 ±0.05		[9] BRANDELIK 79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.03		[9] BARTEL 78B	CNTR	$\psi(2S) \to \gamma\chi_{c2}$
$0.11\ ^{+0.13}_{-0.07}$		[9] SPITZER 78	PLUT	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.08		[9] TANENBAUM 78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28 ±0.13		[9] BIDDICK 77	CNTR	$\psi(2S) \to \gamma X$

[9] Estimated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
$11^{+5}_{-4}\pm4$		[10] BAGLIN 87B	SPEC	$\overline{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 6	90	[7] YAMADA 77	DASP	$e^+e^- \to 3\gamma$

[10] Derived from $\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\overline{p} \to \chi_{c2}(1P) \to \gamma\gamma$ measurement above.

$\chi_{c2}(1P)$ REFERENCES

AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
BAGLIN	87B	PL B187 191	+Baird, Bassompierre, Borreani+	(R704 Collab.)
BAGLIN	86B	PL B172 455		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEE	85	SLAC 282		(SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
Also	82B	Private Comm.	Oreglia	(EFI)
BARATE	81	PR D24 2994	+Astbury+	(SACL, LOIC, SHMP, CERN, IND)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BRANDELIK	79B	NP B160 426	+Cords+	(AACH, DESY, HAMB, MPIM, TOKY)
BRANDELIK	79C	ZPHY C1 233	+	(AACH, DESY, HAMB, MPIM, TOKY)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEID)
SPITZER	78	Kyoto Sum. Inst. 47		(HAMB)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DESY, TOKY)
TRILLING	76	Stanford Symp. 437		(LBL)
WHITAKER	76	PRL 37 1596	+Tanenbaum, Abrams, Alam+	(SLAC, LBL)

OTHER RELATED PAPERS

BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
KIRK	79	PRL 42 619	+Goodman+	(FNAL, HARV, ILL, OXF, TUFT)
FELDMAN	77	PL 33C 285	+Perl	(LBL, SLAC)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
Also Erratum.	75C	PRL 35 1189	Feldman	
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)

$\eta_c(2S)$ or $\eta_c(3590)$

$I^G(J^{PC}) = ?^?(?^{?+})$

OMITTED FROM SUMMARY TABLE

Our latest mini-review on this particle can be found in the 1984 edition. Needs confirmation.

$\eta_c(2S)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3594.0±5.0	[1] EDWARDS 82C	CBAL	$e^+e^- \to \gamma X$

[1] Assuming mass of $\psi(2S) = 3686$ MeV.

$\eta_c(2S)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.0	95	EDWARDS 82C	CBAL	$e^+e^- \to \gamma X$

$\eta_c(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	seen

$\eta_c(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
seen	EDWARDS 82C	CBAL	$e^+e^- \to \gamma X$

$\eta_c(2S)$ REFERENCES

EDWARDS	82C	PRL 48 70	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
PORTER	81	SLAC Summer Inst. 355	+Edwards+	(CIT, HARV, PRIN, STAN, SLAC)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEID)

$\psi(2S)$ or $\psi(3685)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(2S)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3686.00±0.10	413	ZHOLENTZ	80	OLYA	$e^+ e^-$

$\psi(2S) - J/\psi(1S)$ MASS DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
589.07±0.13 OUR AVERAGE				
589.7 ±1.2	LEMOIGNE	82	GOLI	190 GeV π^- Be → 2μ
589.07±0.13	[1] ZHOLENTZ	80	OLYA	$e^+ e^-$
588.7 ±0.8	LUTH	75	MRK1	

[1] Redundant with data in mass above.

$\psi(2S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
243±43 OUR EVALUATION	Uses $\Gamma(ee)$ from ALEXANDER 89 and $B(ee) = (88 \pm 13) \times 10^{-4}$ from FELDMAN 77.

$\psi(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(98.10 ± 0.30) %	
Γ_2	virtual $\gamma \to$ hadrons	(2.9 ± 0.4) %	
Γ_3	$e^+ e^-$	$(8.8 \pm1.3) \times 10^{-3}$	
Γ_4	$\mu^+ \mu^-$	$(7.7 \pm1.7) \times 10^{-3}$	
	Decays into $J/\psi(1S)$ and anything		
Γ_5	$J/\psi(1S)$ anything	(55 ± 7) %	
Γ_6	$J/\psi(1S)$ neutrals	(22.6 ± 2.9) %	
Γ_7	$J/\psi(1S)\pi^+\pi^-$	(16.2 ± 1.6) %	
Γ_8	$J/\psi(1S)\pi^0\pi^0$	(8.6 ± 1.2) %	
Γ_9	$J/\psi(1S)\eta$	(2.7 ± 0.4) %	S=1.6
Γ_{10}	$J/\psi(1S)\pi^0$	$(9.7 \pm2.1) \times 10^{-4}$	
	Hadronic decays		
Γ_{11}	$3(\pi^+\pi^-)\pi^0$	$(3.5 \pm1.6) \times 10^{-3}$	
Γ_{12}	$2(\pi^+\pi^-)\pi^0$	$(3.1 \pm0.7) \times 10^{-3}$	
Γ_{13}	$\pi^+\pi^- K^+ K^-$	$(1.6 \pm0.4) \times 10^{-3}$	
Γ_{14}	$\pi^+\pi^- p\overline{p}$	$(8.0 \pm2.0) \times 10^{-4}$	
Γ_{15}	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	$(6.7 \pm2.5) \times 10^{-4}$	
Γ_{16}	$2(\pi^+\pi^-)$	$(4.5 \pm1.0) \times 10^{-4}$	
Γ_{17}	$\rho^0\pi^+\pi^-$	$(4.2 \pm1.5) \times 10^{-4}$	
Γ_{18}	$\overline{p}p$	$(1.9 \pm0.5) \times 10^{-4}$	
Γ_{19}	$3(\pi^+\pi^-)$	$(1.5 \pm1.0) \times 10^{-4}$	
Γ_{20}	$\overline{p}p\pi^0$	$(1.4 \pm0.5) \times 10^{-4}$	
Γ_{21}	K^+K^-	$(1.0 \pm0.7) \times 10^{-4}$	
Γ_{22}	$\pi^+\pi^-$	$(8 \pm5) \times 10^{-5}$	
Γ_{23}	$\pi^+\pi^-\pi^0$	$(8 \pm5) \times 10^{-5}$	
Γ_{24}	$\Lambda\overline{\Lambda}$	$< 4 \times 10^{-4}$	CL=90%
Γ_{25}	$\Xi^-\overline{\Xi}^+$	$< 2 \times 10^{-4}$	CL=90%
Γ_{26}	$\rho\pi$	$< 8.3 \times 10^{-5}$	CL=90%
Γ_{27}	$K^+K^-\pi^0$	$< 2.96 \times 10^{-5}$	CL=90%
Γ_{28}	$K^+\overline{K}^*(892)^-$ + c.c.	$< 1.79 \times 10^{-5}$	CL=90%
	Radiative decays		
Γ_{29}	$\gamma\chi_{c0}(1P)$	(9.3 ± 0.8) %	
Γ_{30}	$\gamma\chi_{c1}(1P)$	(8.7 ± 0.8) %	
Γ_{31}	$\gamma\chi_{c2}(1P)$	(7.8 ± 0.8) %	
Γ_{32}	$\gamma\eta_c(1S)$	$(2.8 \pm0.6) \times 10^{-3}$	
Γ_{33}	$\gamma\eta_c(2S)$		
Γ_{34}	$\gamma\pi^0$	$< 5.4 \times 10^{-3}$	CL=95%
Γ_{35}	$\gamma\eta'(958)$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{36}	$\gamma\eta$	$< 2 \times 10^{-4}$	CL=90%
Γ_{37}	$\gamma\gamma$	$< 1.8 \times 10^{-4}$	CL=90%
Γ_{38}	$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	[a] $< 1.2 \times 10^{-4}$	CL=90%

[a] See $\eta(1440)$ mini-review.

$\psi(2S)$ PARTIAL WIDTHS

$\Gamma(\text{hadrons})$ Γ_1

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
224±56	LUTH	75	MRK1	$e^+ e^-$

$\Gamma(e^+ e^-)$ Γ_3

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2.14±0.21	ALEXANDER	89	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0 ±0.3	BRANDELIK	79C	DASP	$e^+ e^-$
2.1 ±0.3	[2] LUTH	75	MRK1	$e^+ e^-$

[2] From a simultaneous fit to $e^+ e^-$, $\mu^+ \mu^-$, and hadronic channels assuming $\Gamma(e^+ e^-) = \Gamma(\mu^+ \mu^-)$

$\Gamma(\gamma\gamma)$ Γ_{37}

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<43	90	BRANDELIK	79C	DASP	$e^+ e^-$

$\psi(2S)$ $\Gamma(i)\Gamma(e^+ e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into $e^+ e^-$ and with the total width is obtained from the integrated cross section into channel$_i$ in the $e^+ e^-$ annihilation. We list only data that have not been used to determine the partial width $\Gamma(i)$ or the branching ratio $\Gamma(i)/\text{total}$.

$\Gamma(\text{hadrons}) \times \Gamma(e^+ e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.2±0.4	ABRAMS	75	MRK1	$e^+ e^-$

$\psi(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.981±0.003	[3] LUTH	75	MRK1	$e^+ e^-$

$\Gamma(\text{virtual } \gamma \to \text{hadrons})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.029±0.004	[4] LUTH	75	MRK1	$e^+ e^-$

$\Gamma(e^+ e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
88±13	[5] FELDMAN	77	RVUE	$e^+ e^-$

$\Gamma(\mu^+ \mu^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
77±17	[6] HILGER	75	SPEC	$e^+ e^-$

$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-)$ Γ_4/Γ_3

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.89±0.16	BOYARSKI	75C	MRK1	$e^+ e^-$

[3] Includes cascade decay into $J/\psi(1S)$.

[4] Included in $\Gamma(\text{hadrons})/\Gamma_{\text{total}}$.

[5] From an overall fit assuming equal partial widths for $e^+ e^-$ and $\mu^+ \mu^-$. For a measurement of the ratio see the entry $\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-)$ below. Includes LUTH 75, HILGER 75, BURMESTER 77.

[6] Restated by us using $B(\psi(2S) \to J/\psi(1S) \text{ anything}) = 0.55$.

DECAYS INTO $J/\psi(1S)$ AND ANYTHING

$\Gamma(J/\psi(1S) \text{ anything})/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.55±0.07 OUR AVERAGE				
0.51±0.12	BRANDELIK	79C	DASP	$e^+ e^-$
0.57±0.08	ABRAMS	75	MRK1	$e^+ e^-$

$\Gamma(J/\psi(1S) \text{ neutrals})/\Gamma(J/\psi(1S) \text{ anything})$ Γ_6/Γ_5

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.41±0.02	TANENBAUM	76	MRK1	$e^+ e^-$

$\Gamma(J/\psi(1S)\pi\pi)/\Gamma_{\text{total}}$ $(1.5\Gamma_7+3\Gamma_8)/\Gamma$

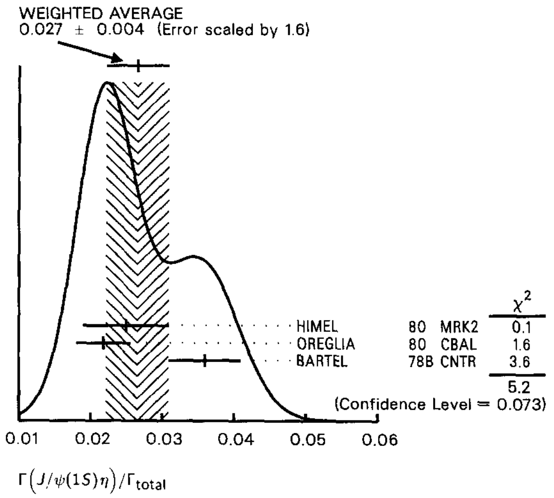
VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.50±0.04 OUR AVERAGE				
0.48±0.06	ABRAMS	75B	MRK1	$e^+ e^- \to J/\psi\pi^+\pi^-$
0.51±0.087	ABRAMS	75B	MRK1	$e^+ e^- \to J/\psi 2\pi^0$
0.54±0.09	WIIK	75	DASP	$e^+ e^- \to J/\psi\pi^+\pi^-$
0.54±0.18	WIIK	75	DASP	$e^+ e^- \to J/\psi 2\pi^0$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma(J/\psi(1S)\pi^+\pi^-)$ Γ_8/Γ_7

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.53±0.06	TANENBAUM	76	MRK1	$e^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64±0.15	[7] HILGER	75	SPEC	$e^+ e^-$

$\Gamma(J/\psi(1S)\eta)/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.027 ±0.004 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.				
0.025 ±0.006	166	HIMEL 80	MRK2	e^+e^-
0.0218±0.0014±0.0035	386	OREGLIA 80	CBAL	$e^+e^- \rightarrow J/\psi 2\gamma$
0.036 ±0.005	164	BARTEL 78B	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035 ±0.009	17	[8] BRANDELIK 79B	DASP	$e^+e^- \rightarrow J/\psi 2\gamma$
0.043 ±0.008	44	[8] TANENBAUM 76	MRK1	e^+e^-



$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
9.7±2.1 OUR AVERAGE				
15 ±6	7	HIMEL 80	MRK2	e^+e^-
9 ±2 ±1	23	OREGLIA 80	CBAL	$\psi(2S) \rightarrow J/\psi 2\gamma$

[7] Ignoring the $J/\psi(1S)\eta$ and $J/\psi(1S)\gamma\gamma$ decays.
[8] Low statistics data removed from average.

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
35±16	6	FRANKLIN 83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
31± 7 OUR AVERAGE				
30± 8	42	FRANKLIN 83	MRK2	e^+e^-
35±15		ABRAMS 75	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
16±4	[9] TANENBAUM 78	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ Γ_{14}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
8±2	[9] TANENBAUM 78	MRK1	e^+e^-

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
6.7±2.5	TANENBAUM 78	MRK1	e^+e^-

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
4.5±1.0	TANENBAUM 78	MRK1	e^+e^-

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
4.2±1.5	TANENBAUM 78	MRK1	e^+e^-

$\Gamma(\overline{p}p)/\Gamma_{\text{total}}$ Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
1.9±0.5 OUR AVERAGE				
1.4±0.8	4	BRANDELIK 79C	DASP	e^+e^-
2.3±0.7		FELDMAN 77	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
1.5±1.0	[9] TANENBAUM 78	MRK1	e^+e^-

$\Gamma(\overline{p}p\pi^0)/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
1.4±0.5	9	FRANKLIN 83	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
1.0±0.7		BRANDELIK 79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.5	90	FELDMAN 77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{22}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
0.8±0.5		BRANDELIK 79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.5	90	FELDMAN 77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
0.85±0.46	4	FRANKLIN 83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{\text{total}}$ Γ_{24}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<4	90	FELDMAN 77	MRK1	e^+e^-

$\Gamma(\Xi^-\overline{\Xi}^+)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<2	90	FELDMAN 77	MRK1	e^+e^-

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_{26}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 0.83	90	1	FRANKLIN 83	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<10	90		BARTEL 76	CNTR	e^+e^-
<10	90		[10] ABRAMS 75	MRK1	e^+e^-

$\Gamma(K^+K^-\pi^0)/\Gamma_{\text{total}}$ Γ_{27}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<2.96	90	1	FRANKLIN 83	MRK2	$e^+e^- \rightarrow$ hadrons

$\Gamma(K^+\overline{K}^*(892)^- + \text{c.c.})/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.79	90	0	FRANKLIN 83	MRK2	$e^+e^- \rightarrow$ hadrons

[9] Assuming entirely strong decay.
[10] Final state $\rho^0\pi^0$.

RADIATIVE DECAYS

$\Gamma(\gamma\chi_{c0}(1P))/\Gamma_{\text{total}}$ Γ_{29}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
9.3±0.8 OUR AVERAGE			
9.9±0.5±0.8	[11] GAISER 86	CBAL	$e^+e^- \rightarrow \gamma X$
7.2±2.3	[11] BIDDICK 77	CNTR	$e^+e^- \rightarrow \gamma X$
7.5±2.6	[11] WHITAKER 76	MRK1	e^+e^-

$\Gamma(\gamma\chi_{c1}(1P))/\Gamma_{\text{total}}$ Γ_{30}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
8.7±0.8 OUR AVERAGE			
9.0±0.5±0.7	[12] GAISER 86	CBAL	$e^+e^- \rightarrow \gamma X$
7.1±1.9	[13] BIDDICK 77	CNTR	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\chi_{c2}(1P))/\Gamma_{\text{total}}$ Γ_{31}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
7.8±0.8 OUR AVERAGE			
8.0±0.5±0.7	[14] GAISER 86	CBAL	$e^+e^- \rightarrow \gamma X$
7.0±2.0	[13] BIDDICK 77	CNTR	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\eta_c(1S))/\Gamma_{\text{total}}$ Γ_{32}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN	COMMENT
0.28±0.06	GAISER 86	CBAL	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\eta_c(2S))/\Gamma_{\text{total}}$ Γ_{33}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.2 to 1.3	95	EDWARDS 82C	CBAL	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\pi^0)/\Gamma_{total}$ Γ_{34}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
< 54	95	[15] LIBERMAN 75	SPEC	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100	90	WIIK 75	DASP	e^+e^-

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ Γ_{35}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID	TECN	COMMENT
<0.11	90	[16] BARTEL 76	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.6	90	[17] BRAUNSCH... 77	DASP	e^+e^-

$\Gamma(\gamma\eta)/\Gamma_{total}$ Γ_{36}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	90	YAMADA 77	DASP	$e^+e^- \rightarrow 3\gamma$

$\Gamma(\gamma\eta(1440) \rightarrow \gamma K\overline{K}\pi)/\Gamma_{total}$ Γ_{38}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.12	90	[18] SCHARRE 80	MRK1	e^+e^-

[11] Angular distribution $(1+\cos^2\theta)$ assumed.
[12] Angular distribution $(1-0.189\cos^2\theta)$ assumed.
[13] Valid for isotropic distribution of the photon.
[14] Angular distribution $(1-0.052\cos^2\theta)$ assumed.
[15] Restated by us using $B(\psi(2S) \rightarrow \mu^+\mu^-) = 0.0077$.
[16] The value is normalized to the branching ratio for $\Gamma(J/\psi(1S)\eta)/\Gamma_{total}$.
[17] Restated by us using total decay width 228 keV.
[18] Includes unknown branching fraction $\eta(1440) \rightarrow K\overline{K}\pi$.

$\psi(2S)$ REFERENCES

ALEXANDER 89 NP B320 45 +Bonvicini, Drell, Frey, Luth (LBL, MICH, SLAC)
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
FRANKLIN 83 PRL 51 963 +Franklin, Feldman, Abrams, Alam+ (LBL, SLAC)
EDWARDS 82C PRL 48 70 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE 82 PL 113B 509 +Barate, Astbury+ (SACL, LOIC, SHMP, IND)
HIMEL 80 PRL 44 920 +Abrams, Alam, Blocker+ (LBL, SLAC)
OREGLIA 80 PRL 45 959 +Partridge+ (SLAC, CIT, HARV, PRIN, STAN)
SCHARRE 80 PL 97B 329 +Trilling, Abrams, Alam, Blocker+ (SLAC, LBL)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
BRANDELIK 79B NP B160 426 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
BRANDELIK 79C ZPHY C1 233 + (AACH, DESY, HAMB, MPIM, TOKY)
BARTEL 78B PL 79B 492 +Dittmann, Duinker, Olsson, O'Neill+ (DESY, HEID)
TANENBAUM 78 PR D17 1731 +Alam, Boyarski+ (SLAC, LBL)
BIDDICK 77 PRL 38 1324 +Burnett+ (UCSD, UMD, PAVI, PRIN, SLAC, STAN)
BRAUNSCH... 77 PL 67B 249 Braunschweig+ (AACH, DESY, HAMB, MPIM+)
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)
FELDMAN 77 PL 33C 285 +Perl (LBL, SLAC)
YAMADA 77 Hamburg Conf. 69 (DESY, TOKY)
BARTEL 76 PL 64B 483 +Duinker, Olsson, Steffen, Heintze+ (DESY, HEID)
TANENBAUM 76 PRL 36 402 +Abrams, Boyarski, Bulos+ (SLAC, LBL) IG
WHITAKER 76 PRL 37 1596 +Tanenbaum, Abrams, Alam+ (SLAC, LBL)
ABRAMS 75 Stanford Symp. 25 (LBL)
ABRAMS 75B PRL 34 1181 +Briggs, Chinowsky, Friedberg+ (LBL, SLAC)
BOYARSKI 75C Palermo Conf. 54 +Breidenbach, Bulos, Abrams, Briggs+ (SLAC, LBL)
HILGER 75 PRL 35 625 +Beron, Ford, Hofstadter, Howell+ (STAN, PENN)
LIBERMAN 75 Stanford Symp. 55 (STAN)
LUTH 75 PRL 35 1124 +Boyarski, Lynch, Breidenbach+ (SLAC, LBL) JPC
WIIK 75 Stanford Symp. 69 (DESY)

OTHER RELATED PAPERS

BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
FRANKLIN 83B SLAC-254 Thesis (STAN)
BARATE 81 PR D24 2994 +Astbury+ (SACL, LOIC, SHMP, CERN, IND)
PARTRIDGE 80B PRL 45 1150 +Peck+ (CIT, HARV, PRIN, STAN, SLAC)
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)
SNYDER 76 PRL 36 1415 +Hom, Lederman, Appel+ (COLU, FNAL, STON)
AUBERT 75B PRL 33 1624 +Becker, Biggs, Burger, Glenn+ (MIT, BNL)
BRAUNSCH... 75B PL 57B 407 Braunschweig+ (AACH, DESY, MPIM, TOKY)
CAMERINI 75 PRL 35 483 +Learned, Prepost, Ash, Anderson+ (WISC, SLAC)
FELDMAN 75B PRL 35 821 +Jean-Marie, Sadoulet, Vannucci+ (LBL, SLAC)
GRECO 75 PL 56B 367 +Pancheri-Srivastava, Srivastava (FRAS)
JACKSON 75 NIM 128 13 +Scharre (LBL)
SIMPSON 75 PRL 35 699 +Beron, Ford, Hilger, Hofstadter+ (STAN, PENN)
ABRAMS 74 PRL 33 1453 +Briggs, Augustin, Boyarski+ (LBL, SLAC)

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(3770)$ MASS

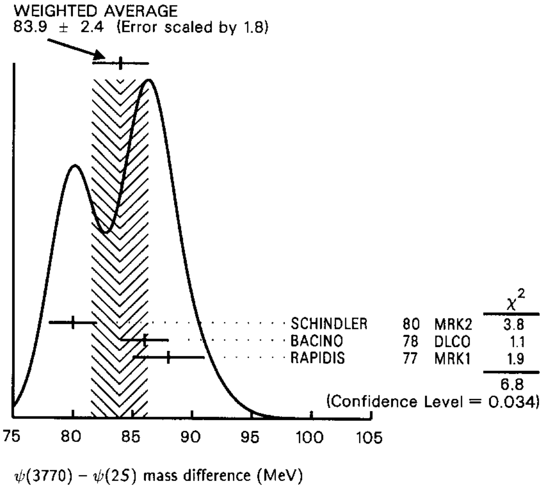
VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3769.9±2.5 OUR EVALUATION	Error includes scale factor of 1.8. From $\psi(3685)$ mass and mass difference below.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3764.0±5.0	[1] SCHINDLER 80	MRK2	e^+e^-
3770 ±6.0	[1] BACINO 78	DLCO	e^+e^-
3772.0±6.0	[1] RAPIDIS 77	MRK1	e^+e^-

[1] Errors include systematic common to all experiments.

$\psi(3770) - \psi(2S)$ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
83.9±2.4 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.		
80.0±2.0	SCHINDLER 80	MRK2	e^+e^-
86.0±2.0	[2] BACINO 78	DLCO	e^+e^-
88.0±3.0	RAPIDIS 77	MRK1	e^+e^-

[2] SPEAR $\psi(2S)$ mass subtracted (see SCHINDLER 80).



$\psi(3770)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
23.6±2.7 OUR FIT	Error includes scale factor of 1.1.		
25.3±2.9 OUR AVERAGE			
24.0±5.0	SCHINDLER 80	MRK2	e^+e^-
24.0±5.0	BACINO 78	DLCO	e^+e^-
28.0±5.0	RAPIDIS 77	MRK1	e^+e^-

$\psi(3770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$D\overline{D}$	dominant	
Γ_2	e^+e^-	$(1.12\pm0.17)\times10^{-5}$	1.2

$\psi(3770)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.26 ±0.04 OUR FIT	Error includes scale factor of 1.2.		
0.24 ±0.05 OUR AVERAGE	Error includes scale factor of 1.2.		
0.276±0.050	SCHINDLER 80	MRK2	e^+e^-
0.18 ±0.06	BACINO 78	DLCO	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.37 ±0.09	[3] RAPIDIS 77	MRK1	e^+e^-

[3] See also $\Gamma(e^+e^-)/\Gamma_{total}$ below.

$\psi(3770)$ BRANCHING RATIOS

$\Gamma(D\overline{D})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
dominant	PERUZZI 77	MRK1	$e^+e^- \rightarrow D\overline{D}$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
1.12±0.17 OUR FIT Error includes scale factor of 1.2.			
1.3 ±0.2	RAPIDIS 77	MRK1	e^+e^-

$\psi(3770)$ REFERENCES

SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
BACINO 78 PRL 40 671 +Baumgarten, Birkwood+ (SLAC, UCLA, UCI)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (SLAC, LBL, NWES, HAWA)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)

$\psi(4040)$

$I^G(J^{PC}) = ?^?(1^{--})$

J^{PC} for the $\psi(4040)$ is known by its production in e^+e^- collisions via single-photon annihilation. I^G is not known, and the interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

$\psi(4040)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4040.0±10.0	BRANDELIK 78C	DASP	e^+e^-

$\psi(4040)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
52.0±10.0	BRANDELIK 78C	DASP	e^+e^-

$\psi(4040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.4\pm0.4)\times10^{-5}$
Γ_2	$D^0\overline{D}^0$	seen
Γ_3	$D^*(2010)^0\overline{D}^0$ + c.c.	seen
Γ_4	$D^*(2010)^0\overline{D}^*(2010)^0$	seen
Γ_5	$J/\psi(1S)$ hadrons	
Γ_6	$\mu^+\mu^-$	

$\psi(4040)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.75±0.15	BRANDELIK 78C	DASP	e^+e^-

$\psi(4040)$ BRANCHING RATIOS

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE (units 10^{-5})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 1.0	FELDMAN 77	MRK1	e^+e^-

$\Gamma(D^0\overline{D}^0)/\Gamma(D^*(2010)^0\overline{D}^0 + \text{c.c.})$ Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.05±0.03	[1] GOLDHABER 77	MRK1	e^+e^-

[1] Phase-space factor (p^3) explicitly removed.

$\Gamma(D^*(2010)^0\overline{D}^*(2010)^0)/\Gamma(D^*(2010)^0\overline{D}^0 + \text{c.c.})$ Γ_4/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
32.0±12.0	[2] GOLDHABER 77	MRK1	e^+e^-

[2] Phase-space factor (p^3) explicitly removed.

$\psi(4040)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
Also 79C ZPHY C1 233 Brandelik+ (AACH, DESY, HAMB, MPIM, TOKY)
FELDMAN 77 PL 33C 285 +Perl (LBL, SLAC)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (LBL, SLAC)

OTHER RELATED PAPERS

HEIKKILA 84 PR D29 110 +Tornqvist, Ono (HELS, TOKY)
ONO 84 ZPHY C26 307 (ORSA)
SIEGRIST 82 PR D26 969 +Schwitters, Alam, Chinowsky+ (SLAC, LBL)
KIRKBY 79B Fermilab Symp. 107 (SLAC)
RICHARDSON 79 PL 82B 272 (SLAC)
LUTH 77 PL 70B 120 +Pierre, Abrams, Alam, Boyarski+ (LBL, SLAC)
PERUZZI 76 PRL 37 569 +Piccolo, Feldman, Nguyen, Wiss+ (SLAC, LBL)
AUGUSTIN 75 PRL 34 764 +Boyarski, Abrams, Briggs+ (SLAC, LBL)
BACCI 75 PL 58B 481 +Bidoli, Penso, Stella+ (ROMA, FRAS)
BOYARSKI 75B PRL 34 762 +Breidenbach, Abrams, Briggs+ (SLAC, LBL)
ESPOSITO 75 PL 58B 478 +Felicetti, Peruzzi+ (FRAS, NAPL, PADO, ROMA)

$\psi(4160)$

$I^G(J^{PC}) = ?^?(1^{--})$

J^{PC} for the $\psi(4160)$ is known by its production in e^+e^- collisions via single-photon annihilation. I^G is not known, and the interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

$\psi(4160)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4159.0±20.0	BRANDELIK 78C	DASP	e^+e^-

$\psi(4160)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
78.0±20.0	BRANDELIK 78C	DASP	e^+e^-

$\psi(4160)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(10\pm4)\times10^{-6}$

$\psi(4160)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.77±0.23	BRANDELIK 78C	DASP	e^+e^-

$\psi(4160)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)

OTHER RELATED PAPERS

ONO 84 ZPHY C26 307 (ORSA)
KIRKBY 79B Fermilab Symp. 107 (SLAC)
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)

$\psi(4415)$

$I^G(J^{PC}) = ?^?(1^{--})$

J^{PC} for the $\psi(4415)$ is known by its production in e^+e^- collisions via single-photon annihilation. I^G is not known, and the interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

$\psi(4415)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4415 ± 6 OUR AVERAGE			
4417.0±10.0	BRANDELIK 78C	DASP	e^+e^-
4414 ± 7	SIEGRIST 76	MRK1	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 4400	KNIES 77	PLUT	$e^+e^- \to \mu^+\mu^-$

$\psi(4415)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
43 ±15 OUR AVERAGE Error includes scale factor of 1.8.			
66.0±15.0	BRANDELIK 78C	DASP	e^+e^-
33 ±10	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	dominant
Γ_2	e^+e^-	$(1.1\pm0.4)\times10^{-5}$

$\psi(4415)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
$0.47^{+0.10}_{-0.09}$ OUR AVERAGE			
0.49±0.13	BRANDELIK 78C	DASP	e^+e^-
0.44±0.14	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
dominant	SIEGRIST	76	MRK1	e^+e^-

$\psi(4415)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (AACH, DESY, HAMB, MPIM, TOKY)
KNIES 77 Hamburg Symp. 93 (PLUTO Collab.)
SIEGRIST 76 PRL 36 700 +Abrams, Boyarski, Breidenbach+ (LBL, SLAC)

OTHER RELATED PAPERS

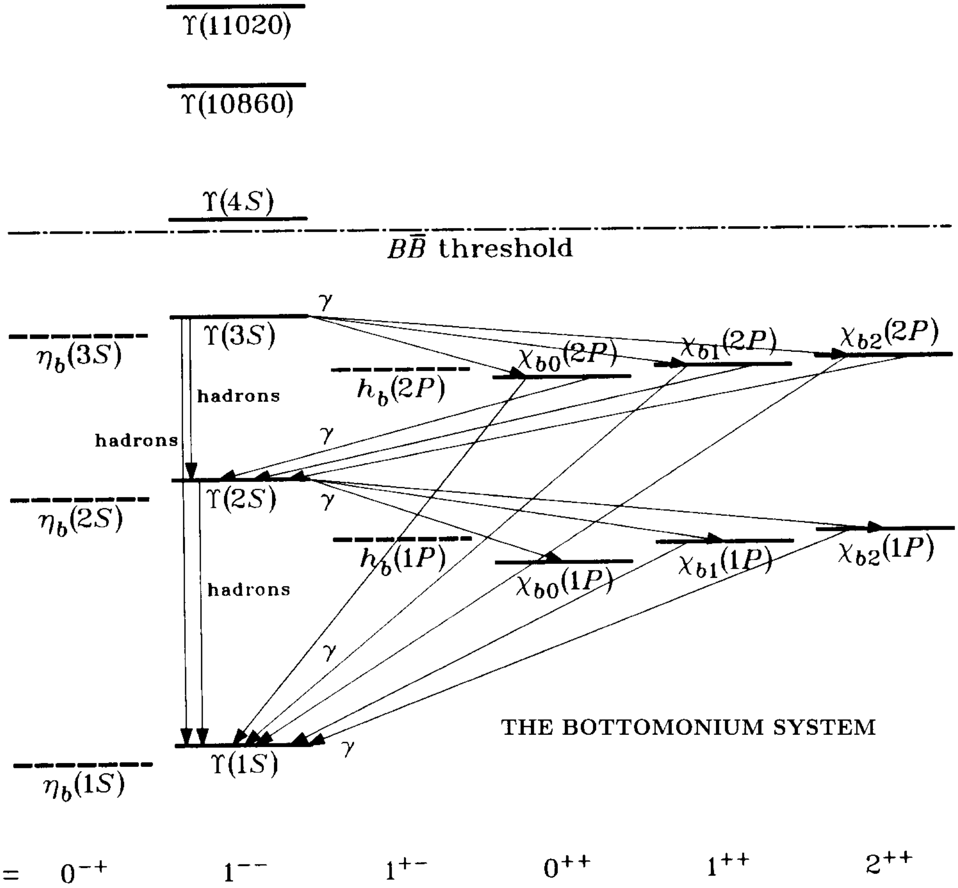
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)
LUTH 77 PL 70B 120 +Pierre, Abrams, Alam, Boyarski+ (LBL, SLAC)

$b\bar{b}$ MESONS

NOTE ON WIDTH DETERMINATIONS OF THE Υ STATES

As is the case for $J/\psi(1S)$ and $\psi(2S)$, the full widths of the bound $b\bar{b}$ states $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ are not directly measurable, since they are much smaller than the energy resolution of the e^+e^- storage rings where these states are produced. The common indirect method to determine Γ starts from

$$\Gamma = \Gamma_{\ell\ell}/B_{\ell\ell} \ , \tag{1}$$



The level scheme of the $b\bar{b}$ states showing experimentally established states with solid lines. Singlet states are called η_b and h_b, triplet states Υ and χ_{bJ}. In parentheses it is sufficient to give the radial quantum number and the orbital angular momentum to specify the states with all their quantum numbers. E.g., $h_b(2P)$ means 2^1P_1 with $n = 2$, $L = 1$, $S = 0$, $J = 1$, $PC = +-$. If found, D-wave states would be called $\eta_b(nD)$ and $\Upsilon_J(nD)$, with $J =$ 1,2,3 and $n = 1, 2, 3, 4, \cdots$. For the χ_b states, the spins of only the $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$ have been experimentally established. The spins of the other χ_b are given as the preferred values, based on the quarkonium models. The figure also shows the observed hadronic and radiative transitions.

where $\Gamma_{\ell\ell}$ is one leptonic partial width and $B_{\ell\ell}$ is the corresponding branching fraction ($\ell = e$, μ, or τ). One then assumes e-μ-τ universality and uses

$$\Gamma_{\ell\ell} = \Gamma_{ee}$$

$$B_{\ell\ell} = \text{average of } B_{ee},\ B_{\mu\mu},\ \text{and } B_{\tau\tau}\ . \tag{2}$$

The electronic partial width Γ_{ee} is also not directly measurable at e^+e^- storage rings, only the combination $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$, where $\Gamma_{\rm had}$ is the hadronic partial width and

$$\Gamma_{\rm had} + 3\Gamma_{ee} = \Gamma\ . \tag{3}$$

This combination is obtained experimentally from the energy-integrated hadronic cross section

$$\int_{\rm resonance} \sigma(e^+e^- \to \Upsilon \to \text{hadrons})dE$$

$$= \frac{6\pi}{M^2}\frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma}C_r = \frac{6\pi}{M^2}\frac{\Gamma^{(0)}_{ee}\Gamma_{\rm had}}{\Gamma}C^{(0)}_r\ , \tag{4}$$

where M is the Υ mass, and C_r and $C^{(0)}_r$ are radiative correction factors. C_r is used for obtaining Γ_{ee} as defined in Eq. (1) and contains corrections from all orders of QED for describing $(b\bar{b}) \to e^+e^-$. The lowest order QED value $\Gamma^{(0)}_{ee}$, relevant for the comparison with potential-model calculations, is defined by the lowest order QED graph (Born term) alone and is about 7% lower than Γ_{ee}. In the past, this distinction had been overlooked by some authors as pointed out by ALEXANDER 89, BARU 86, COOPER 86, KOENIGSMANN 86, and others.

The Listings give experimental results on B_{ee}, $B_{\mu\mu}$, $B_{\tau\tau}$, and $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$. The entries of the latter quantity have been re-evaluated using consistently the correction procedure of KURAEV 85. The partial width Γ_{ee} is obtained from the average values for $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$ and $B_{\ell\ell}$ using

$$\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma(1-3B_{\ell\ell})}\ . \tag{5}$$

The total width Γ is then obtained from Eq. (1). We do not list Γ_{ee} and Γ values of individual experiments. The Γ_{ee} values in the Meson Summary Table are also those defined in Eq. (1) and no longer the lowest order quantities $\Gamma^{(0)}_{ee}$.

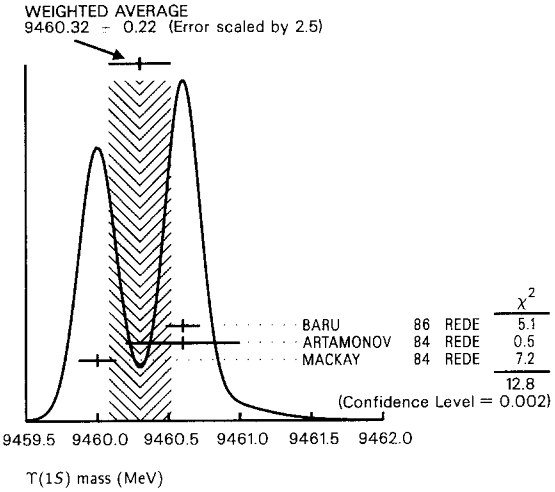
$\Upsilon(1S)$
or $\Upsilon(9460)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(1S)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9460.32±0.22 OUR AVERAGE	Error includes scale factor of 2.5. See the ideogram below.			
9460.59±0.12	BARU	86	REDE	$e^+e^- \to$ hadrons
9460.6 ±0.4	[1] ARTAMONOV	84	REDE	$e^+e^- \to$ hadrons
9459.97±0.11±0.07	MACKAY	84	REDE	$e^+e^- \to$ hadrons

[1] Value includes data of ARTAMONOV 82.



$\Upsilon(1S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
52.1±2.1 OUR EVALUATION	See Υ mini-review.

$\Upsilon(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\tau^+\tau^-$	(2.97 ± 0.35) %	
Γ_2	$\mu^+\mu^-$	(2.57 ± 0.07) %	
Γ_3	e^+e^-	(2.52 ± 0.17) %	
	Hadronic decays		
Γ_4	$J/\psi(1S)$ anything	$(1.1\ \pm0.4\ ) \times 10^{-3}$	
Γ_5	$\rho\pi$	$< 2.1 \times 10^{-3}$	90%
	Radiative decays		
Γ_6	$\gamma\eta'(958)$	$< 1.3 \times 10^{-3}$	90%
Γ_7	$\gamma\eta$	$< 3.5 \times 10^{-4}$	90%
Γ_8	$\gamma f'_2(1525)$	$< 1.35 \times 10^{-4}$	90%
Γ_9	$\gamma f_2(1720) \to \gamma K\overline{K}$	$< 6.4 \times 10^{-5}$	90%
Γ_{10}	$\gamma f_2(1270)$	$< 4.8 \times 10^{-5}$	90%
Γ_{11}	$\gamma f_4(2220) \to \gamma K^+K^-$	$< 1.5 \times 10^{-5}$	90%

$\Upsilon(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\rm total}$ $\Gamma_0\Gamma_3/\Gamma$

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.24±0.04 OUR AVERAGE				
1.23±0.02±0.05	[2] JAKUBOWSKI	88	CBAL	$e^+e^- \to$ hadrons
1.37±0.06±0.09	[3] GILES	84B	CLEO	$e^+e^- \to$ hadrons
1.17±0.06±0.10	[3] TUTS	83	CUSB	$e^+e^- \to$ hadrons
1.23±0.08±0.04	[3] ALBRECHT	82	DASP	$e^+e^- \to$ hadrons
1.13±0.07±0.11	[3] NICZYPORUK	82	LENA	$e^+e^- \to$ hadrons
1.09±0.25	[3] BOCK	80	CNTR	$e^+e^- \to$ hadrons
1.35±0.14	[4] BERGER	79	PLUT	$e^+e^- \to$ hadrons

[2] Radiative corrections evaluated following KURAEV 85.

[3] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

[4] Radiative corrections reevaluated by ALEXANDER 89 using $B(\mu\mu) = 0.026$.

$\Upsilon(1S) = \Upsilon(9460)$

$\Upsilon(1S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_3

VALUE (keV)	DOCUMENT ID
1.34±0.04 OUR EVALUATION	See Υ mini-review.

$\Upsilon(1S)$ BRANCHING RATIOS

$\Gamma(\tau^+\tau^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0297±0.0035 OUR AVERAGE			
0.027 ±0.004 ±0.002	[5] ALBRECHT 85C	ARG	$\Upsilon(2S) \to \pi^+\pi^-\tau^+\tau^-$
0.034 ±0.004 ±0.004	GILES 83	CLEO	$e^+e^- \to \tau^+\tau^-$

[5] Using $B(\Upsilon(1S) \to ee) = B(\Upsilon(1S) \to \mu\mu) = 0.0256$; not used for width evaluations.

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0257±0.0007 OUR AVERAGE				
0.0252±0.0007±0.0007		CHEN 89B	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0261±0.0009±0.0011		KAARSBERG 89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.0230±0.0025±0.0013	86	ALBRECHT 87	ARG	$\Upsilon(2S) \to \pi^+\pi^-\mu^+\mu^-$
0.0284±0.0018±0.0020		BESSON 84	CLEO	$\Upsilon(2S) \to \pi^+\pi^-\mu^+\mu^-$
0.027 ±0.003 ±0.003		ANDREWS 83	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0270±0.0028±0.0014		TUTS 83	CUSB	$e^+e^- \to \mu^+\mu^-$
0.032 ±0.013 ±0.003		ALBRECHT 82	DASP	$e^+e^- \to \mu^+\mu^-$
0.038 ±0.015 ±0.002		NICZYPORUK 82	LENA	$e^+e^- \to \mu^+\mu^-$
$0.014^{+0.034}_{-0.014}$		BOCK 80	CNTR	$e^+e^- \to \mu^+\mu^-$
0.022 ±0.020		BERGER 79	PLUT	$e^+e^- \to \mu^+\mu^-$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0252±0.0017 OUR AVERAGE				
0.0242±0.0014±0.0014	307	ALBRECHT 87	ARG	$\Upsilon(2S) \to \pi^+\pi^-e^+e^-$
0.028 ±0.003 ±0.002		BESSON 84	CLEO	$\Upsilon(2S) \to \pi^+\pi^-e^+e^-$
0.051 ±0.030		BERGER 80C	PLUT	$e^+e^- \to e^+e^-$

$\Gamma(J/\psi(1S)\text{ anything})/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
1.1±0.4±0.2		[6] FULTON 89	CLEO	$e^+e^- \to \mu^+\mu^-X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<20	90	NICZYPORUK 83	LENA	

[6] Using $B((J/\psi) \to \mu^+\mu^-) = (6.9 \pm 0.9)\%$.

$\Gamma(\rho\pi)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
<21	90	NICZYPORUK 83	LENA

$\Gamma(\gamma\eta'(958))/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<1.3	90	SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma\eta)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<3.5	90	SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma f_2'(1525))/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
<13.5	90	[7] BEAN 86	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<19.4	90	[7] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$

[7] Assuming $B(f_2'(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_2(1720) \to \gamma K\overline{K})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
< 3.2	90	[8] BEAN 86	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 5.0	90	[8] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$
< 2.1	90	[9] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<43	90	[10] SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$
< 2.6	90	[9] BEAN 86	CLEO	$\Upsilon(1S) \to \gamma\pi^+\pi^-$

[8] Assuming $B(f_2(1720) \to K^+K^-) = 1.0$.
[9] Assuming $B(f_2(1720) \to \pi^+\pi^-) = 1.0$.
[10] Assuming $B(f_2(1720) \to \eta\eta) = 1.0$.

$\Gamma(\gamma f_2(1270))/\Gamma_{\text{total}}$ Γ_{10}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
< 4.8	90	[11] BEAN 86	CLEO	$\Upsilon(1S) \to \gamma\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<13	90	[11] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<81	90	SCHMITT 88	CBAL	$\Upsilon(1S) \to \gamma X$

[11] Using $B(f_2(1270) \to \pi\pi) = 0.84$.

$\Gamma(\gamma f_4(2220) \to \gamma K^+K^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID	TECN	COMMENT
< 1.5	90	[12] FULTON 90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 2.9	90	[12] ALBRECHT 89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$
<20	90	[12] BARU 89	MD1	$\Upsilon(1S) \to \gamma K^+K^-$
< 3.1	90	[12] BEAN 86	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$

[12] Including unknown branching ratio of $f_4(2220) \to K^+K^-$.

$\Upsilon(1S)$ REFERENCES

FULTON 90B PR D41 1401 +Hempstead (CLEO Collab.)
ALBRECHT 89 ZPHY C42 349 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
ALEXANDER 89 NP B320 45 +Bonvicini, Drell, Frey, Luth (LBL, MICH, SLAC)
BARU 89 ZPHY C42 505 +Beilin, Blinov+ (NOVO)
CHEN 89B PR D39 3528 +McIlwain, Miller+ (CLEO Collab.)
FULTON 89 PL B224 445 +Haas, Hempstead+ (CLEO Collab.)
KAARSBERG 89 PRL 62 2077 +Heintz+ (CUSB Collab.)
BUCHMUEL... 88 HE e^+e^- Physics 412 Buchmueller, Cooper (HANN, MIT)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
JAKUBOWSKI 88 ZPHY C40 49 +Antreasyan, Bartels+ (Crystal Ball Collab.) IGJPC
SCHMITT 88 ZPHY C40 199 +Antreasyan+ (Crystal Ball Collab.)
ALBRECHT 87 ZPHY C35 283 +Binder, Boeckmann, Glaeser+ (ARGUS Collab.)
BARU 86 ZPHY C30 551 +Blinov, Bondar, Bukin+ (NOVO)
BEAN 86 PR D34 905 +Bobbink, Brock, Engler+ (CLEO Collab.)
ALBRECHT 85C PL 154B 452 +Drescher, Heller+ (ARGUS Collab.)
KURAEV 85 SJNP 41 466 +Fadin (ASCI)
Translated from YAF 41 733.
ARTAMONOV 84 PL 137B 272 +Baru, Blinov, Bondar+ (NOVO)
BESSON 84 PR D30 1433 +Green, Hicks, Namjoshi, Sannes+ (CLEO Collab.)
GILES 84B PR D29 1285 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
MACKAY 84 PR D29 2483 +Hasard, Giles, Hempstead+ (CUSB Collab.)
ANDREWS 83 PRL 50 807 +Avery, Berkelman, Cassel+ (CLEO Collab.)
GILES 83 PRL 50 877 + (HARV, OSU, ROCH, RUTG, SYRA, VAND+)
NICZYPORUK 83 ZPHY C17 197 +Jakubowski, Zeludziewicz+ (LENA Collab.)
TUTS 83 Cornell Conf. 284 (CUSB Collab.)
ALBRECHT 82 PL 116B 383 +Hofmann+ (DESY, DORT, HEID, LUND, ITEP)
ARTAMONOV 82 PL 118B 225 +Baru, Blinov, Bondar, Bukin, Groshev+ (NOVO)
NICZYPORUK 82 ZPHY C15 299 +Folger, Bienlein+ (LENA Collab.)
BERGER 80C PL 93B 497 +Lackas+ (AACH, DESY, HAMB, SIEG, WUPP)
BOCK 80 ZPHY C6 125 +Blanar, Blum+ (HEID, MPIM, DESY, HAMB)
BERGER 79 ZPHY C1 343 +Alexander+ (AACH, DESY, HAMB, SIEG, WUPG)

OTHER RELATED PAPERS

COOPER 86 Berkeley Conf. 67 (MIT)
KOENIGS... 86 DESY 86/136 Koenigsmann (DESY)
ALBRECHT 84 PL 134B 137 +Drescher, Heller+ (ARGUS Collab.)
ARTAMONOV 84 PL 137B 272 +Baru, Blinov, Bondar+ (NOVO)
ARTAMONOV 82 PL 118B 225 +Baru, Blinov, Bondar, Bukin, Groshev+ (NOVO)
MAGERAS 81 PRL 46 1115 +Bohringer, Finocchiaro+ (COLU, STON, LSU, MPIM)
MUELLER 81 PRL 46 1181 + (RUTG, SYRA, LEMO, VAND, CORN, ITHA+)
NICZYPORUK 81 PRL 46 92 +Jakubowski, Zeludziewicz, Folger+ (LENA Collab.)
ALBRECHT 80 PL 93B 500 +Hofmann+ (DESY, DORT, HEID, LUND)
ANDREWS 80 PRL 44 1108 +Berkelman, Billing, Cabenda+ (CLEO Collab.)
BOHRINGER 80 PRL 44 1111 +Costantini, Finocchiaro (COLU, STON)
KOURKOU... 80 PL 91B 481 Kourkoumelis+ (ATHU, NTUA, BNL, CERN+)
ANGELIS 79 PL 87B 398 +Besch, Blumenfeld+ (CERN, COLU, OXF, ROCK)
BADIER 79 PL 86B 98 +Boucrot+ (SACL, CERN, CDEF, EPOL, LALO)
DARDEN 79 PL 80B 419 +Hofmann, Schubert+ (DESY, DORT, HEID, LUND)
BERGER 78 PL 76B 243 +Alexander+ (AACH, DESY, HAMB, SIEG, WUPG)
BIENLEIN 78 PL 78B 360 +Glawe, Bock, Blanar+ (DESY, HAMB, HEID, MPIM)
DARDEN 78 PL 76B 246 +Hofmann, Schubert+ (DESY, DORT, HEID, LUND)
GARELICK 78 PR D18 945 +Gauthier, Hicks, Oliver+ (NEAS, WASH, TUFT)
KAPLAN 78 PRL 40 435 +Appel, Herb, Hom+ (STON, FNAL, COLU)
YOH 78 PRL 41 684 +Herb, Hom, Lederman+ (COLU, FNAL, STON)
COBB 77 PL 72B 273 +Iwata, Fabjan+ (BNL, CERN, SYRA, YALE)
HERB 77 PRL 39 252 +Hom, Lederman, Appel, Ito+ (COLU, FNAL, STON)
INNES 77 PRL 39 1240 +Appel, Brown, Herb, Hom+ (COLU, FNAL, STON)

$\chi_{b0}(1P) = \chi_{b0}(9860)$, $\chi_{b1}(1P) = \chi_{b1}(9890)$, $\chi_{b2}(1P) = \chi_{b2}(9915)$

$\chi_{b0}(1P)$ or $\chi_{b0}(9860)$

$I^G(J^{PC}) = ?^?(0 \text{ preferred}^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(1P)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9859.8±1.3 OUR AVERAGE				
9860.0±0.5±1.4	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv. γX
9858.3±1.6±2.7	[1] NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
9864.1±7 ±1	[1] HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv. γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9872.8±0.7±5.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
162.3±1.3 OUR AVERAGE				
162.1±0.5±1.4	ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv. γX
163.8±1.6±2.7	NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
158.0±7 ±1	HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv. γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149.4±0.7±5.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$

$\chi_{b0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\gamma\Upsilon(1S)$	<6 %	90%

$\chi_{b0}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.06	90	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	90	PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b0}(1P)$ REFERENCES

WALK 86 PR D34 2611 +Zschorsch+ (Crystal Ball Collab.)
ALBRECHT 85E PL 160B 331 +Drescher, Heller+ (ARGUS Collab.)
NERNST 85 PRL 54 2195 +Antreasyan, Aschman+ (Crystal Ball Collab.)
HAAS 84 PRL 52 799 +Jensen, Kagan, Kass, Behrends+ (CLEO Collab.)
KLOPFEN... 83 PRL 51 160 Klopfenstein, Horstkotte+ (CUSB Collab.)
PAUSS 83 PL 130B 439 +Dietl, Eigen+ (MPIM, COLU, CORN, LSU, STON)

$\chi_{b1}(1P)$ or $\chi_{b1}(9890)$

$I^G(J^{PC}) = ?^?(1^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 1$ from SKWARNICKI 87.

$\chi_{b1}(1P)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9891.9±0.7 OUR AVERAGE				
9890.8±0.9±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
9890.8±0.3±1.1	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv. γX
9892.0±0.8±2.4	[1] NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
9893.6±0.8±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv. γX
9894.4±0.4±3.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$
9892.0±3.0	[1] PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
130.6±0.7 OUR AVERAGE				
131.7±0.9±1.3	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
131.7±0.3±1.1	ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv. γX
130.6±0.8±2.4	NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
129.0±0.8±1.0	HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv. γX
128.1±0.4±3.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$
130.6±3.0	PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(1S)$	(35±8) %

$\chi_{b1}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.35±0.08 OUR AVERAGE				
0.32±0.06±0.07	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
0.47±0.18	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ REFERENCES

SKWARNICKI 87 PRL 58 972 +Antreasyan, Besset+ (Crystal Ball Collab.) J
WALK 86 PR D34 2611 +Zschorsch+ (Crystal Ball Collab.)
ALBRECHT 85E PL 160B 331 +Drescher, Heller+ (ARGUS Collab.)
NERNST 85 PRL 54 2195 +Antreasyan, Aschman+ (Crystal Ball Collab.)
HAAS 84 PRL 52 799 +Jensen, Kagan, Kass, Behrends+ (CLEO Collab.)
KLOPFEN... 83 PRL 51 160 Klopfenstein, Horstkotte+ (CUSB Collab.)
PAUSS 83 PL 130B 439 +Dietl, Eigen+ (MPIM, COLU, CORN, LSU, STON)

$\chi_{b2}(1P)$ or $\chi_{b2}(9915)$

$I^G(J^{PC}) = ?^?(2^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 2$ from SKWARNICKI 87.

$\chi_{b2}(1P)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9913.2±0.6 OUR AVERAGE				
9915.8±1.1±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
9912.2±0.3±0.9	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv. γX
9912.4±0.8±2.2	[1] NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
9913.3±0.7±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv. γX
9914.6±0.3±2.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$
9914.0±4.0	[1] PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
109.6±0.6 OUR AVERAGE				
107.0±1.1±1.3	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
110.6±0.3±0.9	ALBRECHT	85E	ARG	$\Upsilon(2S) \rightarrow$ conv. γX
110.4±0.8±2.2	NERNST	85	CBAL	$\Upsilon(2S) \rightarrow \gamma X$
109.5±0.7±1.0	HAAS	84	CLEO	$\Upsilon(2S) \rightarrow$ conv. γX
108.2±0.3±2.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma X$
108.8±4.0	PAUSS	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(1S)$	(22±4) %

$\chi_{b2}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.22±0.04 OUR AVERAGE				
0.27±0.06±0.06	WALK	86	CBAL	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$
0.20±0.05	KLOPFEN...	83	CUSB	$\Upsilon(2S) \rightarrow \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ REFERENCES

SKWARNICKI 87 PRL 58 972 +Antreasyan, Besset+ (Crystal Ball Collab.) J
WALK 86 PR D34 2611 +Zschorsch+ (Crystal Ball Collab.)
ALBRECHT 85E PL 160B 331 +Drescher, Heller+ (ARGUS Collab.)
NERNST 85 PRL 54 2195 +Antreasyan, Aschman+ (Crystal Ball Collab.)
HAAS 84 PRL 52 799 +Jensen, Kagan, Kass, Behrends+ (CLEO Collab.)
KLOPFEN... 83 PRL 51 160 Klopfenstein, Horstkotte+ (CUSB Collab.)
PAUSS 83 PL 130B 439 +Dietl, Eigen+ (MPIM, COLU, CORN, LSU, STON)

$\Upsilon(2S)$ or $\Upsilon(10023)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(2S)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.02330±0.00031 OUR AVERAGE			
10.0236 ±0.0005	[1] BARU 86B	REDE	$e^+ e^- \rightarrow$ hadrons
10.0231 ±0.0004	BARBER 84	REDE	$e^+ e^- \rightarrow$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(2S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
43±8 OUR EVALUATION	See Υ mini-review.

$\Upsilon(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Upsilon(1S)\pi^+\pi^-$	(18.5 ±0.8) %	
Γ_2	$\Upsilon(1S)\pi^0\pi^0$	(8.8 ±1.1) %	
Γ_3	$\tau^+\tau^-$	(1.7 ±1.6) %	
Γ_4	$\mu^+\mu^-$	(1.37±0.26) %	
Γ_5	e^+e^-	(1.36±0.26) %	
Γ_6	$\Upsilon(1S)\pi^0$	$< 8 \times 10^{-3}$	90%
Γ_7	$\Upsilon(1S)\eta$	$< 2 \times 10^{-3}$	90%
	Radiative decays		
Γ_8	$\gamma\chi_{b1}(1P)$	(6.7 ±0.9) %	
Γ_9	$\gamma\chi_{b2}(1P)$	(6.6 ±0.9) %	
Γ_{10}	$\gamma\chi_{b0}(1P)$	(4.3 ±1.0) %	
Γ_{11}	$\gamma f_2(1720)$	$< 5.9 \times 10^{-4}$	90%
Γ_{12}	$\gamma f_2'(1525)$	$< 5.3 \times 10^{-4}$	90%
Γ_{13}	$\gamma f_2(1270)$	$< 2.41 \times 10^{-4}$	90%
Γ_{14}	$\gamma f_4(2220)$		

$\Upsilon(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_0\Gamma_5/\Gamma$

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.562±0.027 OUR AVERAGE			
0.54 ±0.04 ±0.02	[2] JAKUBOWSKI 88	CBAL	$e^+ e^- \rightarrow$ hadrons
0.58 ±0.03 ±0.04	[3] GILES 84B	CLEO	$e^+ e^- \rightarrow$ hadrons
0.59 ±0.03 ±0.05	[3] TUTS 83	CUSB	$e^+ e^- \rightarrow$ hadrons
0.60 ±0.12 ±0.07	[3] ALBRECHT 82	DASP	$e^+ e^- \rightarrow$ hadrons
0.54 ±0.07 $^{+0.09}_{-0.05}$	[3] NICZYPORUK 81C	LENA	$e^+ e^- \rightarrow$ hadrons
0.41 ±0.18	[3] BOCK 80	CNTR	$e^+ e^- \rightarrow$ hadrons

[2] Radiative corrections evaluated following KURAEV 85.

[3] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

$\Upsilon(2S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_5

VALUE (keV)	*DOCUMENT ID*
0.586±0.029 OUR EVALUATION	$e^+ e^- \rightarrow$ hadrons. See Υ mini-review.

$\Upsilon(2S)$ BRANCHING RATIOS

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.185±0.008 OUR AVERAGE				
0.181±0.005±0.010	11.6k	ALBRECHT 87	ARG	$e^+ e^- \rightarrow \pi^+\pi^-$ MM
0.169±0.040		GELPHMAN 85	CBAL	$e^+ e^- \rightarrow e^+ e^- \pi^+\pi^-$
0.191±0.012±0.006		BESSON 84	CLEO	$\pi^+\pi^-$ MM
0.189±0.026		FONSECA 84	CUSB	$e^+ e^- \rightarrow \ell^+\ell^-\pi^+\pi^-$
0.21 ±0.07	7	NICZYPORUK 81B	LENA	$e^+ e^- \rightarrow \ell^+\ell^-\pi^+\pi^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.088±0.011 OUR AVERAGE				
0.095±0.019±0.019	25	ALBRECHT 87	ARG	$e^+ e^- \rightarrow \pi^0\pi^0\ell^+\ell^-$
0.080±0.015		GELPHMAN 85	CBAL	$e^+ e^- \rightarrow \ell^+\ell^-\pi^0\pi^0$
0.103±0.023		FONSECA 84	CUSB	$e^+ e^- \rightarrow \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\tau^+\tau^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.017±0.015±0.006	HAAS 84B	CLEO	$e^+ e^- \rightarrow \tau^+\tau^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0137±0.0026 OUR AVERAGE				
0.0138±0.0025±0.0015		KAARSBERG 89	CSB2	$e^+ e^- \rightarrow \mu^+\mu^-$
0.009 ±0.006 ±0.006		[4] ALBRECHT 85	ARG	$e^+ e^- \rightarrow \mu^+\mu^-$
0.018 ±0.008 ±0.005		HAAS 84B	CLEO	$e^+ e^- \rightarrow \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.038	90	NICZYPORUK 81C	LENA	$e^+ e^- \rightarrow \mu^+\mu^-$

[4] Re-evaluated using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-)=0.026$

$\Gamma(\Upsilon(1S)\pi^0)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.008	90	LURZ 87	CBAL	$e^+ e^- \rightarrow \ell^+\ell^-\gamma\gamma$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.002	90	FONSECA 84	CUSB	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.005	90	ALBRECHT 87	ARG	$e^+ e^- \rightarrow \pi^+\pi^-\ell^+\ell^-$ MM
<0.007	90	LURZ 87	CBAL	$e^+ e^- \rightarrow \ell^+\ell^-(\gamma\gamma, 3\pi^0)$
<0.010	90	BESSON 84	CLEO	

$\Gamma(\gamma\chi_{b1}(1P))/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.067±0.009 OUR AVERAGE			
0.091±0.018±0.022	ALBRECHT 85E	ARG	$e^+ e^- \rightarrow \gamma$ conv X
0.065±0.007±0.012	NERNST 85	CBAL	$e^+ e^- \rightarrow \gamma$ X
0.080±0.017±0.016	HAAS 84	CLEO	$e^+ e^- \rightarrow \gamma$ conv X
0.059±0.014	KLOPFEN... 83	CUSB	$e^+ e^- \rightarrow \gamma$ X

$\Gamma(\gamma\chi_{b2}(1P))/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.066±0.009 OUR AVERAGE			
0.098±0.021±0.024	ALBRECHT 85E	ARG	$e^+ e^- \rightarrow \gamma$ conv X
0.058±0.007±0.010	NERNST 85	CBAL	$e^+ e^- \rightarrow \gamma$ X
0.102±0.018±0.021	HAAS 84	CLEO	$e^+ e^- \rightarrow \gamma$ conv X
0.061±0.014	KLOPFEN... 83	CUSB	$e^+ e^- \rightarrow \gamma$ X

$\Gamma(\gamma\chi_{b0}(1P))/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.043±0.010 OUR AVERAGE			
0.064±0.014±0.016	ALBRECHT 85E	ARG	$e^+ e^- \rightarrow \gamma$ conv X
0.036±0.008±0.009	NERNST 85	CBAL	$e^+ e^- \rightarrow \gamma$ X
0.044±0.023±0.009	HAAS 84	CLEO	$e^+ e^- \rightarrow \gamma$ conv X
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.035±0.014	KLOPFEN... 83	CUSB	$e^+ e^- \rightarrow \gamma$ X

$\Gamma(\gamma f_2(1720))/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<59	90	[5] ALBRECHT 89	ARG	$\Upsilon(2S) \rightarrow \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 5.9	90	[6] ALBRECHT 89	ARG	$\Upsilon(2S) \rightarrow \gamma\pi^+\pi^-$

[5] Re-evaluated assuming $B(f_2(1720) \rightarrow K^+K^-) = 0.19$.

[6] Includes unknown branching ratio of $f_2(1720) \rightarrow \pi^+\pi^-$.

$\Gamma(\gamma f_2'(1525))/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<53	90	[7] ALBRECHT 89	ARG	$\Upsilon(2S) \rightarrow \gamma K^+ K^-$

[7] Re-evaluated assuming $B(f_2'(1525) \rightarrow K\overline{K}) = 0.71$.

$\Gamma(\gamma f_2(1270))/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<24.1	90	[8] ALBRECHT 89	ARG	$\Upsilon(2S) \rightarrow \gamma\pi^+\pi^-$

[8] Using $B(f_2(1270) \rightarrow \pi\pi)=0.84$

$\Gamma(\gamma f_4(2220))/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE (units 10^{-5})	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.8	90	[9] ALBRECHT 89	ARG	$\Upsilon(2S) \rightarrow \gamma K^+ K^-$

[9] Includes unknown branching ratio of $f_4(2220) \rightarrow K^+K^-$.

$\Upsilon(2S)$ REFERENCES

ALBRECHT 89 ZPHY C42 349 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
KAARSBERG 89 PRL 62 2077 +Heintz+ (CUSB Collab.)
BUCHMUEL... 88 HE e^+e^- Physics 412 Buchmueller, Cooper (HANN, MIT)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
JAKUBOWSKI 88 ZPHY C40 49 +Antreasyan, Bartels+ (Crystal Ball Collab.) IGJPC
ALBRECHT 87 ZPHY C35 283 +Binder, Boeckmann, Glaeser+ (ARGUS Collab.)
LURZ 87 ZPHY C36 383 +Antreasyan, Besset+ (Crystal Ball Collab.)
BARU 86B ZPHY C32 662 +Blinov, Bondar, Bukin+ (NOVO)
ALBRECHT 85 ZPHY C28 45 +Dreschell, Heller+ (ARGUS Collab.)
ALBRECHT 85E PL 160B 331 +Drescher, Heller+ (ARGUS Collab.)
GELPHMAN 85 PR D11 2893 +Lurz, Antreasyan+ (Crystal Ball Collab.)
KURAEV 85 SJNP 41 466 +Fadin (ASCI)
Translated from YAF 41 733.
NERNST 85 PRL 54 2195 +Antreasyan, Aschman+ (Crystal Ball Collab.)
ARTAMONOV 84 PL 137B 272 +Baru, Blinov, Bondar+ (NOVO)
BARBER 84 PL 135B 498 + (DESY, ARGUS Collab., Crystal Ball Collab.)
BESSON 84 PR D30 1433 +Green, Hicks, Namjoshi, Sannes+ (CLEO Collab.)
FONSECA 84 NP B242 31 +Mageras, Son, Dietl, Eigen+ (CUSB Collab.)
GILES 84B PR D29 1285 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)
HAAS 84 PRL 52 799 +Jensen, Kagan, Kass, Behrends+ (CLEO Collab.)
HAAS 84B PR D30 1996 +Jensen, Kagan, Kass, Behrends+ (CLEO Collab.)
KLOPFEN... 83 PRL 51 160 Klopfenstein, Horstkotte+ (CUSB Collab.)
TUTS 83 Cornell Conf. 284 (CUSB Collab.)
ALBRECHT 82 PL 116B 383 +Hofmann+ (DESY, DORT, HEID, LUND, ITEP)
NICZYPORUK 81B PL 100B 95 +Chen, Folger, Lurz+ (LENA Collab.)
NICZYPORUK 81C PL 99B 169 +Chen, Vogel, Wegener+ (LENA Collab.)
BOCK 80 ZPHY C6 125 +Blanar, Blum+ (HEID, MPIM, DESY, HAMB)

OTHER RELATED PAPERS

ALEXANDER 89 NP B320 45 +Bonvicini, Drell, Frey, Luth (LBL, MICH, SLAC)
COOPER 86 Berkeley Conf. 67 (MIT)
WALK 86 PR D34 2611 +Zschorsch+ (Crystal Ball Collab.)
ALBRECHT 84 PL 134B 137 +Drescher, Heller+ (ARGUS Collab.)
ARTAMONOV 84 PL 137B 272 +Baru, Blinov, Bondar+ (NOVO)
ANDREWS 83 PRL 50 807 +Avery, Berkelman, Cassel+ (CLEO Collab.)
GREEN 82 PRL 49 617 +Sannes, Skubic, Snyder+ (CLEO Collab.)
MAGERAS 81 PRL 46 1115 +Bohringer, Finocchiaro+ (COLU, STON, LSU, MPIM)
MUELLER 81 PRL 46 1181 + (RUTG, SYRA, LEMO, VAND, CORN, ITHA+)
ANDREWS 80 PRL 44 1108 +Berkelman, Billing, Cabenda+ (CLEO Collab.)
ARESTOV 80 IHEP 80-165 +Bogoljubski+ (SERP)
BOHRINGER 80 PRL 44 1111 +Costantini, Finocchiaro (COLU, STON)
KOURKOU... 80 PL 91B 481 Kourkoumelis+ (ATHU, NTUA, BNL, CERN+)
UENO 79 PRL 42 486 +Brown, Herb, Hom, Fisk+ (FNAL, COLU, STON)
BIENLEIN 78 PL 78B 360 +Glawe, Bock, Blanar+ (DESY, HAMB, HEID, MPIM)
DARDEN 78 PL 76B 246 +Hofmann, Schubert+ (DESY, DORT, HEID, LUND)
KAPLAN 78 PRL 40 435 +Appel, Herb, Hom+ (STON, FNAL, COLU)
YOH 78 PRL 41 684 +Herb, Hom, Lederman+ (COLU, FNAL, STON)
COBB 77 PL 72B 273 +Iwata, Fabjan+ (BNL, CERN, SYRA, YALE)
HERB 77 PRL 39 252 +Hom, Lederman, Appel, Ito+ (COLU, FNAL, STON)
INNES 77 PRL 39 1240 +Appel, Brown, Herb, Hom+ (COLU, FNAL, STON)

$\chi_{b0}(2P)$
or $\chi_{b0}(10235)$

$I^G(J^{PC}) = ?^?(0 \text{ preferred}^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(2P)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.2353±0.0011 OUR AVERAGE			
10.2353±0.0016	[1] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$
10.2352±0.0016	[1] LEE-FRANZINI 87	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[1] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 MeV.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
119.3±1.1 OUR AVERAGE			
119.3±1.6	LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$
119.4±1.6	LEE-FRANZINI 87	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\chi_{b0}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(7 ±4) %
Γ_2	$\gamma\Upsilon(1S)$	(1.4±1.0) %

$\chi_{b0}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.069±0.041	[2] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma\gamma\ell^+\ell^-$

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.014±0.010	[2] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma\gamma\ell^+\ell^-$

[2] Using $B(\Upsilon(3S) \to \chi_{b0}(2P)\gamma) = 0.048 \pm 0.014$.

$\chi_{b0}(2P)$ REFERENCES

LEE-FRANZINI 87 Hamburg Conf. 139 (CUSB Collab.)

OTHER RELATED PAPERS

TUTS 83 Cornell Conf. 284 (CUSB Collab.)
EIGEN 82 PRL 49 1616 +Bohringer, Herb+ (CUSB Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)

$\chi_{b1}(2P)$
or $\chi_{b1}(10255)$

$I^G(J^{PC}) = ?^?(1 \text{ preferred}^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b1}(2P)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.2552±0.0004 OUR AVERAGE	Error includes scale factor of 1.2.		
10.2556±0.0005	[1] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$
10.2548±0.00045	[1] LEE-FRANZINI 87	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[1] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 MeV.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
99.6±0.4 OUR AVERAGE	Error includes scale factor of 1.2.		
99.2±0.5	LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$
100.0±0.45	LEE-FRANZINI 87	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\chi_{b1}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(25 ±8) %
Γ_2	$\gamma\Upsilon(1S)$	(6.1±1.7) %

$\chi_{b1}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.247±0.083	[2] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma\gamma\ell^+\ell^-$

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.061±0.017	[2] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma\gamma\ell^+\ell^-$

[2] Using $B(\Upsilon(3S) \to \chi_{b1}(2P)\gamma)=0.120 \pm 0.026$.

$\chi_{b1}(2P)$ REFERENCES

LEE-FRANZINI 87 Hamburg Conf. 139 (CUSB Collab.)

OTHER RELATED PAPERS

TUTS 83 Cornell Conf. 284 (CUSB Collab.)
EIGEN 82 PRL 49 1616 +Bohringer, Herb+ (CUSB Collab.)
HAN 82 PRL 49 1612 +Horstkotte, Imlay+ (CUSB Collab.)

$\chi_{b2}(2P)$
or $\chi_{b2}(10270)$

$I^G(J^{PC}) = ?^?(2 \text{ preferred}^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b2}(2P)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.2690±0.0007 OUR AVERAGE	Error includes scale factor of 2.2.		
10.2682±0.0005	[1] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$
10.2697±0.00045	[1] LEE-FRANZINI 87	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[1] From γ energy below, assuming $\Upsilon(3S)$ mass = 10355.5 MeV.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
85.9±0.7 OUR AVERAGE	Error includes scale factor of 2.1.		
86.7±0.5	LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$
85.3±0.45	LEE-FRANZINI 87	CUSB	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\chi_{b2}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(19 ±7) %
Γ_2	$\gamma\Upsilon(1S)$	(6.3±1.8) %

$\chi_{b2}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(2S))/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.189±0.065	[2] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma\gamma\ell^+\ell^-$

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.063±0.018	[2] LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma\gamma\ell^+\ell^-$

[2] Using $B(\Upsilon(3S) \to \chi_{b2}(2P)\gamma)$=0.128 ± 0.029

$\chi_{b2}(2P)$ REFERENCES

LEE-FRANZINI	87	Hamburg Conf. 139	(CUSB Collab.)

OTHER RELATED PAPERS

TUTS	83	Cornell Conf. 284		(CUSB Collab.)
EIGEN	82	PRL 49 1616	+Bohringer, Herb+	(CUSB Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)

$\Upsilon(3S)$
or $\Upsilon(10355)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(3S)$ MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
10.3553±0.0005	[1] BARU 86B	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(3S)$ WIDTH

VALUE (keV)	*DOCUMENT ID*
24.3±2.9 OUR EVALUATION	See Υ mini-review.

$\Upsilon(3S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Upsilon(2S)$ anything	(10.1 ±1.7) %
Γ_2	$\Upsilon(2S)\pi^+\pi^-$	(2.2 ±0.5) %
Γ_3	$\Upsilon(1S)\pi^+\pi^-$	(3.63±0.31) %
Γ_4	$\mu^+\mu^-$	(1.81±0.17) %
Γ_5	e^+e^-	(1.81±0.25) %
	Radiative decays	
Γ_6	$\gamma\chi_{b2}(2P)$	(12.8 ±2.9) %
Γ_7	$\gamma\chi_{b1}(2P)$	(12.0 ±2.6) %
Γ_8	$\gamma\chi_{b0}(2P)$	(4.8 ±1.4) %

$\Upsilon(3S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_0\Gamma_5/\Gamma$

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.415±0.030 OUR AVERAGE	Error includes scale factor of 1.1.		
0.45 ±0.03 ±0.03	[2] GILES 84B	CLEO	$e^+e^- \to$ hadrons
0.39 ±0.02 ±0.03	[2] TUTS 83	CUSB	$e^+e^- \to$ hadrons

[2] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

$\Upsilon(3S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_5

VALUE (keV)	*DOCUMENT ID*
0.44±0.03 OUR EVALUATION	$e^+e^- \to$ hadrons. See Υ mini-review.

$\Upsilon(3S)$ BRANCHING RATIOS

$\Gamma(\Upsilon(2S)\text{ anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.101±0.017	1.6k	BOWCOCK 87	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(2S)\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.022±0.005 OUR AVERAGE				
0.021±0.005	314	BOWCOCK 87	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
0.031±0.020	5	MAGERAS 82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0363±0.0031 OUR AVERAGE				
0.0347±0.0034	3.9k	BOWCOCK 87	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
0.049 ±0.010	22	GREEN 82	CLEO	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.039 ±0.013	26	MAGERAS 82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.0181±0.0017 OUR AVERAGE				
0.0202±0.0019±0.0033		CHEN 89B	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0173±0.0015±0.0011		KAARSBERG 89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.033 ±0.013 ±0.007	1096	ANDREWS 83	CLEO	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\gamma\chi_{b2}(2P))/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.128±0.012±0.026	LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b1}(2P))/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.120±0.011±0.024	LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b0}(2P))/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.048±0.010±0.010	LEE-FRANZINI 87	CUSB	$e^+e^- \to \gamma X$

$\Upsilon(3S)$ REFERENCES

CHEN	89B	PR D39 3528	+McIlwain, Miller+	(CLEO Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412 Buchmueller, Cooper Editors: A. Ali and P. Soeding, World Scientific, Singapore		(HANN, MIT)
BOWCOCK	87	PRL 58 307	+Giles, Hassard, Kinoshita+	(CLEO Collab.)
LEE-FRANZINI	87	Hamburg Conf. 139		(CUSB Collab.)
BARU	86B	ZPHY C32 662	+Blinov, Bondar, Bukin+	(NOVO)
KURAEV	85	SJNP 41 466 Translated from YAF 41 733.	+Fadin	(ASCI)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
GREEN	82	PRL 49 617	+Sannes, Skubic, Snyder+	(CLEO Collab.)
MAGERAS	82	PL 118B 453	+Herb, Imlay+	(COLU, CORN, LSU, MPIM, STON)

OTHER RELATED PAPERS

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)
PETERSON	82	PL 114B 277	+Giannini, Lee-Franzini+	(CUSB Collab.)
ANDREWS	80	PRL 44 1108	+Berkelman, Billing, Cabenda+	(CLEO Collab.)
BOHRINGER	80	PRL 44 1111	+Costantini, Finocchiaro	(COLU, STON)
UENO	79	PRL 42 486	+Brown, Herb, Hom, Fisk+	(FNAL, COLU, STON)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\Upsilon(4S)$ or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(4S)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.5800±0.0035	[1] BEBEK	87	CLEO	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.5774±0.0010	[2] LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

[1] Reanalysis of BESSON 85.

[2] No systematic error given.

$\Upsilon(4S)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
23.8±2.2 OUR AVERAGE				
20.0±2 ±4	BESSON	85	CLEO	$e^+e^- \to$ hadrons
25 ±2.5	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(4S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.01\pm0.21)\times10^{-5}$

$\Upsilon(4S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.24 ±0.05 OUR AVERAGE	Error includes scale factor of 1.7.			
0.192±0.007±0.038	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.283±0.037	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(4S)$ REFERENCES

BEBEK	87	PR D36 1289	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

OTHER RELATED PAPERS

ANDREWS	80B	PRL 45 219	+Berkelman, Cabenda, Cassel+	(CLEO Collab.)
FINOCCHI...	80	PRL 45 222	Finocchiaro, Giannini, Lee-Franzini+	(CUSB Collab.)

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(10860)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.865±0.008 OUR AVERAGE	Error includes scale factor of 1.1.			
10.868±0.006±0.005	BESSON	85	CLEO	$e^+e^- \to$ hadrons
10.845±0.020	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(10860)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
110 ±13 OUR AVERAGE				
112.0±17 ±23	BESSON	85	CLEO	$e^+e^- \to$ hadrons
110.0±15.0	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(10860)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(2.8\pm0.7)\times10^{-6}$

$\Upsilon(10860)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.31 ±0.07 OUR AVERAGE	Error includes scale factor of 1.3.			
0.22 ±0.05 ±0.07	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.365±0.070	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(10860)$ REFERENCES

BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(11020)$ MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
11.019±0.008 OUR AVERAGE				
11.019±0.005±0.007	BESSON	85	CLEO	$e^+e^- \to$ hadrons
11.020±0.030	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(11020)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
79 ±16 OUR AVERAGE				
61.0±13 ±22	BESSON	85	CLEO	$e^+e^- \to$ hadrons
90.0±20.0	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(11020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.6\pm0.5)\times10^{-6}$

$\Upsilon(11020)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.130±0.030 OUR AVERAGE				
0.095±0.03 ±0.035	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.156±0.040	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(11020)$ REFERENCES

BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

NON-$q\overline{q}$ CANDIDATES

We include here mini-reviews and reference lists on non-$q\overline{q}$ candidates. These are divided into two subsections:
1) Gluonium candidates, and
2) Other non-$q\overline{q}$ candidates: $q\overline{q}q\overline{q}$ and $q\overline{q}g$ hybrids.
See also $N\overline{N}$(1100–3600) for possible bound states.

NOTE ON NON-$q\overline{q}$ MESONS

The existence of a gluon self coupling in QCD suggests that in addition to the conventional $q\overline{q}$ meson states, there may be bound states including gluons: gluonia or glueballs, and hybrids ($q\overline{q}g$). Another example of non-$q\overline{q}$ mesons could be multiquark states. For detailed reviews see, e.g., CLOSE 87, COOPER 86, MESHKOV 86, HEUSCH 86, TOKI 88.

The theoretical guidance on the properties of unusual states is often contradictory, and models which agree in the $q\overline{q}$ sector often differ in their predictions about new states. Among the naively expected signatures for gluonium are:

(i) no place in $q\overline{q}$ nonets,
(ii) flavor-singlet couplings,
(iii) enhanced production in gluon-rich channels such as $J/\psi(1S)$ decay,
(iv) reduced $\gamma\gamma$ coupling,
(v) exotic quantum numbers not allowed for $q\overline{q}$ (in some cases).

However it must be pointed out that mixing effects and other dynamical effects will obscure these simple signatures. If the mixing is large, only counting the number of observed states remains a clear signal for non-exotic non-$q\overline{q}$ states.

For recent reviews on the $f_2(1720)$, see COOPER 86, MALLIK 87.

The three f_2 resonances between 2 and 2.4 GeV, have been observed in an OZI-rule-forbidden process $\pi p \to \phi\phi n$ (ETKIN 88). The OZI suppression has been used as a strong argument for favoring a gluonium interpretation of these states. The argument is, however, not fully compelling, since broad resonances, by unitarity, are expected to mix substantially, and therefore the OZI rule may not apply. Moreover, one of these resonances, the one closest to the $\phi\phi$ threshold, could possibly be interpreted as a $\phi\phi$ molecule (mesonium) candidate. A similar $\phi\phi$ mass spectrum is seen by ARMSTRONG 89B in the Ω spectrometer.

The DM2 and MARK-III collaborations see threshold $\phi\phi$ production but favor $J^P = 0^-$, not 2^+.

The ASTERIX collaboration (MAY 89) finds a 2^{++} resonance in $p\bar p$ P-wave annihilation at 1565 MeV in the $\pi^+\pi^-\pi^0$ final state which may be a 4-quark state since there is no natural place in the $q\bar q$ model.

Other exotic or non-$q\bar q$ candidates: An isovector $\phi\pi^0$ resonance at 1480 MeV has been reported by BITYUKOV 87 in $\pi^- p \to \phi\pi^0 n$ [see $\rho(1450)$]. Preliminary indications favor $J^{PC} = 1^{--}$, i.e. nonexotic, but the large OZI rule violating branching ratio $\phi\pi : \omega\pi$ seems peculiar for a $(u\bar u - d\bar d)$ $I = 1$ $q\bar q$ object, (although ACHASOV 88 shows that a two step process can violate the rule, and an identification with $\rho(1450)$ could still be possible). In addition the small coupling to the photon makes an identification with the $\rho(1450)$ difficult (CLEGG 88). Therefore a $qq\bar q\bar q$ interpretation comes to mind.

Another exotic candidate is the $\hat\rho(1405)$ (ALDE 88B, IDDIR 88) seen in one experiment under the $a_2(1320)$ in $\pi^- p \to \eta\pi^0 n$ with the exotic quantum numbers $J^{PC} = 1^{-+}$. See however TUAN 88 for a critical discussion. For another possible 1^{-+} candidate see the isosinglet $X(1910)$.

A narrow resonance has been reported at $\approx$ 3100 MeV (BOURQUIN 86, KEKELIDZE 90) in several ($\Lambda\bar p$ + pions) and ($\bar\Lambda p$ + pions) states. The observation of the doubly charged states ($\Lambda\bar p\pi^-$ and $\bar\Lambda p\pi^+$) implies $I \geq 3/2$, clearly outside the $q\bar q$ system. In addition, a narrow peak is observed at $\approx$ 3250 MeV in the "hidden strangeness" combinations containing a pair of baryon-antibaryon (KEKELIDZE 90). However all these observations need confirmation.

Gluonium Candidates

OMITTED FROM SUMMARY TABLE

GLUONIUM CANDIDATES REFERENCES

KEKELIDZE	90	Hadron 89 Conf.	+Aleev+	(BIS-2 Collab.)
ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, LPNP)
ARMSTRONG	89D	PL B227 186	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF)
MAY	89	PL B225 450	+Duch, Heel+	(ASTERIX Collab.)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ACHASOV	88	PL B207 199	+Kozhevnikov	(NOVO)
ALDE	88	PL B201 160	+Bellazini, Binon+	(SERP, BELG, LANL, LAPP, PISA)
ALDE	88B	PL B205 397	+Binon, Boutemeur+	(SERP, BELG, LANL, LAPP)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, TOKY)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, SMAS)
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
GOUNARIS	88	PL B213 541	+Neufeld	(CERN)
IDDIR	88	PL B205 564	+Le Yaouanc, Ono+	(LPTP, TOKY)
SLAUGHTER	88	MPL A3 1361		(LANL)
TOKI	88	AIP Conf.		(SLAC)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, TOKY)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
CHANOWITZ	87	PL B187 409		(LBL)
CLOSE	87	RPP 51 833		(RHEL)
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
GIDAL	87B	PRL 59 2016	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
MALLIK	87	SLAC-PUB-4238		(Mark III Collab.)
PARTRIDGE	87	Moriond XXII Conf.	Patridge	(SLAC)
SINHA	87	PR D35 952	+Okubo, Tuan	(ROCH, HAWA)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
AIHARA	86C	PRL 57 2500	+Alston-Garnjost+	(TPC-2γ Collab.)
AIHARA	86D	PRL 57 51	+Alston-Garnjost+	(TPC-2γ Collab.)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
ALDE	86B	PL B177 120	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
ALDE	86C	PL B182 105	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, TOKY, TSUK+)
ARMSTRONG	86D	Berkeley Conf. 7870		(CERN)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)
BRAMON	86B	ZPHY C32 467	+Casulleras	(BARC)
CHUNG	86	Berkeley Conf. 725		(BNL)
COOPER	86	Berkeley Conf. 67		(MIT)
EISNER	86	Berkeley Conf. 1211		(SLAC)
HEUSCH	86	Seewinkel Symposium on Multiparticle Dynamics		(SLAC)
LINDENBAUM	86	BNL 37412 preprint		(BNL)
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
MESHKOV	86	Aspen Winter Conf.		(NBS)
AUGUSTIN	85	Moriond XX 1 479	+Calcaterra, Cosme+	(ORSA, CLER, PADO, FRAS)
BALTRUSAIT...	85D	PR D32 566	Baltrusaitis, Coffman+	(CIT, UCSC, ILL, SLAC, WASH)
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, SMAS)
COOPER	85	Bari Conf. 947		(SLAC)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	85	PL 165B 202	+Longacre	(BNL)
LINDENBAUM	85B	BNL 36610 preprint	+Longacre	(BNL)
RYBICKI	85	ZPHY C28 65	+Sakrejda	(CRAC)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN)
AU	84	PL 167B 229	+Morgan, Pennington	(RL)
BINON	84C	NC 80A 363	+Bricman, Donskov+	(BELG, LAPP, SERP, CERN)
DAUM	84	ZPHY C23 339	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
GERSHTEIN	84	ZPHY C24 305	+Likhoded, Prokoshkin	(SERP)
LINDENBAUM	84B	PL 149B 407	+Lipkin	(BNL, FNAL)
MORGAN	84	PL 137B 411	+Pennington	(RHEL, DURH)
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, LPNP, PAVI)
BAUBILLIER	83	ZPHY C17 309	+	(BIRM, CERN, GLAS, MSU, LPNP)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
ONO	83	ZPHY C21 109	+Pene	(AACH, ORSA)
TEPER	83	Brighton Conf. 4		(LAPP)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFT, VAND)
LIPKIN	82	PL 109B 326		(ANL)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)
DAUM	81D	PL 104B 246	+Bardsley+	(ACCMOR Collab.)
DONOGHUE	81	PL 99B 416	+Johnson, Li	(MIT)
LINDENBAUM	81	NC 65A 222		(BNL)
SCHARRE	81	Bonn Conf. 163		(SLAC)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)
JAFFE	80	PRL 34 1645	+Johnson	(MIT)
STANTON	79	PRL 42 346	+Brockman+	(OSU, CARL, MCGI, TNTO)
ROBSON	77	NP B130 328		(LIVP)
JAFFE	76	PL 60B 201	+Johnson	(MIT)
BAILLON	67	NC 50A 393	+Edwards, D'Andlau, Astier+	(CERN, CDEF, IRAD)

Other Non-$q\bar q$ Candidates

OMITTED FROM SUMMARY TABLE

OTHER NON-$q\bar q$ CANDIDATES REFERENCES

KEKELIDZE	90	Hadron 89 Conf.	+Aleev+	(BIS-2 Collab.)
ACHASOV	88B	ZPHY C41 309	+Shestakov	(NOVO)
SHOEMAKER	88	PR D37 1120	+Ko, Michael, Lander, Pellet+	(UCD)
BITYUKOV	87	PL B188 383	+Dzhelyadin, Dorofeev, Golovkin+	(SERP)
CHANOWITZ	87	PL B187 409		(LBL)
LIU	87	PRL 58 2288	+Kiu, Li	(STON)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BISELLO	86	PL B179 289	+Busetto, Castro, Limentani+	(DM2 Collab.)
BOURQUIN	86	PL B172 113	+Brown+	(GEVA, RAL, HEID, LAUS, BRIS, CERN)
BRIDGES	86	PRL 56 211	+Brown+	(BLSU, BNL, CASE, COLU, UMD, SYRA)
BRIDGES	86B	PRL 56 215	+Daftari, Kalogeropoulos, Debbe+	(SYRA, CASE)
BRIDGES	86C	PRL 57 1534	+Daftari, Kalogeropoulos+	(SYRA)
ACHASOV	85	ZPHY C27 99	+Devyanin, Shestakov	(NOVO)
DOVER	84	PL 146B 103		(ORSA)
JENKINS	84	PR D30 1409	+Diamond, Kirsch+	(FSU, BRAN, BNL, CINC, SMAS)
KITAZOE	84	ZPHY C24 143	+Wada, Kaburagi, Kawaguchi, Mori+	(KOBE, MIT)
ONO	84	ZPHY C26 307		(ORSA)
AGUILAR ...	81C	ZPHY C6 109	Aguilar-Benitez+	(CERN, CDEF, MADR, STOH)
APEL	81	NP B193 269	+Augenstein, Bertolucci, Donskov+	(SERP, CERN)
BIONTA	81	PRL 46 970	+Carroll, Edelstein+	(BNL, CMU, FNAL, SMAS)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
FRAME	81	PL 107B 301	+Hughes, Colley, Armstrong+	(GLAS, BIRM, CERN)
IRVING	81B	NP B193 1	+Loverre+	(CERN, CDEF, MADR, STOH)
KOOIJMAN	80	PRL 45 316	+Arenton, Ayres, Diebold, May+	(ANL, EFI)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ALAM	78	PRL 40 1685	+Baggett, Baglin+	(IND, PURD, SLAC, VAND)
ARMSTRONG	78	PL 77B 447	+Frame, Hughes, Bienlein+	(GLAS, DESY)
HOLMGREN	78	PL 77B 304	+Pennington	(STOH, CERN)
BOUCROT	77	NP B121 251	+Navach, Rivet+	(LALO, CERN, CDEF, EPOL)
HOOGLAND	77	NP B126 109	+Grayer, Hyams, Blum, Dietl+	(AMST, CERN, MPIM)
MOSER	77	NP B129 28		(EFI)
BRUNDIERS	76	PL 64B 107	+Brun, Fluri+	(FREI, SACL, ETH)
BALTAY	75B	PL 57B 293	+Cautis, Cohen, Kalelkar, Pisello+	(COLU, BING)
DAVIS	75B	NP B96 426	+Ammar, Kropac, Yarger+	(KANS, CCAC, ANL)
ALAM	74	PL 53B 207	+Brabson, Galloway+	(IND, PURD, SLAC, VAND)
COHEN	74	Boston Conf. 79		(COLU)

OREN 74 NP B71 189 +Cooper, Fields, Rhines, Allison+ (ANL, OXF)
COHEN 73B NP B53 1 +Ferbel, Slattery, Werner (ROCH)
DURUSOY 73 PL 45B 517 +Baubillier, George, Armenise+ (LPNP, BARI)
FAIMAN 73 PL 43B 307 +Goldhaber, Zarmi (CERN)
LIPKIN 73 PR D7 2262 (ANL, FNAL)
BUHL 72 NP B37 421 +Cline, Terrell (WISC)
CHO 70B PL 32B 409 +Derrick, Johnson, Musgrave+ (ANL, NWES, KANS)
GIACOMELLI 70 PL 33B 373 + (BGNA, SACL, AMST, REHO, EPOL)
LYS 70 PR D2 2525 + (MICH)
ROSNER 70 Exp. Meson Spectroscopy 499
DODD 69 PR 177 1991 +Joldersma, Palmer, Samios (BNL)
ROSENFELD 68 Phil. Conf. 455 (LRL)
ROSNER 68 PRL 21 950,1468 (TELA)

HEAVY QUARK SEARCHES

Searches for Top and Fourth Generation Hadrons

Experiments at e^+e^- colliders search for both top-flavored hadrons and vector toponium states, whereas experiments at $p\overline{p}$ colliders search only for top-flavored hadrons. Theoretical uncertainties are relatively small in e^+e^- collisions although details of the production cross section at threshold are not known, but uncertainties in $p\overline{p}$ collisions are somewhat larger due to our present ignorance of the details of the parton distributions in a proton and (to a lesser extent) of higher-order QCD corrections. Current $p\overline{p}$ collider experiments have limits which depend on the assumption that no two-body mode such as $t \rightarrow bH^+$ is available.

MASS LIMITS for Top Hadrons in e^+e^- Collisions

The last column specifies measured quantities: S = Sphericity, T = Thrust.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.8	95	[1] DECAMP	90F	ALEP	isolated charged particle and aplanarity
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>30.2	95	ABE	90D	VNS	Event shape
>44.5	95	[2] AKRAWY	90B	OPAL	Acoplanarity
>40.7	95	[3] ABRAMS	89C	MRK2	Event shape
>42.5	95	ABRAMS	89C	MRK2	$t \rightarrow bH^+$, $H^+ \rightarrow c\overline{s}$
>29.9	95	[4] ADACHI	89C	TOPZ	μ
>29.9	95	[5] ENO	89	AMY	μ, e
>25.8	95	[6] ADACHI	88	TOPZ	R, T, Acoplanarity
>25.9	95	[7] IGARASHI	88	AMY	$T + (\mu,e)$
>25.9	95	[8] SAGAWA	88	AMY	R, T
none E_{cm}=50	95	[9] ABE	87	VNS	R, T, Acoplanarity
>25.5	95	[10] YOSHIDA	87	VNS	R, T, Acoplanarity
none E_{cm} = 39.79–46.78	95	[11] ADEVA	86	MRKJ	R, T, μ
none E_{cm} = 40–46.78	95	[12] ADEVA	85	MRKJ	μ
none E_{cm} = 39.8–45.2		[13] ALTHOFF	84C	TASS	R, event shape
none E_{cm} = 12.–43.		[14] ALTHOFF	84I	TASS	Aplanarity
none E_{cm} = 33–36.72	95	[15] BEHREND	84D	CELL	Aplanarity
none E_{cm} = 38.66–46.78	95	[15] BEHREND	84D	CELL	Aplanarity
none E_{cm} < 38.54	99	[16] ADEVA	83	MRKJ	R, T, $(\mu^+\mu^- X)$
none E_{cm} < 38		ADEVA	83B	MRKJ	$p_T(\mu)$, T
none E_{cm} = 14–36.7		[17] BRANDELIK	82	TASS	R
none E_{cm} = 33–35.8		[18] BARTEL	81	JADE	μ
none E_{cm} = 30–36		[19] BARBER	80	MRKJ	R, T, μ
none E_{cm} = 12–31.6		[20] BERGER	80	PLUT	μ
none E_{cm} = 31.6		[21] BARBER	79	MRKJ	R, S, T
none E_{cm} = 22–31.6		[22] BARTEL	79	JADE	R
none E_{cm} = 22–31.6		[23] BARTEL	79B	JADE	S
none E_{cm} = 22–31.6		[24] BERGER	79B	PLUT	R, S, T, μ

[1] DECAMP 90F search was near the Z peak at LEP.

[2] AKRAWY 90B search was restricted to data near the Z peak at $\sqrt{s}$ = 91.26 GeV at LEP. The excluded region is between 23.4 and 44.5 GeV if no H^+ decays exist. A charged Higgs decay shrinks the excluded region by increasing 23.4 GeV to $(m(H^+) + 5$ GeV$)$.

[3] The ABRAMS 89C limit from an isolated track search is 40.0 GeV.

[4] ADACHI 89C search was at $\sqrt{s}$ = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.

[5] ENO 89 search at $\sqrt{s}$ = 50–60.8 GeV at TRISTAN.

[6] ADACHI 88 set limit σ(top) < 8.2 pb at CL=95% for top-flavored-hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark-parton model cross-section formula with first-order QCD corrections near the threshold, the above limit leads to a lower mass limit of 25.8 GeV at 95% confidence level for top quarks.

[7] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(t)$ < 0.15 (95% CL) at $\sqrt{s}$ = 50–52 GeV.

[8] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 25.9 GeV for charge 2/3 quarks.

[9] ABE 87 set limit σ(top) < 16 pb at CL=95% for top-flavored hadron production, which should be compared with the full top-quark production cross section of 45.9 pb.

[10] YOSHIDA 87 set limit σ(top) < 17 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. This limit should be compared with the full top-quark production cross section of 34 pb, which takes into account the effect of weak neutral current but neglects its axial-vector coupling contribution expected to be suppressed near threshold. After considering the radiative effects, top quarks of mass below 25.5 GeV can be excluded by the above limit.

[11] ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section, ΔR, as a function of the minimum c.m. energy (see their figure 3). An increase of the hadronic cross section predicted for full top-quark production ($\Delta R_{top} \sim 1.5$) is then excluded up to E_{cm} = 46.6 GeV. Toponium search sets limit $\Gamma(e^+e^-)$B(hadrons) < 3 keV at CL=95% at E_{cm} = 44–46 GeV. Also reported is an observation of eight low-thrust hadron events containing muons, which remains unexplained.

[12] ADEVA 85 exclude toponium below 46.6 GeV and open top continuum below 23.3 GeV at CL = 95%. Toponium search sets limit $\Gamma(e^+e^-)$B(hadrons) <3 keV.

[13] ALTHOFF 84C narrow state search sets limit $\Gamma(e^+e^-)$B(hadrons) <2.4 keV CL = 95% and heavy charge 2/3 quark pair production m > 22 GeV, CL = 95%.

[14] ALTHOFF 84I exclude heavy quark pair production for masses in GeV 5 <m <20.3 (2/3 charge) using aplanarity distributions (CL = 95%).

[15] BEHREND 84D exclude toponium below 46.7 GeV and continuum production below 23.3 GeV (2/3 charge) and 22.7 GeV (1/3 charge) at CL = 90%. Toponium search sets limit $\Gamma(e^+e^-)$B(hadrons) <2.9 keV where toponium is expected to have $\Gamma(e^+e^-)$ = 4–5 keV.

[16] ADEVA 83 energy scan excludes open top continuum below 38.54 GeV and toponium between 29.90 and 38.63 GeV $\Gamma(e^+e^-)$B(hadrons) <2.0 keV at CL = 95%). Also set limit B($B \rightarrow \mu^+\mu^- X$) <0.007 (CL = 95%) which excludes flavor-changing neutral current in topless models.

[17] BRANDELIK 82 got $R = 4.01 \pm 0.03 \pm 0.2$ with no step for W >14 GeV. Narrow state search for W = 33–36.7 GeV sets $\Gamma(e^+e^-)$B(hadrons) <1.5 keV (CL = 95%).

[18] BARTEL 81 measures inclusive muons with momentum >1.4 GeV/c. Agree with expected semileptonic decays from charmed and bottom mesons.

[19] BARBER 80 find no evidence for an open top-antitop threshold in R, thrust distributions and inclusive muons. Energy scan in the range 29.9 < E_{cm} <31.6 GeV reveals no hadron resonance corresponding to a (top-quark antitop-quark) bound state.

[20] BERGER 80 measures inclusive muons with momentum >2 GeV/c. Agree with expected semileptonic decays from charmed and bottom mesons.

[21] BARBER 79 R, thrust, spherocity indicate top production unlikely.

[22] BARTEL 79 saw no evidence of new Q = 2/3 quark production in R-ratio.

[23] BARTEL 79B observe no significant accumulation of spherical events.

[24] BERGER 79B find R = 3.88+0.22 which along with sphericity and thrust behaviors is against open top-antitop channel below 30 GeV. Final muons are also consistent with expectation without top-quark state.

MASS LIMITS for Top Hadrons in $p\overline{p}$ Collisions

These experiments assume that no two-body mode such as $t \rightarrow bH^+$ is available.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>77	95	[25] ABE	90C	CDF	e + jets + missing E_T
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>72	95	[26] ABE	90B	CDF	$e + \mu$
>69	95	[27] AKESSON	90	UA2	e + jets + missing E_T
>41	95	[28] ALBAJAR	88	UA1	e or μ + jets

[25] ABE 90C cannot exclude $m(t)$ < 40 GeV, but this region is ruled out by other experiments. They study events with an energetic electron, missing transverse energy and two or more jets. Only the $t\overline{t}$ contribution (not $W \rightarrow tb$) is relevant for these masses.

[26] ABE 90B exclude the region 28–72 GeV.

[27] AKESSON 90 searched for events having an electron with p_T > 12 GeV, missing momentum > 15 GeV, and a jet with E_T > 10 GeV, $|\eta|$ < 2.2, and excluded $m(t)$ between 30 and 69 GeV.

[28] ALBAJAR 88 study events at E_{cm} = 546 and 630 GeV with a muon or isolated electron, accompanied by one or more jets and find agreement with Monte Carlo predictions for the production of charm and bottom, without the need for a new quark. The top-quark mass bound is obtained by using the $W \rightarrow t\overline{b}$ cross section normalized to their own $W \rightarrow \ell\overline{\nu}$ rate and by adding to it the $t\overline{t}$ contribution with a conservative value of the cross section with the lowest-order calculation. The analysis is not sensitive to the $W \rightarrow t\overline{b}$ process alone. The value quoted here is revised using the full $O(\alpha_s^3)$ cross section of ALTARELLI 88.

MASS LIMITS for b' (Fourth Generation) Hadrons in e^+e^- Collisions

Search for hadrons containing a fourth-generation −1/3 quark denoted b'.

The last column specifies the assumption for the decay mode (CC denotes the conventional charged-current decay) and the event signature which is looked for.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>46.0	95	[29] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 19.4–28.2	95	ABE	90D	VNS	Any decay; event shape
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[30] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[30] AKRAWY	90B	OPAL	B(CC) = 1; acoplanarity
>27.5	95	[31] ABE	89E	VNS	B(CC) =1; μ, e
none 11.4–27.3	95	[32] ABE	89G	VNS	B($b' \rightarrow b\gamma$) > 10%; isolated γ
>44.7	95	[33] ABRAMS	89C	MRK2	B(CC)= 100%; isol. track
>42.7	95	[33] ABRAMS	89C	MRK2	B(bg)= 100%; event shape
>42.0	95	[33] ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[34,35] ADACHI	89C	TOPZ	B(CC) =1; μ
>28.8	95	[36] ENO	89	AMY	B(CC) $\gtrsim$ 90%; μ, e
>27.2	95	[36,37] ENO	89	AMY	any decay; event shape
>29.0	95	[36] ENO	89	AMY	B($b' \rightarrow bg$) $\gtrsim$ 85%; event shape

N BARYONS
$(S = 0, I = 1/2)$
$p, N^+ = uud$; $n, N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

p MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnote. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
938.27231±0.00028	[1] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
938.2796 ±0.0027	COHEN	73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = 1.007276470 \pm 0.000000012$ u.

$\overline{p}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
938.22 ±0.04 OUR AVERAGE				
938.30 ±0.13	ROBERTS	78	CNTR	
938.229±0.049	ROBERSON	77	CNTR	
938.179±0.058	HU	75	CNTR	Exotic atoms
938.3 ±0.5	BAMBERGER	70	CNTR	

p MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	*DOCUMENT ID*		*TECN*	*COMMENT*
2.792847386±0.000000063	COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.7928456 ±0.0000011	COHEN	73	RVUE	1973 CODATA value

$\overline{p}$ MAGNETIC MOMENT

A few early results have been omitted.

VALUE (μ_N)	*DOCUMENT ID*		*TECN*	*COMMENT*
−2.800 ±0.008 OUR AVERAGE				
−2.8005±0.0090	KREISSL	88	CNTR	$\overline{p}\,^{208}$Pb 11→ 10 X-ray
−2.817 ±0.048	ROBERTS	78	CNTR	
−2.791 ±0.021	HU	75	CNTR	Exotic atoms

p ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-23} e-cm)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
− 3.7± 6.3		CHO	89	NMR	Tl F molecules
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 400		DZUBA	85	THEO	Uses ^{129}Xe moment
130 ± 200		[2] WILKENING	84		
900 ±1400		[3] WILKENING	84		
700 ± 900	1G	HARRISON	69	MBR	Molecular beam

[2] This WILKENING 84 value includes a finite-size effect and a magnetic effect.

[3] This WILKENING 84 value is more cautious than the other and excludes the finite-size effect, which relies on uncertain nuclear integrals.

$|q_p + q_e|$ CHARGE MAGNITUDE DIFFERENCE

See DYLLA 73 for a summary of experiments on the neutrality of matter. See also "*n* CHARGE" in the neutron Listings.

VALUE (10^{-21} e)	*DOCUMENT ID*		*COMMENT*
<1.0	[4] DYLLA	73	Neutrality of SF_6
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.8	MARINELLI	84	Magnetic levitation

[4] Assumes that $q_n = q_p + q_e$.

NOTE ON PROTON MEAN LIFE LIMITS

(by M. Goldhaber, Brookhaven National Laboratory, and F. Reines, University of California, Irvine)

Current ideas on the unification of the weak, electromagnetic, and strong forces suggest that baryon number might not be strictly conserved, so that the proton could decay. In the Particle Properties Summary Tables there are nearly thirty particles listed with a mass smaller than that of the proton (if we count both particles and antiparticles and different members of multiplets separately). Ten of these particles are fermions and the remainder bosons. There are then a great many possible two-body decay modes of the proton and an even larger number of three-body, etc., decay modes which satisfy charge, energy, momentum, and angular momentum conservation. Each decay mode has to contain at least one fermion to satisfy angular momentum conservation. Figure 1 shows masses of possible decay products of the proton.

The "decay signature" distributions as well as the backgrounds depend on detector characteristics (the material from which the detector is made, the method of detection, timing information, time resolution, etc.). The background, due chiefly to atmospheric neutrinos, depends also on the geomagnetic latitude and on the phase of the solar cycle with which the magnetic field of the sun is associated. The depth-dependent cosmic ray background is due to cosmic ray muons and their progeny. For each possible proton decay signature there is a finite probability of a background event with a similar signature, where the probability depends on the detector characteristics.

The simplest grand unified theory, minimal SU(5), predicts $e^+\pi^0$ to be the predominant proton decay mode; see Table I. The IMB lower limit on the partial mean life for this mode, 3.1×10^{32} years, is a factor of 40 higher than predicted by minimal SU(5) theory.

See also the reviews in Refs. 1–5.

See also the neutron-antineutron oscillations section in the neutron Full Listings below for another test of baryon conservation.

References

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2. D.H. Perkins, Ann. Rev. Nucl. Part. Sci. **34**, 1 (1984).
3. J.M. LoSecco, Comments Nucl. Part. Phys. **15**, 23 (1985).
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5. M. Goldhaber et al., in *Proceedings XXIII International Conference on High Energy Physics*, Berkeley, 1986, ed. S.C. Loken (World Scientific, Singapore, 1986), p. 248.

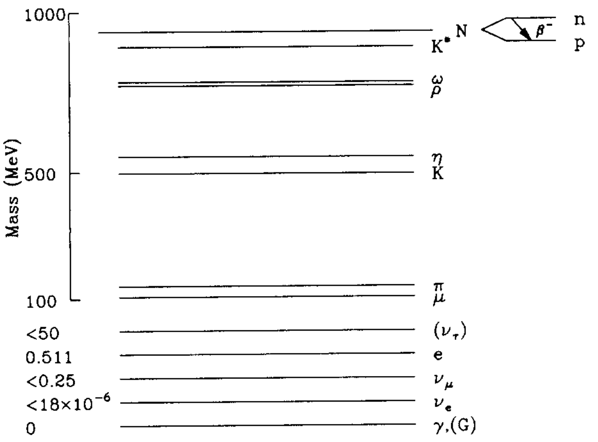

Figure 1. Masses of particles (in MeV) into which a proton might decay. The hypothetical graviton (G) is included.

Table I. Approximate ranges of the branching ratios

$$\mathrm{BR}(N \to \ell + M) = \frac{\Gamma(N \to \ell + M)}{\Gamma(N \to \text{2-body})}$$

for the two-body proton decay $p \to \ell + M$ in the minimal conventional SU(5) model. This table was taken from Ref. 4.

Decay mode	Branching ratio (%)
$p \to e^+\pi^0$	31–46
$p \to e^+\eta$	0–8
$p \to e^+\rho^0$	2–18
$p \to e^+\omega$	15–29
$p \to \nu_e\pi^+$	11–17
$p \to \nu_e\rho^+$	1–7
$p \to \mu^+K^0$	1–20
$p \to \nu_\mu K^+$	0–1

p MEAN LIFE

Test of baryon conservation. See proton partial mean lives section for limits which depend on decay modes. *p* = proton, *n* = bound neutron.

LIMIT (years)	PARTICLE	DOCUMENT ID		TECN
$>1.6 \times 10^{25}$	*p, n*	[5,6] EVANS	77	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>3. \times 10^{23}$	*p*	[6] DIX	70	CNTR
$>3. \times 10^{23}$	*p, n*	[6,7] FLEROV	58	

[5] Mean lifetime of nucleons in ^{130}Te nuclei.
[6] Converted to mean life by dividing half-life by ln(2) = 0.693.
[7] Mean lifetime of nucleons in ^{232}Th nuclei.

$\overline{p}$ MEAN LIFE

LIMIT (years)	PARTICLE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$>1.1 \times 10^{7}$				[8] GOLDEN	79	SPEC	$\overline{p} \to X$
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>0.08		90	1	[9] BELL	79	CNTR	$\overline{p} \to e^- \pi^0$
$>3.7 \times 10^{-3}$				[10] BREGMAN	78	CNTR	$\overline{p} \to X$

[8] GOLDEN 79 value inferred from $\overline{p}/p$ ratio in cosmic rays.
[9] BELL 79 stored antiprotons in ICE storage ring for 10 days.
[10] BREGMAN 78 stored antiprotons in ICE storage ring at CERN 85 hours.

p DECAY MODES

For *N* decays, *p* and *n* distinguish proton and neutron partial lifetimes.

	Mode	Partial mean life (10^{30} years)	Confidence level
τ_1	$N \to e^+$ anything	>0.6 (*n, p*)	90%
τ_2	$N \to \mu^+$ anything	>12 (*n, p*)	90%
τ_3	$N \to \nu$ anything		
τ_4	$N \to e^+\pi^0$ anything	>0.6 (*n, p*)	90%
τ_5	$N \to e^+\pi$	>130 (*n*), >310 (*p*)	90%
τ_6	$N \to \mu^+\pi$	>100 (*n*), >270 (*p*)	90%
τ_7	$N \to \nu\pi$	>100 (*n*), >25 (*p*)	90%
τ_8	$N \to e^+K$	>1.3 (*n*), >150 (*p*)	90%
τ_9	$N \to \mu^+K$	>1.1 (*n*), >120 (*p*)	90%
τ_{10}	$N \to \nu K$	>86 (*n*), >100 (*p*)	90%
τ_{11}	$N \to e^+\rho$	>58 (*n*), >75 (*p*)	90%
τ_{12}	$N \to \mu^+\rho$	>23 (*n*), >110 (*p*)	90%
τ_{13}	$N \to \nu\rho$	>19 (*n*), >27 (*p*)	90%
τ_{14}	$p \to e^+\omega$	>45	90%
τ_{15}	$p \to \mu^+\omega$	>57	90%
τ_{16}	$n \to \nu\omega$	>43	90%
τ_{17}	$p \to e^+\eta$	>140	90%
τ_{18}	$p \to \mu^+\eta$	>69	90%
τ_{19}	$n \to \nu\eta$	>54	90%
τ_{20}	$p \to e^+K^*(892)$	>52	90%
τ_{21}	$N \to \nu K^*(892)$	>22 (*n*), >20 (*p*)	90%
τ_{22}	$p \to e^+\gamma$	>460	90%
τ_{23}	$p \to e^+e^+e^-$	>510	90%
τ_{24}	$p \to \mu^+\gamma$	>380	90%
τ_{25}	$p \to \mu^+\mu^+\mu^-$	>190	90%
τ_{26}	$n \to \nu\gamma$	>9	90%
τ_{27}	$n \to e^+e^-\nu$	>45	90%
τ_{28}	$n \to \mu^+\mu^-\nu$	>16	90%
τ_{29}	$n \to 3\nu$	>0.0005	90%
τ_{30}	$p \to e^+\mu^+\mu^-$	>5.0	90%
τ_{31}	$p \to e^-\mu^+\mu^+$	>6.0	90%
τ_{32}	$p \to e^-\pi^+\pi^+$	>2.0	90%
τ_{33}	$p \to \mu^+\pi^+\pi^-$	>3.3	90%
τ_{34}	$p \to \mu^-\pi^+\pi^+$	>7.8	90%
τ_{35}	$n \to e^-\pi^+$	>65	90%
τ_{36}	$n \to \mu^-\pi^+$	>49	90%
τ_{37}	$n \to e^-K^+$	>0.23	90%
τ_{38}	$n \to \mu^-K^+$	>4.7	90%
τ_{39}	$n \to e^-\rho^+$	>62	90%
τ_{40}	$n \to \mu^-\rho^+$	>7	90%

p PARTIAL MEAN LIVES

Mean life divided by branching fraction.

Decaying particle — *p* = proton or *n* = bound neutron. Same event may appear under more than one partial decay mode. Background estimates may be accurate to a factor of 2.

$\tau(N \to e^+ \text{ anything})$ τ_1

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>0.6	*p, n*	90			[11] LEARNED	79	RVUE

[11] The electron may be primary or secondary.

$\tau(N \to \mu^+ \text{ anything})$ τ_2

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>12	*p, n*	90	2		[12,13] CHERRY	81	HOME
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 1.8	*p, n*	90			[13] COWSIK	80	CNTR
> 6	*p, n*	90			[13] LEARNED	79	RVUE

[12] We have converted 2 possible events to 90% CL limit.
[13] The muon may be primary or secondary.

$\tau(N \to \nu \text{ anything})$ τ_3

Anything = π, ρ, K, etc.

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>0.0002	*p, n*	90	0		LEARNED	79	RVUE

$\tau(N \to e^+\pi^0$ anything) τ_4

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>0.6	*p*, *n*	90	0		LEARNED	79	RVUE

$\tau(N \to e^+\pi)$ τ_5

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>130	*n*	90	0	<0.2	HIRATA	89C	KAMI
>310	*p*	90	0	0.6	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>260	*p*	90	0	<0.04	HIRATA	89C	KAMI
>100	*n*	90	0	1.6	SEIDEL	88	IMB
> 1.3	*n*	90	0		BARTELT	87	SOUD
> 1.3	*p*	90	0		BARTELT	87	SOUD
>250	*p*	90	0	0.3	HAINES	86	IMB
> 31	*n*	90	8	9	HAINES	86	IMB
> 64	*p*	90	0	<0.4	ARISAKA	85	KAMI
> 26	*n*	90	0	<0.7	ARISAKA	85	KAMI
> 82	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>250	*p*	90	0	0.2	BLEWITT	85	IMB
> 25	*n*	90	4	4	PARK	85	IMB
> 15	*p*, *n*	90	0		BATTISTONI	84	NUSX
> 0.5	*p*	90	1	0.3	[14] BARTELT	83	SOUD
> 0.5	*n*	90	1	0.3	[14] BARTELT	83	SOUD
> 5.8	*p*	90	2		[15] KRISHNA...	82	KOLR
> 5.8	*n*	90	2		[15] KRISHNA...	82	KOLR
> 0.1	*n*	90			[16] GURR	67	CNTR

[14] Limit based on zero events.

[15] We have calculated 90% CL limit from 1 confined event.

[16] We have converted half-life to 90% CL mean life.

$\tau(N \to$ 2 bodies, ν-free) $(\tau_5+\tau_6+\tau_8+\tau_9)$

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>1.3	*p*, *n*	90	0		ALEKSEEV	81	BAKS

$\tau(N \to \mu^+\pi)$ τ_6

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>100	*n*	90	0	<0.2	HIRATA	89C	KAMI
>270	*p*	90	0	0.5	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>230	*p*	90	0	<0.07	HIRATA	89C	KAMI
> 63	*n*	90	0	0.5	SEIDEL	88	IMB
> 76	*p*	90	2	1	HAINES	86	IMB
> 23	*n*	90	8	7	HAINES	86	IMB
> 46	*p*	90	0	<0.7	ARISAKA	85	KAMI
> 20	*n*	90	0	<0.4	ARISAKA	85	KAMI
> 59	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>100	*p*	90	1	0.4	BLEWITT	85	IMB
> 38	*n*	90	1	4	PARK	85	IMB
> 10	*p*, *n*	90	0		BATTISTONI	84	NUSX
> 1.3	*p*, *n*	90	0		ALEKSEEV	81	BAKS

$\tau(N \to \nu\pi)$ τ_7

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 25	*p*	90	32	32.8	HIRATA	89C	KAMI
>100	*n*	90	1	3	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 13	*n*	90	1	1.2	BERGER	89	FREJ
> 10	*p*	90	11	14	BERGER	89	FREJ
> 6	*n*	90	73	60	HAINES	86	IMB
> 2	*p*	90	16	13	KAJITA	86	KAMI
> 40	*n*	90	0	1	KAJITA	86	KAMI
> 7	*n*	90	28	19	PARK	85	IMB
> 7	*n*	90	0		BATTISTONI	84	NUSX
> 2	*p*	90	≤ 3		BATTISTONI	84	NUSX
> 5.8	*p*	90	1		[17] KRISHNA...	82	KOLR
> 0.3	*p*	90	2		[18] CHERRY	81	HOME
> 0.1	*p*	90			[19] GURR	67	CNTR

[17] We have calculated 90% CL limit from 1 confined event.

[18] We have converted 2 possible events to 90% CL limit.

[19] We have converted half-life to 90% CL mean life.

$\tau(N \to e^+K)$ τ_8

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>150	*p*	90	0	<0.27	HIRATA	89C	KAMI
> 1.3	*n*	90	0		ALEKSEEV	81	BAKS

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 70	*p*	90	0	1.8	SEIDEL	88	IMB
> 77	*p*	90	5	4.5	HAINES	86	IMB
> 38	*p*	90	0	<0.8	ARISAKA	85	KAMI
> 24	*p* (free)	90	7	8.5	BLEWITT	85	IMB
> 77	*p*	90	5	4	BLEWITT	85	IMB
> 1.3	*p*	90	0		ALEKSEEV	81	BAKS

$\tau(N \to \mu^+K)$ τ_9

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>120	*p*	90	1	0.4	HIRATA	89C	KAMI
> 1.1	*n*	90	0		BARTELT	87	SOUD

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 3.0	*p*	90	0	0.7	PHILLIPS	89	HPW
> 19	*p*	90	3	2.5	SEIDEL	88	IMB
> 1.5	*p*	90	0		[20] BARTELT	87	SOUD
> 40	*p*	90	7	6	HAINES	86	IMB
> 19	*p*	90	1	<1.1	ARISAKA	85	KAMI
> 6.7	*p* (free)	90	11	13	BLEWITT	85	IMB
> 40	*p*	90	7	8	BLEWITT	85	IMB
> 6	*p*	90	1		BATTISTONI	84	NUSX
> 0.6	*p*	90	0		[21] BARTELT	83	SOUD
> 0.4	*n*	90	0		[21] BARTELT	83	SOUD
> 5.8	*p*	90	2		[22] KRISHNA...	82	KOLR
> 2.0	*p*	90	0		CHERRY	81	HOME
> 0.2	*n*	90			[23] GURR	67	CNTR

[20] BARTELT 87 limit applies to $p \to \mu^+ K^0_S$.

[21] Limit based on zero events.

[22] We have calculated 90% CL limit from 1 confined event.

[23] We have converted half-life to 90% CL mean life.

$\tau(N \to \nu K)$ τ_{10}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>100	*p*	90	9	7.3	HIRATA	89C	KAMI
> 86	*n*	90	0	2.4	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 15	*n*	90	1	1.8	BERGER	89	FREJ
> 15	*p*	90	1	1.8	BERGER	89	FREJ
> 0.28	*p*	90	0	0.7	PHILLIPS	89	HPW
> 0.3	*p*	90	0		BARTELT	87	SOUD
> 0.75	*n*	90	0		[24] BARTELT	87	SOUD
> 10	*p*	90	6	5	HAINES	86	IMB
> 15	*n*	90	3	5	HAINES	86	IMB
> 28	*p*	90	3	3	KAJITA	86	KAMI
> 32	*n*	90	0	1.4	KAJITA	86	KAMI
> 1.8	*p* (free)	90	6	11	BLEWITT	85	IMB
> 9.6	*p*	90	6	5	BLEWITT	85	IMB
> 10	*n*	90	2	2	PARK	85	IMB
> 5	*n*	90	0		BATTISTONI	84	NUSX
> 2	*p*	90	0		BATTISTONI	84	NUSX
> 0.3	*n*	90	0		[25] BARTELT	83	SOUD
> 0.1	*p*	90	0		[25] BARTELT	83	SOUD
> 5.8	*p*	90	1		[26] KRISHNA...	82	KOLR
> 0.3	*n*	90	2		[27] CHERRY	81	HOME

[24] BARTELT 87 limit applies to $n \to \nu K^0_S$.

[25] Limit based on zero events.

[26] We have calculated 90% CL limit from 1 confined event.

[27] We have converted 2 possible events to 90% CL limit.

$\tau(N \to e^+\rho)$ τ_{11}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>75	*p*	90	2	2.7	HIRATA	89C	KAMI
>58	*n*	90	0	1.9	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>38	*n*	90	2	4.1	SEIDEL	88	IMB
> 1.2	*p*	90	0		BARTELT	87	SOUD
> 1.5	*n*	90	0		BARTELT	87	SOUD
>17	*p*	90	7	7	HAINES	86	IMB
>14	*n*	90	9	4	HAINES	86	IMB
>12	*p*	90	0	<1.2	ARISAKA	85	KAMI
> 6	*n*	90	2	<1	ARISAKA	85	KAMI
> 6.7	*p* (free)	90	6	6	BLEWITT	85	IMB
>17	*p*	90	7	7	BLEWITT	85	IMB
>12	*n*	90	4	2	PARK	85	IMB
> 0.6	*n*	90	1	0.3	[28] BARTELT	83	SOUD
> 0.5	*p*	90	1	0.3	[28] BARTELT	83	SOUD
> 9.8	*p*	90	1		[29] KRISHNA...	82	KOLR
> 0.8	*p*	90	2		[30] CHERRY	81	HOME

[28] Limit based on zero events.

[29] We have calculated 90% CL limit from 0 confined events.

[30] We have converted 2 possible events to 90% CL limit.

$\tau(N \to \mu^+\rho)$ τ_{12}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>110	*p*	90	0	1.7	HIRATA	89C	KAMI
> 23	*n*	90	1	1.8	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 4.3	p	90	0	0.7	PHILLIPS	89	HPW
> 30	p	90	0	0.5	SEIDEL	88	IMB
> 11	n	90	1	1.1	SEIDEL	88	IMB
> 16	p	90	4	4.5	HAINES	86	IMB
> 7	n	90	6	5	HAINES	86	IMB
> 12	p	90	0	<0.7	ARISAKA	85	KAMI
> 5	n	90	1	<1.2	ARISAKA	85	KAMI
> 5.5	p (free)	90	4	5	BLEWITT	85	IMB
> 16	p	90	4	5	BLEWITT	85	IMB
> 9	n	90	1	2	PARK	85	IMB

$\tau(N \to \nu\rho)$ τ_{13}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>27	p	**90**	**5**	**1.5**	HIRATA	89C	KAMI
>19	n	**90**	**0**	**0.5**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 9	n	90	4	2.4	BERGER	89	FREJ
>24	p	90	0	0.9	BERGER	89	FREJ
>13	n	90	4	3.6	HIRATA	89C	KAMI
>13	p	90	1	1.1	SEIDEL	88	IMB
> 8	p	90	6	5	HAINES	86	IMB
> 2	n	90	15	10	HAINES	86	IMB
>11	p	90	2	1	KAJITA	86	KAMI
> 4	n	90	2	2	KAJITA	86	KAMI
> 4.1	p (free)	90	6	7	BLEWITT	85	IMB
> 8.4	p	90	6	5	BLEWITT	85	IMB
> 2	n	90	7	3	PARK	85	IMB
> 0.9	p	90	2		[31] CHERRY	81	HOME
> 0.6	n	90	2		[31] CHERRY	81	HOME

[31] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+\omega)$ τ_{14}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>45	p	**90**	**2**	**1.45**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>26	p	90	1	1.0	SEIDEL	88	IMB
> 1.5	p	90	0		BARTELT	87	SOUD
>37	p	90	6	5.3	HAINES	86	IMB
>25	p	90	1	<1.4	ARISAKA	85	KAMI
>12	p (free)	90	6	7.5	BLEWITT	85	IMB
>37	p	90	6	5.7	BLEWITT	85	IMB
> 0.6	p	90	1	0.3	[32] BARTELT	83	SOUD
> 9.8	p	90	1		[33] KRISHNA...	82	KOLR
> 2.8	p	90	2		[34] CHERRY	81	HOME

[32] Limit based on zero events.

[33] We have calculated 90% CL limit from 0 confined events.

[34] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+\omega)$ τ_{15}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>57	p	**90**	**2**	**1.9**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 4.4	p	90	0	0.7	PHILLIPS	89	HPW
>10	p	90	2	1.3	SEIDEL	88	IMB
>23	p	90	2	1	HAINES	86	IMB
> 6.5	p (free)	90	9	8.7	BLEWITT	85	IMB
>23	p	90	8	7	BLEWITT	85	IMB

$\tau(n \to \nu\omega)$ τ_{16}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>43	n	**90**	**3**	**2.7**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>17	n	90	1	0.7	BERGER	89	FREJ
> 6	n	90	2	1.3	SEIDEL	88	IMB
>12	n	90	6	6	HAINES	86	IMB
>18	n	90	2	2	KAJITA	86	KAMI
>16	n	90	1	2	PARK	85	IMB
> 2.0	n	90	2		[35] CHERRY	81	HOME

[35] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+\eta)$ τ_{17}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>140	p	**90**	**0**	**<0.04**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>100	p	90	0	0.6	SEIDEL	88	IMB
>200	p	90	5	3.3	HAINES	86	IMB
> 64	p	90	0	<0.8	ARISAKA	85	KAMI
> 64	p (free)	90	5	6.5	BLEWITT	85	IMB
>200	p	90	5	4.7	BLEWITT	85	IMB
> 1.2	p	90	2		[36] CHERRY	81	HOME

[36] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+\eta)$ τ_{18}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>69	p	**90**	**1**	**<0.08**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 1.3	p	90	0	0.7	PHILLIPS	89	HPW
>34	p	90	1	1.5	SEIDEL	88	IMB
>46	p	90	7	6	HAINES	86	IMB
>26	p	90	1	<0.8	ARISAKA	85	KAMI
>17	p (free)	90	6	6	BLEWITT	85	IMB
>46	p	90	7	8	BLEWITT	85	IMB

$\tau(n \to \nu\eta)$ τ_{19}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>54	n	**90**	**2**	**0.9**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>29	n	90	0	0.9	BERGER	89	FREJ
>16	n	90	3	2.1	SEIDEL	88	IMB
>25	n	90	7	6	HAINES	86	IMB
>30	n	90	0	0.4	KAJITA	86	KAMI
>18	n	90	4	3	PARK	85	IMB
> 0.6	n	90	2		[37] CHERRY	81	HOME

[37] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+ K^*(892))$ τ_{20}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>52	p	**90**	**2**	**1.55**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>10	p	90	1	<1	ARISAKA	85	KAMI

$\tau(N \to \nu K^*(892))$ τ_{21}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>22	n	**90**	**0**	**2.1**	BERGER	89	FREJ
>20	p	**90**	**5**	**2.1**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>17	p	90	0	2.4	BERGER	89	FREJ
>21	n	90	4	2.4	HIRATA	89C	KAMI
>10	p	90	7	6	HAINES	86	IMB
> 5	n	90	8	7	HAINES	86	IMB
> 8	p	90	3	2	KAJITA	86	KAMI
> 6	n	90	2	1.6	KAJITA	86	KAMI
> 5.8	p (free)	90	10	16	BLEWITT	85	IMB
> 9.6	p	90	7	6	BLEWITT	85	IMB
> 7	n	90	1	4	PARK	85	IMB
> 2.1	p	90	1		[38] BATTISTONI	82	NUSX

[38] We have converted 1 possible event to 90% CL limit.

$\tau(p \to e^+\gamma)$ τ_{22}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>460	p	**90**	**0**	**0.6**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>360	p	90	0	0.3	HAINES	86	IMB
> 87	p (free)	90	0	0.2	BLEWITT	85	IMB
>360	p	90	0	0.2	BLEWITT	85	IMB
> 0.1	p	90			[39] GURR	67	CNTR

[39] We have converted half-life to 90% CL mean life.

$\tau(p \to e^+ e^+ e^-)$ τ_{23}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>510	p	**90**	**0**	**0.3**	HAINES	86	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 89	p (free)	90	0	0.5	BLEWITT	85	IMB
>510	p	90	0	0.7	BLEWITT	85	IMB

$\tau(p \to \mu^+\gamma)$ τ_{24}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>380	p	**90**	**0**	**0.5**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 97	*p*	90	3	2	HAINES	86	IMB
> 61	*p* (free)	90	0	0.2	BLEWITT	85	IMB
>280	*p*	90	0	0.6	BLEWITT	85	IMB
> 0.3	*p*	90			[40] GURR	67	CNTR

[40] We have converted half-life to 90% CL mean life.

$\tau(p \to \mu^+\mu^+\mu^-)$ τ_{25}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>190	*p*	90	1	0.1	HAINES	86	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 10.5	*p*	90	0	0.7	PHILLIPS	89	HPW
> 44	*p* (free)	90	1	0.7	BLEWITT	85	IMB
>190	*p*	90	1	0.9	BLEWITT	85	IMB
> 2.1	*p*	90	1		[41] BATTISTONI	82	NUSX

[41] We have converted 1 possible event to 90% CL limit.

$\tau(n \to \nu\gamma)$ τ_{26}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
> 9	*n*	90	73	60	HAINES	86	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>11	*n*	90	28	19	PARK	85	IMB

$\tau(n \to e^+e^-\nu)$ τ_{27}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>45	*n*	90	5	5	HAINES	86	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>26	*n*	90	4	3	PARK	85	IMB

$\tau(n \to \mu^+\mu^-\nu)$ τ_{28}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>16	*n*	90	14	7	HAINES	86	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 5.1	*n*	90	0	0.7	PHILLIPS	89	HPW
>19	*n*	90	4	7	PARK	85	IMB

$\tau(n \to 3\nu)$ τ_{29}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>0.0005	*n*	90	0		LEARNED	79	RVUE

$\tau(p \to e^+\mu^+\mu^-)$ τ_{30}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>5.0	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^-\mu^+\mu^+)$ τ_{31}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>6.0	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^-\pi^+\pi^+)$ τ_{32}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>2.0	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to \mu^+\pi^+\pi^-)$ τ_{33}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>3.3	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to \mu^-\pi^+\pi^+)$ τ_{34}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>7.8	*p*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to e^-\pi^+)$ τ_{35}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>65	*n*	90	0	1.6	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>16	*n*	90	9	7	HAINES	86	IMB
>25	*n*	90	2	4	PARK	85	IMB

$\tau(n \to \mu^-\pi^+)$ τ_{36}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>49	*n*	90	0	0.5	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 2.7	*n*	90	0	0.7	PHILLIPS	89	HPW
>25	*n*	90	7	6	HAINES	86	IMB
>27	*n*	90	2	3	PARK	85	IMB

$\tau(n \to e^-K^+)$ τ_{37}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>0.23	*n*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^-K^+)$ τ_{38}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>4.7	*n*	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to e^-\rho^+)$ τ_{39}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>62	*n*	90	2	4.1	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>12	*n*	90	13	6	HAINES	86	IMB
>12	*n*	90	5	3	PARK	85	IMB

$\tau(n \to \mu^-\rho^+)$ τ_{40}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BACKGROUND ESTIMATE	DOCUMENT ID		TECN
>7	*n*	90	1	1.1	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

>2.6	*n*	90	0	0.7	PHILLIPS	89	HPW
>9	*n*	90	7	5	HAINES	86	IMB
>9	*n*	90	2	2	PARK	85	IMB

REFERENCES FOR *p*

BERGER	89	NP B313 509	*+Froehlich, Moench+*	(FREJUS Collab.)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
HIRATA	89C	PL B220 308	+Kajita, Kifune, Kihara+	(Kamiokande Collab.)
PHILLIPS	89	PL B224 348	+Matthews, Aprile, Cline+	(HPW Collab.)
KREISSL	88	ZPHY C37 557	+	(KARL, BASL, STOC, STRB, THES, MUNI, MISS)
SEIDEL	88	PRL 61 2522	+Bionta, Blewitt, Bratton+	(IMB Collab.)
BARTELT	87	PR D36 1990	+Courant, Heller+	(Soudan Collab.)
Also	89	PR D40 1701 erratum	Bartelt, Courant, Heller+	(Soudan Collab.)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
HAINES	86	PRL 57 1986	+Bionta, Blewitt, Bratton, Casper+	(IMB Collab.)
KAJITA	86	JPSJ 55 711	+Arisaka, Koshiba, Nakahata+	(Kamiokande Collab.)
ARISAKA	85	JPSJ 54 3213	+Kajita, Koshiba, Nakahata+	(Kamiokande Collab.)
BLEWITT	85	PRL 55 2114	+LoSecco, Bionta, Bratton+	(IMB Collab.)
DZUBA	85	PL 154B 93	+Flambaum, Silvestrov	(NOVO)
PARK	85	PRL 54 22	+Blewitt, Cortez, Foster+	(IMB Collab.)
BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
MARINELLI	84	PL 137B 439	+Morpurgo	(GENO)
WILKENING	84	PR A29 425	+Ramsey, Larson	(HARV, VIRG)
BARTELT	83	PRL 50 651	+Courant, Heller, Joyce, Marshak+	(MINN, ANL)
BATTISTONI	82	PL 118B 461	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
KRISHNA...	82	PL 115B 349	Krishnaswamy, Menon+	(TATA, OSKC, TOKY)
ALEKSEEV	81	JETPL 33 651 Translated from ZETFP 33 664.	+Bakatanov, Butkevich, Voevodskii+	(LENI)
CHERRY	81	PRL 47 1507	+Deakyne, Lande, Lee, Steinberg+	(PENN, BNL)
COWSIK	80	PR D22 2204	+Narasimhan	(TATA)
BELL	79	PL 86B 215	+Calvetti, Carron, Chaney, Cittolin+	(CERN)
GOLDEN	79	PRL 43 1196	+Horan, Mauger, Badhwar, Lacy+	(NASA, PSLL)
LEARNED	79	PRL 43 907	+*Reines, Soni*	*(UCI)*
BREGMAN	78	PL 78B 174	+Calvetti, Carron, Cittolin, Hauer, Herr+	(CERN)
ROBERTS	78	PR D17 358		(WILL, RHEL)
EVANS	77	Science 197 989	+Steinberg	(BNL, PENN)
ROBERSON	77	PR C16 1945	+King, Kunselman+	(WYOM, CIT, CMU, VPI, WILL)
HU	75	NP A254 403	+Asano, Chen, Cheng, Dugan+	(COLU, YALE)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DYLLA	73	PR A7 1224	+King	(MIT)
BAMBERGER	70	PL 33B 233	+Lynen, Piekarz+	(MPIH, CERN, KARL)
DIX	70	Case Thesis		(CASE)
HARRISON	69	PRL 22 1263	+Sandars, Wright	(OXF)
GURR	67	PR 158 1321	+Kropp, Reines, Meyer	(CASE, WITW)
FLEROV	58	DOKL 3 79	+Klochkov, Skobkin, Terentev	(USSR)

OTHER RELATED PAPERS

MAMYRIN	83	JETP 57 1152 Translated from ZETF 84 1980.	+Aruev, Alekseenko	(IOFF)
FRANKLIN	77	PR D16 910		(HAIF) P
KALOGERO...	76	PRL 37 1037	Kalogeropoulos, Chiu, Sudarshan	(SYRA, TEXA) P

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

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n MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnotes. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
939.56563±0.00028	[1] COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
939.56564±0.00028	[2,3] GREENE 86	SPEC	$np \rightarrow d\gamma$
939.5731 ±0.0027	[3] COHEN 73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: m = 1.008664904 ± 0.000000014 u.

[2] The mass is known much more precisely in u: m = 1.008664919 ± 0.000000014 u.

[3] These determinations are not independent of the $n - p$ mass difference measurements below.

$\overline{n}$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
939.485±0.051	59	[4] CRESTI 86	HBC	$\overline{p}p \rightarrow \overline{n}n$

[4] This is a corrected result (see the erratum). The error is statistical. The maximum systematic error is 0.029 MeV.

$n - p$ MASS DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1.293318 ±0.000009	[5] COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.2933328±0.0000072	GREENE 86	SPEC	$np \rightarrow d\gamma$
1.293429 ±0.000036	COHEN 73	RVUE	1973 CODATA value

[5] Calculated by us from the COHEN 87 ratio $m(n)/m(p)$ = 1.001378404 ± 0.000000009. In u, $m(n) - m(p)$ = 0.001388434 ± 0.000000009 u.

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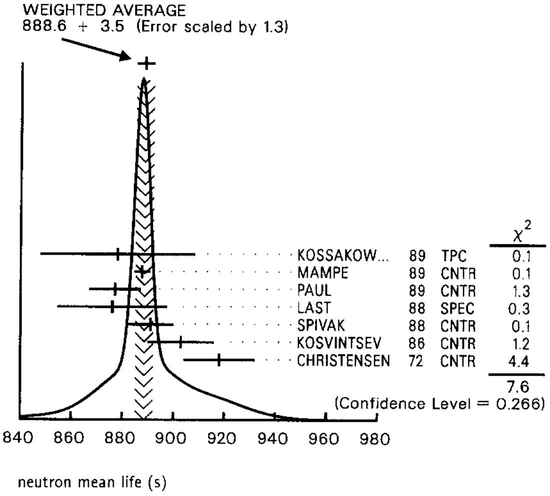
n MEAN LIFE

We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. (Limits on lifetimes for *bound* neutrons are given in the section "*p* PARTIAL MEAN LIVES.")

For a review, see EROZOLIMSKII 89 and papers that follow it. The issue in which these articles appear is the "Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons" (Grenoble 1989).

VALUE (s)	*DOCUMENT ID*	*TECN*	*COMMENT*
888.6± 3.5 OUR AVERAGE	Error includes scale factor	of 1.3.	See the ideogram below.
878 ±27 ±14	KOSSAKOW... 89	TPC	Pulsed beam
887.6± 3.0	MAMPE 89	CNTR	Ultracold neutrons
877 ±10	PAUL 89	CNTR	Ultracold neutrons
876 ±10 ±19	LAST 88	SPEC	Pulsed beam
891 ± 9	SPIVAK 88	CNTR	Thermal neutrons
903 ±13	KOSVINTSEV 86	CNTR	Ultracold neutrons
918 ±14	CHRISTENSEN72	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
937 ±18	[6] BYRNE 80	CNTR	
875 ±95	KOSVINTSEV 80	CNTR	
881 ± 8	BONDAREN... 78	CNTR	See SPIVAK 88

[6] This measurement has been withdrawn (J. Byrne, private communication, 1990).



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n MAGNETIC MOMENT

VALUE (μ_N)	*DOCUMENT ID*	*TECN*	*COMMENT*
−1.91304275±0.00000045	COHEN 87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−1.91304277±0.00000048	[7] GREENE 82	MRS	

[7] GREENE 82 measures the moment to be (1.04187564 ± 0.00000026) × 10^{-3} Bohr magnetons. The value above is obtained by multiplying this by $m(p)/m(e)$ = 1836.152701 ± 0.000037 (the 1986 CODATA value from COHEN 87).

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n ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance. See RAMSEY 82B for a review. A number of early results have been omitted.

VALUE (10^{-26} *e–cm*)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 12	95	SMITH 90	MRS	$d = (-3 \pm 5) \times 10^{-26}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 26	95	ALTAREV 86	MRS	$d = (-14 \pm 6) \times 10^{-26}$
3±48		PENDLEBURY 84	MRS	Ultracold neutrons
< 60	90	ALTAREV 81	MRS	$d = (21 \pm 24) \times 10^{-26}$
<160	90	ALTAREV 79	MRS	$d = (40 \pm 75) \times 10^{-26}$

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n ELECTRIC POLARIZABILITY α_n

Following is the electric polarizability α_n defined in terms of the induced electric dipole moment by $D = 4\pi\epsilon_0\alpha_n E$. For a review, see SCHMIEDMAYER 89.

VALUE (10^{-3} fm^3)	*DOCUMENT ID*	*TECN*	*COMMENT*
$1.1^{+0.4}_{-0.6}$ OUR AVERAGE			
$1.17^{+0.43}_{-1.17}$	ROSE 90	CNTR	$\gamma d \rightarrow \gamma np$
0.8 ±1.0	KOESTER 88	CNTR	*n* Pb, *n* Bi transmission
1.2 ±1.0	SCHMIEDM... 88	CNTR	*n* Pb, *n* C transmission

---

n CHARGE

See also "$|q_p + q_e|$ CHARGE MAGNITUDE DIFFERENCE" in the proton Listings.

VALUE (10^{-21} *e*)	*DOCUMENT ID*	*TECN*	*COMMENT*
− 0.4± 1.1	[8] BAUMANN 88		Cold *n* deflection
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−15 ±22	[9] GAEHLER 82	CNTR	Reactor neutrons

[8] The BAUMANN 88 error ±1.1 gives the 68% CL limits about the the value −0.4.

[9] The GAEHLER 82 error ±22 gives the 90% CL limits about the the value −15.

Limit on $n\overline{n}$ Oscillations

MEAN TIME FOR $n\overline{n}$ TRANSITION IN VACUUM

Test of baryon conservation. Limits are derived from experimental limits on $\Delta B = 2$ nuclear decay processes, using theoretical assumptions for nuclear physics effects. Theoretical discussions of the motivations for $n\overline{n}$ oscillations appear in MOHAPATRA 80 and MOHAPATRA 89. Phenomenological analyses are in DOVER 83 and DOVER 85. There is some controversy about whether nuclear physics and model dependence can complicate the analysis for bound neutrons (from which the best limit comes); for a discussion see DOVER 89 and KABIR 83 (see also papers submitted to Phys. Rev. C by Kabir and Noble and by Dover *et al.*).

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>1.2 \times 10^{8}$	90	TAKITA	86	CNTR	Kamiokande
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>4.7 \times 10^{5}$	90	BRESSI	89	CNTR	Reactor neutrons
$>1. \times 10^{6}$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8 \times 10^{7}$	90	PARK	85B	CNTR	
$>3. \times 10^{7}$		BATTISTONI	84	NUSX	
$> 2.7 \times 10^{7}–1.1 \times 10^{8}$		JONES	84	CNTR	
$>2. \times 10^{7}$		CHERRY	83	CNTR	
$>3. \times 10^{7}$		ALBERICO	82	THEO	
$>1. \times 10^{8}$		CHETYRKIN	81	THEO	
$>5. \times 10^{7}$	90	COWSIK	81	THEO	

n DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p e^- \overline{\nu}_e$	100 %	
	Charge conservation (Q) violating mode		
Γ_2	$p \nu_e \overline{\nu}_e$	Q $< 9 \times 10^{-24}$	90%

n BRANCHING RATIOS

$\Gamma(p\nu_e\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_2/Γ

Forbidden by charge conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<9 \times 10^{-24}$	90	BARABANOV	80	CNTR	$^{71}\text{Ga} \to {}^{71}\text{Ge}\,X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<9.7 \times 10^{-18}$	90	ROY	83	CNTR	$^{113}\text{Cd} \to {}^{113m}\text{In}$ neut.
$<7.9 \times 10^{-21}$		VAIDYA	83	CNTR	$^{87}\text{Rb} \to {}^{87m}\text{Sr}$ neut.
$<3 \times 10^{-19}$		NORMAN	79	CNTR	$^{87}\text{Rb} \to {}^{87m}\text{Sr}$ neut.

NOTE ON BARYON DECAY PARAMETERS

(by E.D. Commins, University of California, Berkeley)

Baryon semileptonic decays

The typical baryon semileptonic decay is described by a matrix element, the hadronic part of which may be written as:

$$\overline{B}_f \left[f_1(q^2)\gamma_\lambda + i\ f_2(q^2)\sigma_{\lambda\mu}q^\mu + g_1(q^2)\gamma_\lambda\gamma_5 + g_3(q^2)\gamma_5 q_\lambda \right] B_i \ .$$

Here B_i and $\overline{B}_f$ are spinors describing the initial and final baryons and $q = p_i - p_f$, while the terms in f_1, f_2, g_1, and g_3 account for vector, induced tensor ("weak magnetism"), axial vector, and induced pseudoscalar contributions.[1] Second-class current contributions are ignored here. In the limit of zero momentum transfer, f_1 reduces to the vector coupling constant g_V, and g_1 reduces to the axial-vector coupling constant g_A. The latter coefficients are related by Cabibbo's theory,[2] generalized to six quarks (and three mixing angles) by Kobayashi and Maskawa.[3] The g_3 term is negligible for transitions in which an $e^\pm$ is emitted, and gives a very small correction, which can be estimated by PCAC,[4] for $\mu^\pm$ modes. Recoil effects include weak magnetism, and are taken into account adequately by considering terms of first order in

$$\delta = (m_i - m_f)/(m_i + m_f) \ ,$$

where m_i and m_f are the masses of the initial and final baryons.

The experimental quantities of interest are the total decay rate, the lepton-neutrino angular correlation, the asymmetry coefficients in the decay of a polarized initial baryon, and the polarization of the decay baryon in its own rest frame for an unpolarized initial baryon. Formulae for these quantities are derived by standard means[5] and are analogous to similar formulae for beta decay.[6] For comparison with high-precision experiments, it is necessary to modify the form factors at $q^2 = 0$ by a "dipole" q^2 dependence, and also to apply appropriate radiative corrections.[7]

The ratio g_A/g_V may be written as

$$g_A/g_V = |\, g_A/g_V \,|\, e^{i\phi_{AV}} \ .$$

The presence of a "triple correlation" term in the transition probability, proportional to $\text{Im}(g_A/g_V)$ and of the form

$$\boldsymbol{\sigma}_i \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for initial baryon polarization or

$$\boldsymbol{\sigma}_f \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for final baryon polarization, would indicate failure of time-reversal invariance. The phase angle ϕ has been measured precisely only in neutron decay (and in ^{19}Ne nuclear beta decay), and the results are consistent with T invariance.

Hyperon nonleptonic decays

The most general decay amplitude for $J^P = 1/2^+$ hyperons may be written in the form

$$M = G_F\, m_\pi^2 \cdot \overline{B}_f\, (A - B\gamma_5)\, B_i \ ,$$

where A and B are constants.[1] Then the transition rate is proportional to

$$R = 1 + \gamma\ \hat{\omega}_f \cdot \hat{\omega}_i + (1 - \gamma)(\,\hat{\omega}_f \cdot \hat{\mathrm{n}})(\,\hat{\omega}_i \cdot \hat{\mathrm{n}}) + \alpha(\,\hat{\omega}_f \cdot \hat{\mathrm{n}} + \hat{\omega}_i \cdot \hat{\mathrm{n}}) - \beta\, \hat{\mathrm{n}} \cdot (\,\hat{\omega}_f \times \hat{\omega}_i) \ ,$$

where $\hat{\mathrm{n}}$ is a unit vector in the direction of the final baryon momentum, and $\hat{\omega}_i$ and $\hat{\omega}_f$ are unit vectors in the directions of the initial and final baryon spins. Also,

$$\alpha = 2\,\text{Re}(s^*p)/(\,|\,s\,|^2 + |\,p\,|^2) \ ,$$

$$\beta = 2\,\text{Im}(s^*p)/(\,|\,s\,|^2 + |\,p\,|^2) \ ,$$

and

$$\gamma = (\,|\,s\,|^2 - |\,p\,|^2)/(\,|\,s\,|^2 + |\,p\,|^2) \ ,$$

where $s = A$ and $p = |\,\mathbf{p}_f\,|\, B/(E_f + m_f)$; here E_f and $\mathbf{p}_f$ are the energy and momentum of the final baryon. The parameters α, β, and γ satisfy

$$\alpha^2 + \beta^2 + \gamma^2 = 1 \ .$$

An additional parameter ϕ is defined by

$$\beta = (1 - \alpha^2)^{1/2}\, \sin\phi \ .$$

In the Listings, we compile α and ϕ for each decay, since these quantities are most closely related to experiment and are essentially uncorrelated. When necessary, we have changed the signs of reported values to agree with our sign conventions.

In the Baryon Summary Table, we give α, ϕ, and Δ (defined below) with errors, and also give the value of γ without error.

Time-reversal invariance requires, in the absence of final-state interactions, that s and p be relatively real, and therefore that $\beta = 0$. However, for the decays discussed here, the final-state interaction is strong. Thus

$$s = |\,s\,|\,e^{i\delta_s} \text{ and } p = |\,p\,|\,e^{i\delta_p}\ ,$$

where δ_s and δ_p are the pion-baryon s- and p-wave strong interaction phase shifts. We then have

$$\beta = \frac{-2\,|\,s\,|\ |\,p\,|}{|\,s\,|^2 + |\,p\,|^2}\ \sin(\delta_s - \delta_p)\ .$$

One also defines $\Delta = -\tan^{-1}(\beta/\alpha)$. If T invariance holds, $\Delta = \delta_s - \delta_p$. For $\Lambda \to p\pi^-$ decay, the value of Δ may be compared with the s- and p-wave phase shifts in low-energy $\pi^- p$ scattering, and the results are consistent with T invariance.

References

1. E.D. Commins and P.H. Bucksbaum, *Weak Interactions of Leptons and Quarks* (Cambridge University Press, Cambridge, England, 1983).
2. N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
3. M. Kobayashi and T. Maskawa, Progr. Theor. Phys. **49**, 652 (1973).
4. M.L. Goldberger and S.B. Treiman, Phys. Rev. **111**, 354 (1958).
5. P.H. Frampton and W.K. Tung, Phys. Rev. **D3**, 1114 (1971).
6. J.D. Jackson, S.B. Treiman, and H.W. Wyld, Jr., Phys. Rev. **106**, 517 (1957), and Nucl. Phys. **4**, 206 (1957).
7. Y. Yokoo, S. Suzuki, and M. Morita, Progr. Theor. Phys. **50**, 1894 (1973).

$n \to pe^-\nu$ DECAY PARAMETERS

See the above Note on Baryon Decay Parameters.

g_A / g_V

VALUE	DOCUMENT ID	TECN	COMMENT
−1.261±0.004 OUR AVERAGE			
−1.262±0.005	BOPP 86	SPEC	*e* mom-*n* spin corr.
−1.261±0.012	[10] EROZOLIM... 79	CNTR	*e* mom-*n* spin corr.
−1.259±0.017	[10] STRATOWA 78	CNTR	proton recoil spectrum
−1.258±0.015	[11] KROHN 75	CNTR	*e* mom-*n* spin corr.
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−1.226±0.042	MOSTOVOY 83	RVUE	
−1.263±0.015	EROZOLIM... 77	CNTR	See EROZOLIMSKII 79
−1.250±0.036	[10] DOBROZE... 75	CNTR	See STRATOWA 78
−1.263±0.016	[12] KROPF 74	RVUE	*n* decay alone
−1.250±0.009	[12] KROPF 74	RVUE	*n* decay + nuclear ft

[10] These experiments measure the absolute value of g_A/g_V only.
[11] KROHN 75 includes events of CHRISTENSEN 70.
[12] KROPF 74 reviews all data through 1972.

β ASYMMETRY PARAMETER *A*

This is the neutron-spin electron-momentum correlation coefficient.

VALUE	DOCUMENT ID	TECN
−0.1144±0.0017 OUR AVERAGE		
−0.1146±0.0019	[13] BOPP 86	SPEC
−0.114 ±0.005	[14] EROZOLIM... 79	CNTR
−0.113 ±0.006	[14] KROHN 75	CNTR

[13] The BOPP 86 value is corrected for radiative effects and weak magnetism.
[14] These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.

$\bar\nu$ ASYMMETRY PARAMETER *B*

This is the neutron-spin antineutrino-momentum correlation coefficient.

VALUE	DOCUMENT ID	TECN
0.997±0.028 OUR AVERAGE		
0.995±0.034	CHRISTENSEN 70	CNTR
1.00 ±0.05	EROZOLIM... 70C	CNTR

e-$\bar\nu$ ANGULAR CORRELATION COEFFICIENT *a*

VALUE	DOCUMENT ID	TECN	COMMENT
−0.102 ±0.005 OUR AVERAGE			
−0.1017±0.0051	STRATOWA 78	CNTR	Proton recoil spectrum
−0.091 ±0.039	GRIGOREV 68	SPEC	Proton recoil spectrum

ϕ_{AV}, PHASE ANGLE OF g_A RELATIVE TO g_V

Time reversal invariance requires this to be 0 or 180°.

VALUE (°)	DOCUMENT ID	TECN	COMMENT
180.07±0.18 OUR EVALUATION	Using the average value for quantity *D* given in the next data block and $\lambda \equiv g_A/g_V$ in $\sin\phi_{AV} = D(1+3\lambda^2)/2\lambda$.		
180.09±0.18 OUR AVERAGE			
179.71±0.39	EROZOLIM... 78	CNTR	Polarized neutrons
180.35±0.43	EROZOLIM... 74	CNTR	Polarized neutrons
180.14±0.22	STEINBERG 74	CNTR	Polarized neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •			
181.1 ±1.3	[15] KROPF 74	RVUE	*n* decay

[15] KROPF 74 reviews all data through 1972.

TRIPLE CORRELATION COEFFICIENT *D*

These are measurements of the component of *n* spin perpendicular to the decay plane in β decay. Should be zero if *T* invariance is not violated.

VALUE	DOCUMENT ID	TECN	COMMENT
$(-0.5\ \pm1.4\ )\times10^{-3}$ OUR AVERAGE			
+ 0.0022±0.0030	EROZOLIM... 78	CNTR	Polarized neutrons
− 0.0027±0.0050	[16] EROZOLIM... 74	CNTR	Polarized neutrons
− 0.0011±0.0017	STEINBERG 74	CNTR	Polarized neutrons

[16] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to 0.003, thus increasing the EROZOLIMSKII 74 error to 0.005. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

REFERENCES FOR *n*

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

ROSE	90	PL B234 460	+Zurmuehl, Rulthusen, Ludwig+	(GOET, MPHY, MANZ)
SMITH	90	PL B234 191	+Crampin+	(SUSS, RAL, HARV, WASH, ILLG, MUNT)
BRESSI	89	ZPHY C43 175	+Calligarich, Cambiaghi+	(INFN, MILA, PAVI, ROMA)
DOVER	89	NIM A284 13	+Gal, Richard	(BNL, HEBR, ISNG)
EROZOLIM...	89	NIM A284 89	Erozolimskii	(LENI)
KOSSAKOW...	89	NP A503 473	Kossakowski, Grivot+	(LAPP, SAVO, ISNG, ILLG)
MAMPE	89	PRL 63 593	+Ageron, Bates, Pendlebury, Steyerl	(ILLG, RISL, SUSS, URI)
MOHAPATRA	89	NIM A284 1		(UMD)
PAUL	89	ZPHY C45 25	+Anton, Paul, Paul, Mampe	(BONN, WUPP, MPIH, ILLG)
SCHMIEDM...	89	NIM A284 137	Schmiedmayer, Rauch, Riehs	(WIEN)
BAUMANN	88	PR D37 3107	+Gaehler, Kalus, Mampe	(BAYR, MUNI, ILLG)
KOESTER	88	ZPHY A329 229	+Waschkowski, Meier	(MUNI, MUNT)
LAST	88	PRL 60 995	+Arnold, Doehner, Dubbers+	(HEID, ILLG, ANL)
SCHMIEDM...	88	PRL 61 1065	Schmiedmayer, Rauch, Riehs	(TUW)
Also	88B	PRL 61 2509 erratum	Schmiedmayer, Rauch, Riehs	(TUW)
SPIVAK	88	JETP 67 1735		(KIAE)
		Translated from ZETF 94 1.		
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
ALTAREV	86	JETPL 44 460	+Borisov, Borovikova, Brandin, Egorov+	(LENI)
		Translated from ZETFP 44 360.		
BOPP	86	PRL 56 919	+Dubbers, Hornig, Klemt, Last+	(HEID, ANL, ILLG)
Also	88	ZPHY C37 179	Klemt, Bopp, Hornig, Last+	(HEID, ANL, ILLG)
CRESTI	86	PL B177 206	+Pasquali, Peruzzo, Pinori, Sartori	(PADO)
Also	88	PL B200 587 errat.	Cresti, Pasquali, Peruzzo, Pinori, Sartori	(PADO)
GREENE	86	PRL 56 819	+Kessler, Deslattes, Boerner	(NBS, ILLG)
KOSVINTSEV	86	JETPL 44 571	+Morozov, Terekhov	(KIAE)
		Translated from ZETFP 44 444.		
TAKITA	86	PR D34 902	+Arisaka, Kajita, Kifune, Koshiba+	(KEK, TOKY)
DOVER	85	PR C31 1423	+Gal, Richard	(BNL)
FIDECARO	85	PL 156B 122	+Lanceri+	(CERN, ILLG, PADO, RAL, SUSS)
PARK	85B	NP B252 261	+Blewitt, Cortez, Foster+	(IMB Collab.)
BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
JONES	84	PRL 52 720	+Bionta, Blewitt, Bratton+	(IMB Collab.)
PENDLEBURY	84	PL 136B 327	+Smith, Golub, Byrne+	(SUSS, HARV, RAL, ILLG)
CHERRY	83	PRL 50 1354	+Lande, Lee, Steinberg, Cleveland	(PENN, BNL)
DOVER	83	PR D27 1090	+Gal, Richards	(BNL)
KABIR	83	PRL 51 231		(HARV)
MOSTOVOY	83	JETPL 37 196		(KIAE)
		Translated from ZETFP 37 162.		
ROY	83	PR D28 1770	+Vaidya, Ephraim, Datar, Bhatki+	(TATA)
VAIDYA	83	PR D27 486	+Roy, Ephraim, Datar, Bhattacherjee	(TATA)
ALBERICO	82	PL 114B 266	+Bottino, Molinari	(CERN, TORI)
GAEHLER	82	PR D25 2887	+Kalus, Mampe	(BAYR, ILLG)
GREENE	82	Metrologia 18 93	+	(YALE, HARV, ILLG, SUSS, ORNL, CENG)
RAMSEY	82B	RPP 45 95		(HARV)
ALTAREV	81	PL 102B 13	+Borisov, Borovikova, Brandin, Egorov+	(LENI)
CHETYRKIN	81	PL 99B 358	+Kazarnovsky, Kuzmin+	(INRM)
COWSIK	81	PL 101B 237	+Nussinov	(UMD)
BARABANOV	80	JETPL 32 359	+Veretenkin, Gavrin+	(LENI)
		Translated from ZETFP 32 384.		
BYRNE	80	PL 92B 274	+Morse, Smith, Shaikh, Green, Greene	(SUSS, RL)
KOSVINTSEV	80	JETPL 31 236	+Kushnir, Morozov, Terekhov	(JINR)
		Translated from ZETFP 31 257.		
MOHAPATRA	80	PRL 44 1316	+Marshak	(CUNY, VPI)
ALTAREV	79	JETPL 29 730	+Borisov, Brandin, Egorov, Ezhov, Ivanov+	(LENI)
		Translated from ZETFP 29 794.		
EROZOLIM...	79	SJNP 30 356	Erozolimskii, Frank, Mostovoy+	(KIAE)
		Translated from YAF 30 692.		
NORMAN	79	PRL 43 1226	+Seamster	(WASH)
BONDAREN...	78	JETPL 28 303	Bondarenko, Kurguzov, Prokofev+	(KIAE)
		Translated from ZETFP 28 328.		
Also	82	Smolenice Conf.	Bondarenko	(KIAE)
EROZOLIM...	78	SJNP 28 48	Erozolimskii, Mostovoy, Fedunin, Frank+	(KIAE)
		Translated from YAF 28 98.		
STRATOWA	78	PR D18 3970	+Dobrozemsky, Weinzierl	(SEIB)
EROZOLIM...	77	JETPL 23 663	Erozolimskii, Frank, Mostovoy+	(KIAE)
		Translated from ZETFP 23 720.		
STEINBERG	76	PR D13 2469	+Liaud, Vignon, Hughes	(YALE, ISNG)
DOBROZE...	75	PR D11 510	Dobrozemsky, Kerschbaum, Moraw, Paul+	(SEIB)
KROHN	75	PL 55B 175	+Ringo	(ANL)
EROZOLIM...	74	JETPL 20 345	Erozolimskii, Mostovoy, Fedunin, Frank+	
		Translated from ZETFP 20 745.		

KROPF 74 ZPHY 267 129 +Paul (LINZ)
Also 70 NP A154 160 Paul (VIEN)
STEINBERG 74 PRL 33 41 +Liaud, Vignon, Hughes (YALE, ISNG)
COHEN 73 JPCRD 2 663 +Taylor (RISC, NBS)
CHRISTENSEN 72 PR D5 1628 +Nielson, Bahnsen, Brown+ (RISO)
CHRISTENSEN 70 PR C1 1693 +Krohn, Ringo (ANL)
EROZOLIM... 70C PL 33B 351 Erozolimskii, Bondarenko, Mostovoy, Obinyakov+ (KIAE)
GRIGOREV 68 SJNP 6 239 Grigor'ev, Grishin, Vladimirsky, Nikolaevskii+ (ITEP)
Translated from YAF 6 329.

NOTE ON N AND Δ RESONANCES

I. Introduction

(by G. Höhler, University of Karlsruhe)

The excited states of the nucleon have been studied in a large number of formation and production experiments. Production experiments are unsuitable for accurate determination of resonance parameters but will be essential in searching for the many nucleon resonances predicted to exist but also to decouple from the πN channel.[1]

The masses, widths, and elasticities of the N and Δ resonances in the Baryon Summary Table come almost entirely from partial-wave analyses of πN total, elastic, and charge-exchange scattering data (see Sec. II). Partial-wave analyses have also been used on much smaller data sets to get $N\eta$, ΛK, and ΣK branching fractions. Other branching fractions come from isobar-model analyses of $\pi N \rightarrow N\pi\pi$ data (Sec. III). Finally, some $N\gamma$ branching fractions have been determined from photoproduction experiments (Sec. IV).

Table 1 lists all the N and Δ entries in the Baryon Listings and gives our evaluation of the status of each, both overall and channel by channel. Only the established resonances (overall status 3 or 4 stars) appear in the Baryon Summary Table. We consider a resonance to be established only if it has been seen in at least two independent analyses and the relevant partial-wave amplitudes do not behave erratically or have large errors. Some recent data[2,3] above 1 GeV/c differ appreciably from earlier data and thus also from predictions of the existing analyses, so a cautious attitude is called for. Problems at lower momenta will be discussed in Sec. II.

The Baryon Listings give, in addition to the usual Breit-Wigner parameters, the positions and residues of the poles of the resonant partial waves on the second sheet of the complex energy plane. These come from $\pi N \rightarrow \pi N$ partial-wave analyses and from $\pi N \rightarrow N\pi\pi$ isobar-model analyses.

There are two extensive reviews of nucleon resonances,[4,5] and there have in recent years been several Conferences and Workshops on πN Physics.[6–9]

Further progress in understanding N and Δ resonances will depend on investigations of three types.

(1) New data: Much new data has been published in recent years by groups working at LAMPF,[10] and there is also some new data from Leningrad[11] and Moscow.[3] The results include preliminary spin-rotation data, the first such in the resonance region. Some results were available long before publication[12] and were included in one of the Karlsruhe analyses (see Sec. II).

Table 1. The status of the N and Δ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1540)$	P_{13}	*					*	*	
$N(1650)$	S_{11}	****	****	*	***	**	***	*	***
$N(1675)$	D_{15}	****	****	*	*		****	*	***
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	*	*
$N(1960)$	?	*				*			
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*			
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*						
$N(2190)$	G_{17}	****	****	*	*	*			*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1550)$	P_{31}	*		o			*	*	*
$\Delta(1600)$	P_{33}	**	**	r			**	*	**
$\Delta(1620)$	S_{31}	****	****	b			****	****	***
$\Delta(1700)$	D_{33}	****	****	i		*	***	**	***
$\Delta(1900)$	S_{31}	***	***		d	*		*	*
$\Delta(1905)$	F_{35}	****	****		d	*	**	*	***
$\Delta(1910)$	P_{31}	****	****		e	*	*	*	*
$\Delta(1920)$	P_{33}	***	***		n	*	*		*
$\Delta(1930)$	D_{35}	***	***	F		*			*
$\Delta(1940)$	D_{33}	*	*	o					
$\Delta(1950)$	F_{37}	****	****	r		*	***	*	***
$\Delta(2000)$	F_{35}	**		b				**	
$\Delta(2150)$	S_{31}	*	*	i					
$\Delta(2200)$	G_{37}	*	*		d				
$\Delta(2300)$	H_{39}	**	**		d				
$\Delta(2350)$	D_{35}	*	*		e				
$\Delta(2390)$	F_{37}	*	*		n				
$\Delta(2400)$	G_{39}	**	**						
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

****	Good, clear, and unmistakable.
***	Good, but in need of clarification or not absolutely certain.
**	Not established; needs confirmation.
*	Evidence weak; could disappear.

New high-precision data in the low-energy region (see Ref. 7 and W. Kluge's review and other contributions in Ref. 6) are of some relevance to the lower resonances, insofar as dispersion relations need input from all momenta. They are more important for analytic continuations into the unphysical region below threshold for tests of predictions from chiral perturbation theory, for instance for the πN σ term (see Gasser and Sainio's contribution to Ref. 6 and mine to Ref. 7). Unfortunately, the new low-energy experiments don't all agree with one another.

(2) New analyses: Existing partial-wave solutions will need to be adjusted to get a good fit to the new data. First should come single-energy analyses combined with a study of the zeros of invariant and transversity scattering amplitudes, as was done in earlier work of our group[4] and of the Leningrad group.[13] The zeros must lie on trajectories and fulfill conditions derived from the Mandelstam hypothesis (see Sec. 2.4.3 in Ref. 4 and also Ref. 14). Instead of cutting off the tail of high partial waves, one should use Koch's results.[15]

Around the $\Delta(1232)$ and below, the electromagnetic corrections are fairly large. They should be treated using the relativistic dispersion-relation method developed by the NORDITA group.[16] Less reliable methods based on potential models are unfortunately still in use.

New data on πN scattering reactions leading to inelastic final states should be included. Related to this is the search for shadow poles (see Sec. II).

Finally, a new analysis of the type carried out by the CMU-LBL and Karlsruhe-Helsinki groups is essential, but these groups lack the manpower to do it. Without an analysis on this level of sophistication, new data will not significantly improve our knowledge of the resonance parameters.

Single-energy analyses in accord with the program described above have recently been carried out by the Karlsruhe group on all new data below 700 MeV/c (excepting data on inelastic reactions). Apparently the only other group working in this field is the VPI group (see Arndt in Ref. 6). This group's SAID facility includes a program for single-energy analysis and it also distributes results of an energy-dependent partial-wave analysis four times per year. However, the group's methods of analysis do not take into account some of the essential points noted above. A detailed documentation of the method and a comparison with other solutions are not available. See Sec. II for further comments.

(3) New theoretical investigations: Many theoretical authors disregard the fact that the Breit-Wigner resonance parameters we give are different from the quantities they calculate in their models. This is no problem for Skyrmion models,[17] which predict scattering amplitudes, but in quark shell models or lattice calculations the authors calculate energies of stable excited states and ignore the mass shifts expected from the strong coupling to the decay channels. It is essential to estimate these mass shifts before making detailed comparisons between the theoretical results and the experimentally determined resonance parameters.

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II. Two-body partial-wave analyses and determination of resonance parameters

(by G. Höhler, University of Karlsruhe)

πN partial-wave analysis: Even if all measurable $\pi p \rightarrow \pi p$ scattering data were known with high accuracy, it would not be possible to obtain a unique set of partial waves from the data alone, since a common phase of all transversity amplitudes is not determined. It is essential to add the theoretical constraints of unitarity, isospin invariance, and analyticity. See Ref. 1 for a precise mathematical statement and a discussion of the stability problem, and Ref. 2 (Sec. 2.1) for a brief review.

The strength of the unitarity constraint alone (that is, without analyticity) for $\pi^+ p$ scattering was investigated by Atkinson et al.[3] The lesson is that the tail of high partial waves should not be cut off sharply (as was done by the pioneers in this field, but also in some recent analyses[4,5]), since equally good fits can sometimes be obtained with changes of the small tail coupled with substantial changes in low partial waves. In general, there are a few high partial waves that are too large to be neglected but too small to be determined accurately. We return to this point below.

In QCD, isospin is not exactly conserved in strong interactions because the masses of the up and down quarks are not identical. However, despite some earlier reports for violations of isospin invariance, the only confirmed violation is seen in total cross section data in the $\Delta(1232)$ region, the manifestation being the slightly different masses and widths of the Δ^{++} and Δ^0. See Ref. 6 for a recent test of isospin invariance at intermediate energies.

The problem of getting a unique solution remains even if one includes differential-cross-section, polarization, and spin-rotation data from all three reactions ($\pi^{\pm}p \rightarrow \pi^{\pm}p$ and $\pi^{-}p \rightarrow \pi^{0}n$), plus the constraints of unitarity and isospin invariance. It is still necessary to add analyticity constraints, and much stronger ones than just the forward dispersion relations. Constraints based on the Mandelstam hypothesis[7] have been used successfully only in the CMU-LBL[8] and KH[9] analyses. In these analyses, long tails of high partial waves were admitted, but only global results about the high waves, not details about a particular one of them, are reliable. The two groups worked with different sets of data. For example, a large elastic $\pi^{\pm}p$ data set of Bardsley et al. (Rutherford Lab, 1976) was not used in the KH analyses (it was never published). The groups made independent decisions in cases of discrepancies between data sets or normalizations, and they used different dispersion constraints. Nevertheless, there is reasonable agreement between the two sets of partial-wave amplitudes, which are shown in Fig. 1. The solutions shown in Fig. 1 will be referred to below as the CMU-LBL and KH80 solutions.

In subsequent investigations, the KH group has tested the consistency of its KH80 solution with various consequences of the Mandelstam hypothesis.[2,10–12] The results confirm that there exists a prescription based on general principles for obtaining a unique partial-wave solution. Furthermore, they show that at present there is no evidence for additional singularities that could possibly follow from QCD. However, problems may arise if discrepancies in the low-energy region (see Sec. I) are resolved in favor of certain data sets. A quantitative calculation of πN scattering amplitudes in the physical region is far beyond the possibilities of the present techniques available in QCD.

The resonance parameters in the Baryon Summary Table are mainly determined from the CMU-LBL and KH analyses. More details of the CMU-LBL, KH80, and KA84 (see below) solutions, including speed plots, may be found in Ref. 13.

The results of phase-shift analyses of the VPI group[4] are not shown in Fig. 1 for the following reasons. The VPI analyses are based on a special parametrization of the partial-wave amplitudes using a large number of adjustable parameters. This parametrization ignores the well-known left-hand singularities of these amplitudes[14] (even the nucleon Born term), which start not far below threshold. The discontinuities along the nearby parts of these cuts have been calculated by many authors, in particular by J. Hamilton et al. and more recently by R. Koch.[11] The solution obtained by the VPI group is not unique, since it would be equally justified to use other parametrizations that would lead to more or less different results. Furthermore, the VPI analysis does not use data above 1.1 GeV, so that it is unlikely that the left wings of the strongly coupled resonances located above this energy are well described. Finally, electromagnetic corrections are calculated using an old method based on a potential model instead of on the NORDITA method mentioned in Sec. I.

It is remarkable that many experimentalists disregard the importance of dispersion-relation constraints and uniqueness, and treat the VPI analysis on an equal footing with the CMU-LBL and KH analyses. They use the SAID program package of Arndt et al., although they know only vaguely what these programs do. The SAID facility is useful, but it suffers from the above-mentioned shortcomings of the phase-shift analysis and from a lack of documentation.

An improvement of the methods used in the CMU-LBL and KH80 analyses has been developed by Koch, based on our evaluation of Mandelstam's double spectral function near the physical region,[15] and in connection with his new evaluation of the πN partial-wave dispersion relations.[11] The result is a prediction for the high partial waves. Detailed figures are shown in Refs. 13 and 16.

Since the KH80 solution[9] as well as the "data points" of the CMU-LBL solution[8] shown in Fig. 1 result from an iteration procedure that ends with a fit to the data, the amplitudes fluctuate somewhat with energy. The CMU-LBL group then used energy-dependent fits to obtain smoothed amplitudes (see Fig. 1). From the KH80 solution, Koch produced two smooth solutions (not shown in Fig. 1) by using KH80 for evaluations of the partial-wave dispersion relations[11] (solution KA84) and for evaluations of the partial-wave projections of the fixed-t dispersion relations[12] (KA85). The latter method is an exact version of the approach of Chew et al.[17] It can be applied only up to about 0.5 GeV/c. These smoothed versions do not have the erratic properties seen in Fig. 1 on the left wings of some of the resonances. The approximate agreement of the two results[12] supports the validity of the Mandelstam hypothesis.

Plots of the zero trajectories of invariant and transversity amplitudes calculated from the CMU-LBL and KA84 solutions show that, at some energies, the present results are not satisfactory.[18] The need for corrections follows also from discrepancies of the analyses with some of the new data mentioned in Sec. I, in particular with the data of Kim et al. (Ref. 10 in Sec. I).

We have made preliminary single-energy analyses using only data up to 700 MeV/c measured after the completion of the KH80 analysis.[19] A few of the lower partial waves were varied and the higher partial waves were fixed as given by the KA84 solution. The analysis will be extended to higher momenta.

The discrepancies of predictions from the KH80 and KA84 solutions with the data between 427 and 687 MeV/c (see Ref. 10 in Sec. I) can easily be removed by relatively small changes of a few partial waves. The only resonant amplitude in this range, the P_{11}, changes only slightly. The largest correction, which occurs in the S_{11} amplitude, could be used in a new analysis of the $N(1535)S_{11}$ resonance. However, the new data lie only on the left wing of this resonance, on which the inelasticity increases rapidly due to the opening of the $n\eta$ channel.

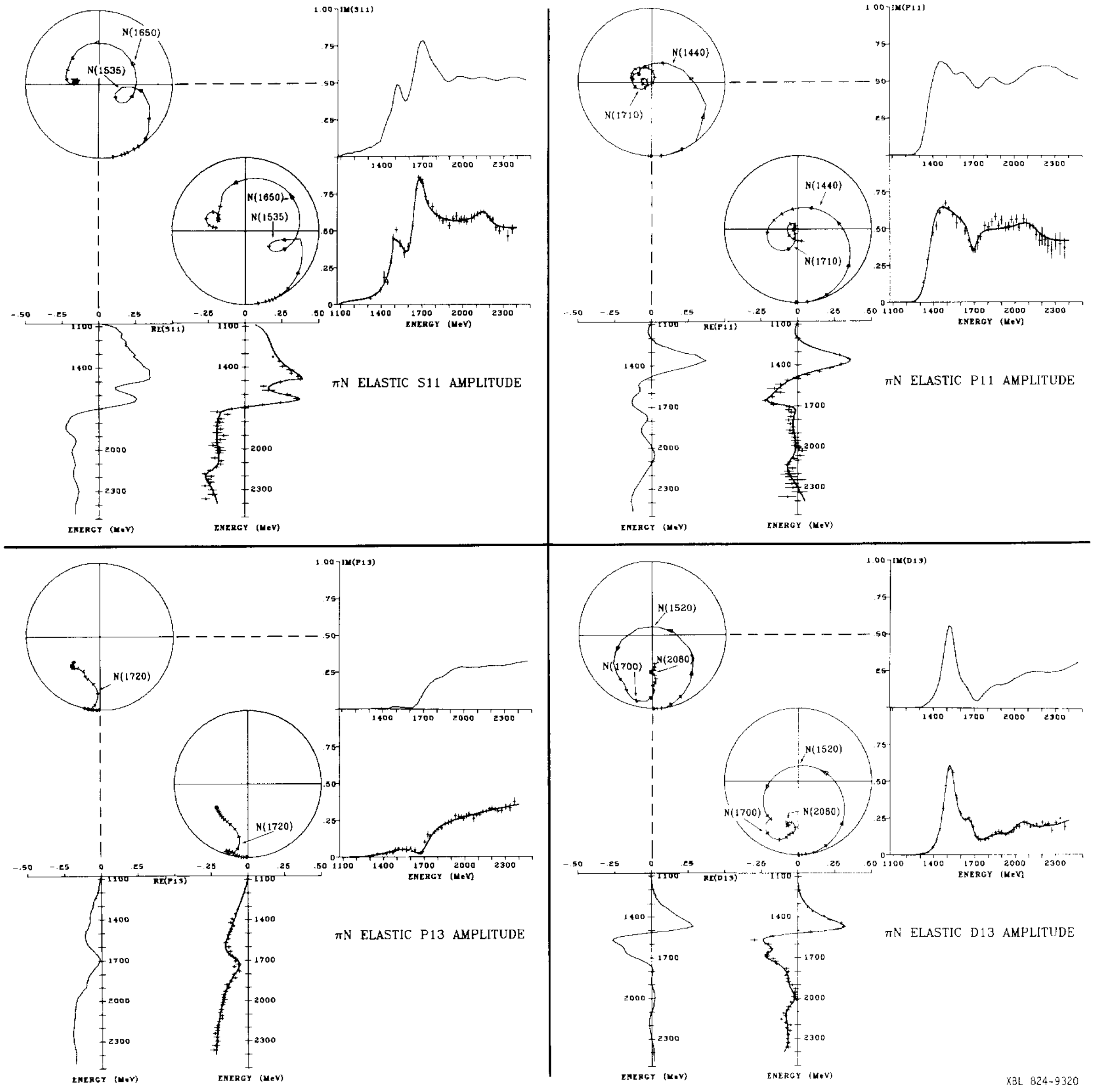

Fig. 1(a). The $L_{2I \cdot 2J} = S_{11}$, P_{11}, P_{13}, and D_{13} partial-wave amplitudes for πN elastic scattering. The upper plot for each amplitude is from HOEHLER 79 and the lower one is from CUTKOSKY 80. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots (in the projections of the CUTKOSKY 80 amplitudes, the "data points" are results of energy-independent fits, and the curves are from an energy-dependent fit to join them).

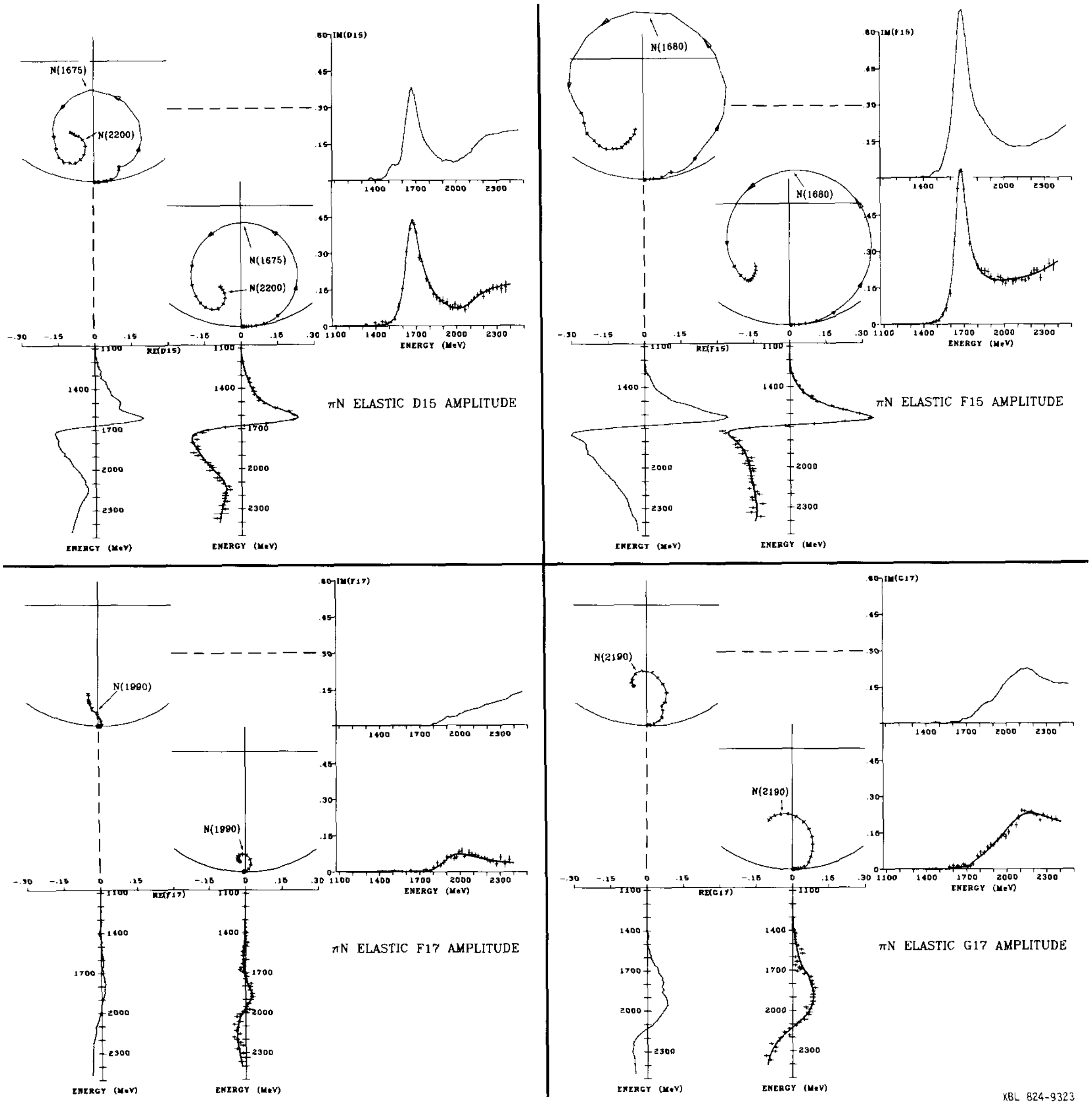

Fig. 1(b). The $L_{2I\cdot 2J} = D_{15}$, F_{15}, F_{17}, and G_{17} partial-wave amplitudes for πN elastic scattering. The upper plot for each amplitude is from HOEHLER 79 and the lower one is from CUTKOSKY 80. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots (in the projections of the CUTKOSKY 80 amplitudes, the "data points" are results of energy-independent fits, and the curves are from an energy-dependent fit to join them).

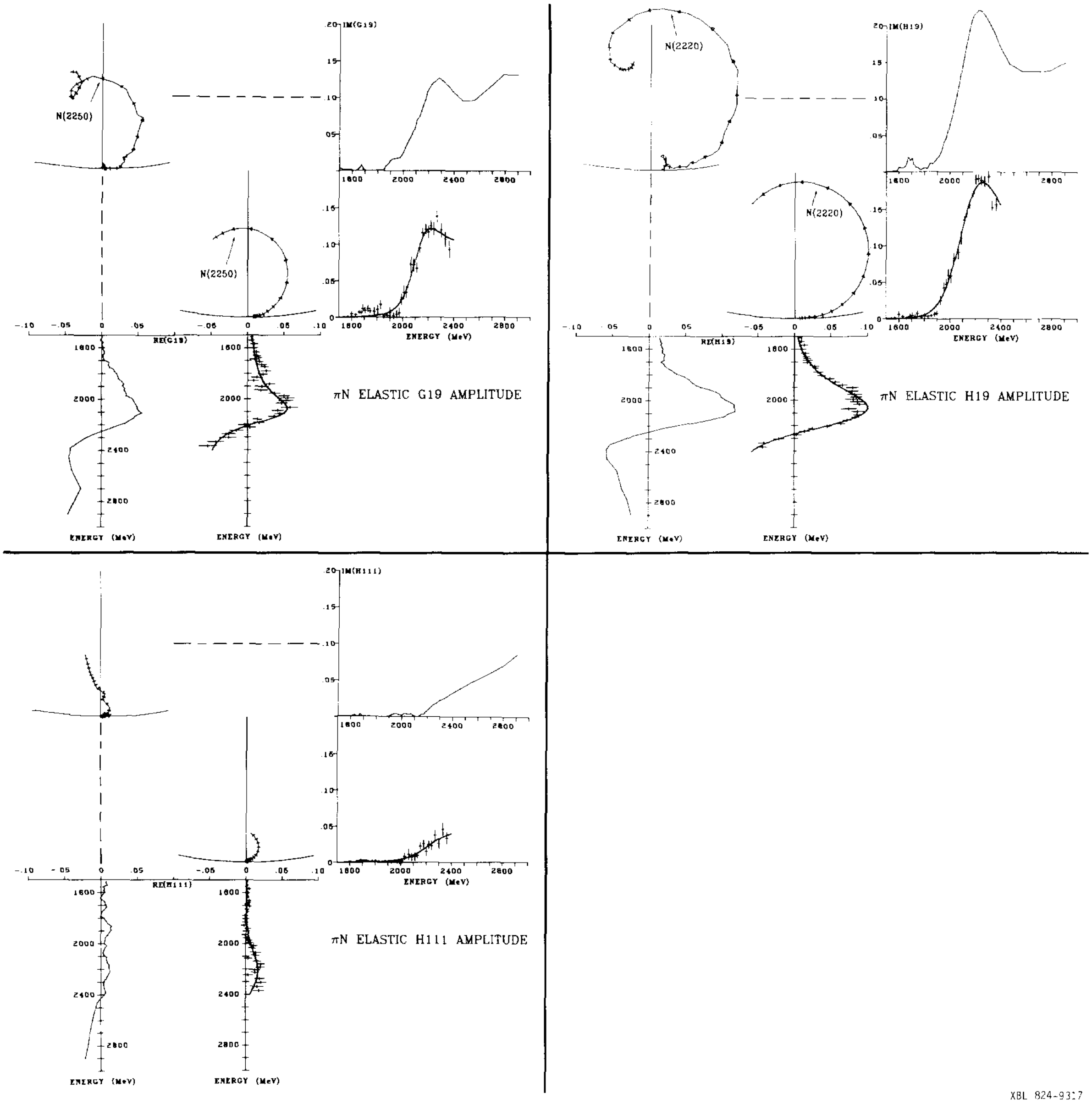

Fig. 1(c). The $L_{2I \cdot 2J} = G_{19}$, H_{19}, and $H_{1\,11}$ partial-wave amplitudes for πN elastic scattering. The upper plot for each amplitude is from HOEHLER 79 and the lower one is from CUTKOSKY 80. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots (in the projections of the CUTKOSKY 80 amplitudes, the "data points" are results of energy-independent fits, and the curves are from an energy-dependent fit to join them).

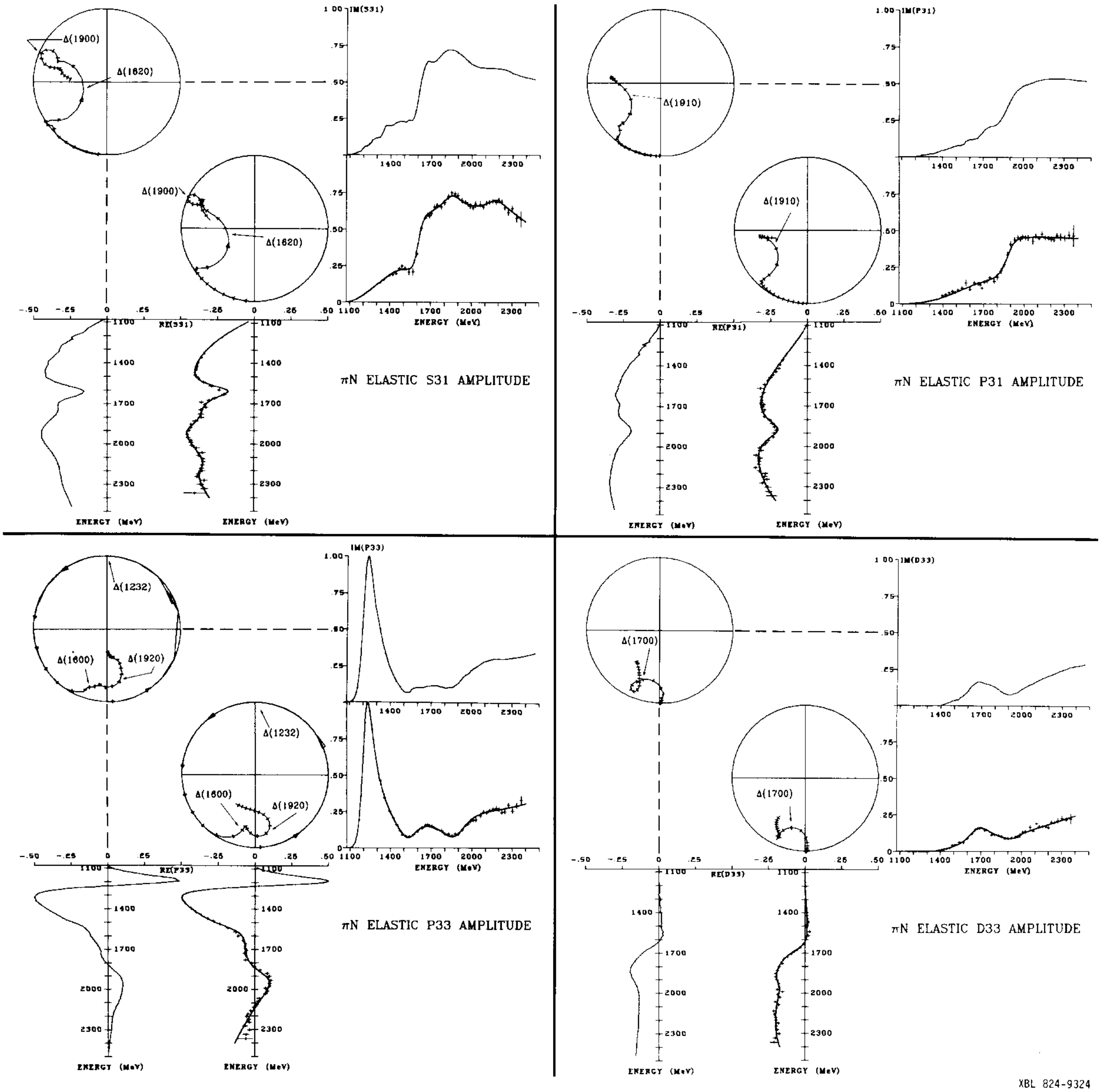

Fig. 1(d). The $L_{2I \cdot 2J} = S_{31}$, P_{31}, P_{33}, and D_{33} partial-wave amplitudes for πN elastic scattering. The upper plot for each amplitude is from HOEHLER 79 and the lower one is from CUTKOSKY 80. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots (in the projections of the CUTKOSKY 80 amplitudes, the "data points" are results of energy-independent fits, and the curves are from an energy-dependent fit to join them).

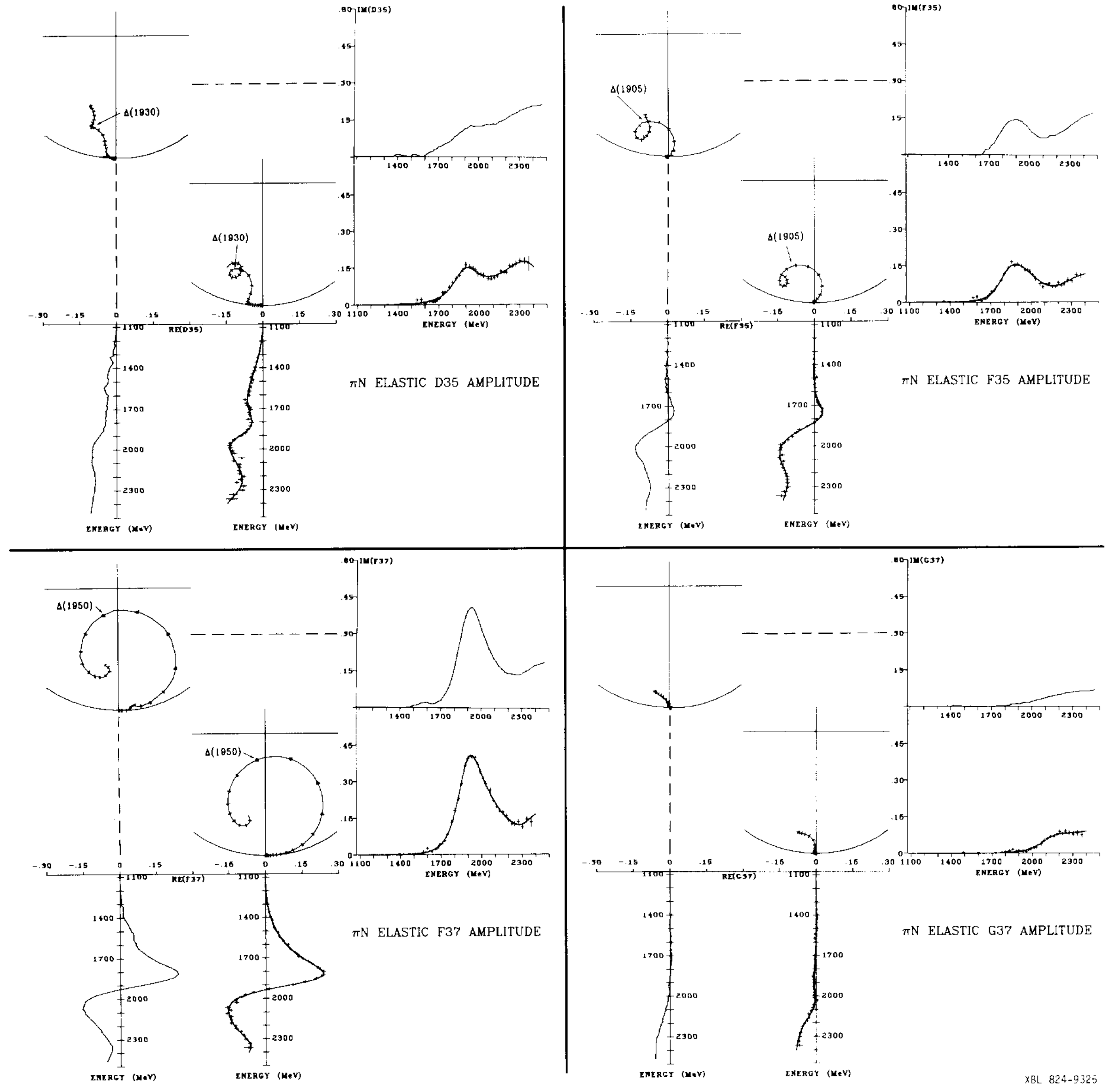

Fig. 1(e). The $L_{2I \cdot 2J} = D_{35}$, F_{35}, F_{37}, and G_{37} partial-wave amplitudes for πN elastic scattering. The upper plot for each amplitude is from HOEHLER 79 and the lower one is from CUTKOSKY 80. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots (in the projections of the CUTKOSKY 80 amplitudes, the "data points" are results of energy-independent fits, and the curves are from an energy-dependent fit to join them).

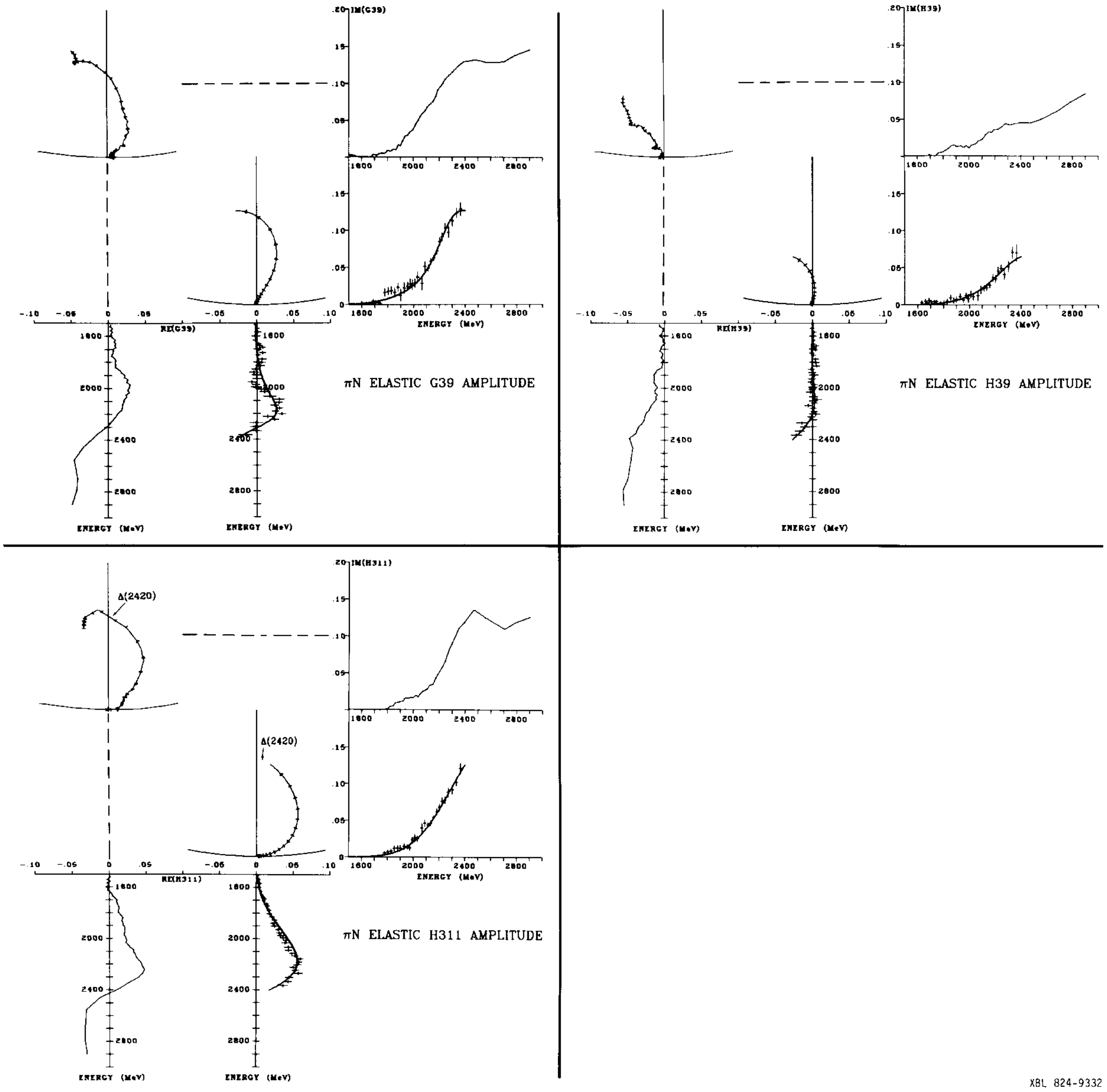

Fig. 1(f). The $L_{2I \cdot 2J} = G_{39}$, H_{39}, and H_{311} partial-wave amplitudes for πN elastic scattering. The upper plot for each amplitude is from HOEHLER 79 and the lower one is from CUTKOSKY 80. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots (in the projections of the CUTKOSKY 80 amplitudes, the "data points" are results of energy-independent fits, and the curves are from an energy-dependent fit to join them).

The preliminary measurements of spin-rotation parameters[20] are in reasonable agreement with the CMU-LBL and KH80 solutions, in particular if one plots the spin-rotation angle. These parameters vary dramatically near the kinematical points where a zero trajectory of the transversity amplitude intersects the physical region and the polarization is ±1 (Ref. 18), but it seems they are not as helpful as one might hope for in the determination of resonance parameters. In principle, they allow a test of isospin invariance at each energy and scattering angle where data exist, but due to the errors it is not clear that this test is useful in practice. For more on this subject, see my contribution to Ref. 6 of Sec. I.

The conclusion from our preliminary analysis is that some corrections to the large partial waves of the KH and CMU-LBL solutions can be estimated, but the small partial waves, such as the small P waves, are still not well determined. Dispersion-relation constraints will be helpful only after the discrepancies between the new low-energy experiments are resolved.

Experiments carried out at Los Alamos and at Leningrad have much improved the information on cross sections and polarization parameters. However, even at six selected momenta, the polarization parameters in some important kinematical regions have large errors or have not been measured. In our analysis, we have problems with the charge-exchange differential cross sections of Borcherding et al.[21] (which have not been published). The discrepancies between the total cross section data are sometimes much larger than the errors (see Sec. 2.2.1.2 in Ref. 2).

Above 2.2 GeV/c, the data are still too sparse for a good determination of the larger number of important partial waves. Evidence for resonances in this region has been reported by Hendry[22] and by Koch.[9] Hendry used an energy-dependent parametrization without analyticity constraints. Koch used analyticity constraints and additional data (Ref. 23, and Ref. 12 in Sec. I). A table of his partial-wave amplitudes from 2 to 6 GeV/c may be found in Ref. 2, pp. 86–91.

Determination of resonance parameters: The differences between the CMU-LBL and KH partial-wave amplitudes would decrease if the analyses were repeated with a more accurate and uniform set of data. This is not true, however, for the differences between the two sets of resonance parameters. At present, no dynamical theory gives a clear prescription for getting the parameters from the amplitudes, so there is no unique and generally accepted definition of these parameters. Usually, of course, generalized Breit-Wigner formulas are fit to the amplitudes where appropriate, but every author has his favored parametrization, and the errors are related to the choice. The parameters given by the KH group and in the earlier work of the CMU-LBL group are of this sort. The groups differ, for example, in the treatment of thresholds for inelastic final states and in assumptions about the background. A more sophisticated multichannel coupled resonance scheme was used in the final CMU-LBL analysis,[8] and their parameters should be preferred to those of the KH group.

It is often clear that some who quote resonance parameters from the Baryon Summary Table are not well-informed on how these parameters have been determined. They treat the values and their errors as "experimental data," that is, too seriously, without understanding the uncertainties. Or they do not distinguish clearly between a phase-shift analysis and the determination of resonance parameters. As noted above, from a given phase-shift solution one can derive considerably different resonance parameters. See also the last paragraph of Sec. I.

One difficulty that becomes increasingly important as the energy increases is that "background terms," namely diffraction and ρ exchange, make contributions to the partial waves that look like highly inelastic resonances (see Ref. 2, Sec. 2.4.1.1). The energy dependences are different, but at high energies data are insufficient to determine accurately the speed with which a partial-wave amplitude traverses the complex plane. Furthermore, it is a dynamical question whether or not this background is part of the resonance mechanism.

If the resonances are ordered according to the shapes of their Argand plots, there is a continuous transition from clean textbook-type resonances to tiny wiggles on large backgrounds. The Baryon Summary Table lists all objects that have a "resonance-like" shape on the Argand diagram and a maximum of the speed. The reader must decide which of these are "resonances" in the framework of his or her model.

Resonance poles: The Baryon Listings give a second set of resonance parameters, the positions and residues of the resonance poles of the partial-wave amplitudes on the second sheet of the s plane. These may be determined in a more or less model-independent way. Table 2 summarizes some of the recent results.[4,8,24] Note, however, that Fonda et al.[25] were able to fit even the P_{33} amplitude in the vicinity of 1230 MeV *without a pole*. A theoretical assumption or argument that excludes such parametrizations is needed.

A special situation arises when a resonance is located near the threshold of an inelastic channel that is strongly coupled to the πN system. For example, the $\Delta\pi$ threshold is near the $N(1440)P_{11}$, and the $N\eta$ threshold is near the $N(1535)S_{11}$. In these cases, a single resonance usually has poles on more than one sheet of the Riemannian surface.[26]

The CMU-LBL group has listed only the poles nearest the real s-axis.[8] Using a coupled-channel K-matrix formalism, Arndt et al.[4] found two poles on different sheets for the $N(1440)P_{11}$, but only one pole for the $N(1535)S_{11}$. There was speculation about a "splitting of the P_{11}," but Cutkosky[27] concluded that it is most likely that the second pole is the shadow pole investigated in Ref. 26. Recently, Pearce and Gibson studied the observable effects of poles and shadow poles in coupled-channel systems in a model,[28] and pointed out that for two coupled P waves and small coupling the Argand diagram looks remarkably like that of the KH80 P_{11} amplitude in the range up to about 800 MeV. This may suggest a relation between the $N(1440)P_{11}$ and $N(1710)P_{11}$ resonances. (The latter resonance was not seen in Ref. 4.)

This interpretation differs from Cutkosky's, so further work is necessary. Best would be to use the method of Cutkosky et al.[8] to search for shadow poles.

In a recent paper, Elsey and Afnan[30] calculated directly the complex poles of the S-matrix in the cloudy bag model instead of starting as usual with stable bound states. Their application to the Roper resonance should be reconsidered, taking into account the above-mentioned results.

It should be emphasized that the details of the partial-wave solution are less important than the method used to extract the poles. For example, Arndt using his method finds two poles for the $N(1440)P_{11}$ even when applying it to the KH solution!

Table 2. Determinations of pole parameters of 3- and 4-star N and Δ resonances. Cutkosky et al.[8] and Arndt et al.[4] take into account inelastic channels in the isobar approximation. Sararu[24] uses Koch's smoothed version[11] of the Karlsruhe solution without taking into account inelastic scattering. In the inelastic region, a resonance generally has poles in several sheets of the energy plane. The parameters here are of the pole reached most directly from the physical region. This condition can be ambiguous when a strong inelastic channel ($\Delta\pi$, $N\eta$, $N\rho$, etc.) opens within the width of the resonance. Two poles are given for the $N(1440)P_{11}$ (Ref. 4).

	Pole position (MeV)		Residue		
Resonance	ReW	$-2\times$ImW	$\lvert r\rvert$(MeV)	$\theta(^\circ)$	Ref.†
$N(1440)P_{11}$	1375 ± 30	180 ± 40	52 ± 5	-100 ± 35	C
	1355	200	62	-108	A
	1416	156	118	-4	
$N(1520)D_{13}$	1510 ± 5	114 ± 10	35 ± 2	-12 ± 5	C
	1508	124	40	-9	A
$N(1535)S_{11}$	1510 ± 50	260 ± 80	120 ± 40	$+15 \pm 45$	C
	1464	150	40	-44	A
$N(1650)S_{11}$	1640 ± 20	150 ± 30	60 ± 10	-75 ± 25	C
	1656	108	34	-54	A
$N(1675)D_{15}$	1660 ± 10	140 ± 10	31 ± 5	-30 ± 10	C
	1658	136	32	-20	A
$N(1680)F_{15}$	1667 ± 5	110 ± 10	34 ± 2	-25 ± 5	C
	1668	110	33	-18	A
	1671	122	25	-20	S
$N(1700)D_{13}$	1660 ± 30	90 ± 40	6 ± 3	0 ± 50	C
	1676	48	2	$+43$	A
$N(1710)P_{11}$	1690 ± 20	80 ± 20	8 ± 2	$+175 \pm 35$	C
	(not seen)				A
$N(1720)P_{13}$	1680 ± 30	120 ± 40	8 ± 2	-160 ± 30	C
	1690	66	3.7	-138	A
	1670	188	8	-127	S
$N(2190)G_{17}$	2100 ± 50	400 ± 160	25 ± 10	-30 ± 50	C
	2056	580	40	-18	S
$N(2220)H_{19}$	2160 ± 80	480 ± 100	45 ± 20	-45 ± 25	C
	2130	340	19	-47	S
$N(2250)G_{19}$	2150 ± 50	360 ± 100	20 ± 6	-50 ± 20	C
$N(2600)I_{1\,11}$	2589	460			S
$\Delta(1232)P_{33}$	1210 ± 1	100 ± 2	53 ± 2	-47 ± 1	C
	1211	102	56	-30	A
	1209	100			S
$\Delta(1620)S_{31}$	1600 ± 15	120 ± 20	15 ± 2	-110 ± 20	C
	1592	108	13	-117	A
$\Delta(1700)D_{33}$	1675 ± 25	220 ± 40	13 ± 3	-20 ± 25	C
	1674	336	32	-24	A
	1680	226	14	$+34$	S
$\Delta(1900)S_{31}$	1870 ± 40	180 ± 50	10 ± 3	$+20 \pm 40$	C
$\Delta(1905)F_{35}$	1830 ± 40	280 ± 60	25 ± 8	-50 ± 20	C
	1872	228	23	-13	A
	1850	220	10	-11	S
$\Delta(1910)P_{31}$	1880 ± 30	200 ± 40	20 ± 4	-90 ± 30	C
	1883	392	27	-89	S
$\Delta(1920)P_{33}$	1900 ± 80	300 ± 100	24 ± 4	-150 ± 30	C
	(not seen)				A
$\Delta(1930)D_{35}$	1890 ± 50	260 ± 60	18 ± 6	-20 ± 40	C
$\Delta(1950)F_{37}$	1890 ± 15	260 ± 40	50 ± 7	-33 ± 8	C
	1864	216	50	-20	A
	1890	242	32	-22	S
$\Delta(2420)H_{3\,11}$	2360 ± 100	420 ± 100	18 ± 6	-30 ± 40	C

(continued)

†C = Cutkosky et al.,[8] A = Arndt et al.,[4] and S = Sararu.[24]

It would be of interest to extend the search for a shadow pole to the $N(1535)S_{11}$, which is closely related to the $n\eta$ threshold (see, for instance, Ref. 29). The rapid increase of inelasticity at the $n\eta$ threshold leads in the partial-wave dispersion relation to a positive contribution to the real part, and thereby to a resonance-like wiggle in the Argand diagram.[31]

Remarkably, there exist families of resonances in which the pole positions are the same within errors; i.e., degeneracy is not excluded (see Sec. 2.4.1.6 in Ref. 2). For example, all six isospin-1/2 partial waves from S_{11} to F_{15} have a well-established resonance with a pole near $\sqrt{s} = (1665{-}60i)$ MeV, and at least six of the seven possible isospin-3/2 resonances from S_{31} to F_{37} have a pole near $(1880{-}120i)$ MeV.

We have not included in the Listings the zeros of the partial-wave amplitudes given in Ref. 4, because a zero in the neighborhood of a resonance pole only gives information about the background. However, zero trajectories of the invariant and transversity amplitudes may be of fundamental importance (Ref. 2, Sec. 2.4.3).

Inelastic 2-body reactions: Analyses of the reactions $\pi N \to N\eta, \pi N \to \Lambda K$, and $\pi N \to \Sigma K$ are similar to analyses of the elastic channel. However, the data are far less complete and accurate, and energy-dependent parametrizations must be used.

The best results, giving resonance masses and widths as well as couplings, follow from the $\pi^- p \to \Lambda K^0$ data of the Rutherford group.[32] One analysis used a reggeized K^*-exchange term to represent the nonresonant and high partial waves. Another used a Lagrangian model for the long-range forces.[33] In general, agreement with the $\pi N \to \pi N$ analyses is good, but there are differences about the $N(1675)D_{15}$ and $N(1710)P_{11}$ widths and the $N(2200)D_{15}$ mass.

In an analysis of the less accurate $\pi^- p \to n\eta$ data,[34] partial waves were parametrized as Breit-Wigner resonances without background. The resonance spectrum was taken from the $\pi N \to \pi N$ analyses, and the data were used to determine the $n\eta$ couplings. For the resonances with relatively large couplings, the masses and widths were varied in a second step.

The results derived from the bubble-chamber data for $\pi^+ p \to \Sigma^+ K^+$ have large uncertainties.[35] Values of the resonance masses were assumed and Breit-Wigner forms and an empirical ansatz for the background were used for partial waves up to F waves (the G waves are probably not negligible at 1.7 GeV/c). The addition of precise data from 1820 to 2350 MeV[36] allowed an improved analysis.[37] A unique solution was found. Above 2 GeV, all the resonances with two or more stars are seen, but none of the 1-star states is supported. Recently new $\pi^+ p \to \Sigma^+ K^+$ data, polarization parameters from 1.49 to 2.069 GeV/c and spin-rotation parameters from 1.69 to 1.88 GeV/c, have been published.[38] These will be important for future analyses.

Isgur[39] has pointed out that distortions of resonance couplings can occur in cases such as $\pi N \to \Delta \to \Sigma K$ if the threshold is just below the resonance mass.

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III. The $\pi N \to N\pi\pi$ reaction

(by D.M. Manley, Kent State University)

The $\pi N \to N\pi\pi$ reaction has been studied up to c.m. energies of about 2000 MeV using isobar models. Isobar models parametrize partial-wave amplitudes with a coherent sum of terms that describe quasi-2-body scattering processes; e.g., $\pi N \rightarrow \Delta(1232)\pi$, $\pi N \rightarrow N\rho$, and $\pi N \rightarrow N(1440)\pi$. The models rest on the observation that almost all $\pi N \rightarrow N\pi\pi$ events lie in quasi-2-body bands in the Dalitz plots. The couplings obtained from the analyses provide stringent constraints on quark models of baryon structure. Details of the isobar-model formalism are given in our 1982 edition.[1]

The Listings give the results from five analyses, none of them new.

LONGACRE 75[2] and LONGACRE 78[3] (LBL-SLAC) estimated resonance parameters based, in part, on $\pi N \rightarrow N\pi\pi$ partial-wave amplitudes obtained from an analysis of 170,000 $\pi^- p \rightarrow n\pi^-\pi^+$, $\pi^- p \rightarrow p\pi^-\pi^0$, and $\pi^+ p \rightarrow p\pi^+\pi^0$ events with c.m. energies between 1300 and 1990 MeV.[4] The analysis included the $\Delta(1232)\pi$, $N\rho$, and $N(\pi\pi)_S$ intermediate states, where $(\pi\pi)_S$ is the strong isospin-0 S-wave $\pi\pi$ interaction. Our Listings give masses, widths, and couplings for nine N and five Δ resonances from LONGACRE 75, and pole positions for ten N and seven Δ resonances from LONGACRE 78. The resonance parameters included in this edition were estimated from a T matrix that satisfies unitarity and which was derived from a K-matrix parametrization of $\pi N \rightarrow N\pi$ and $\pi N \rightarrow N\pi\pi$ partial-wave amplitudes. Parameters we give from LONGACRE 75 were estimated by drawing Breit-Wigner circles through Argand plots (Method II of that paper). Parameters from LONGACRE 78 were estimated by searching for poles in the T matrix (following Method III of LONGACRE 75). We do not include in this edition parameters from Method I of LONGACRE 75, since the masses and widths were taken from an elastic partial-wave analysis and the couplings violate unitarity. Those parameters may be found in our 1986 edition.[5]

LONGACRE 77[6] (Saclay) is a similar but independent analysis of 91,000 $\pi^- p \rightarrow n\pi^-\pi^+$, $\pi^- p \rightarrow p\pi^-\pi^0$, and $\pi^+ p \rightarrow p\pi^+\pi^0$ events with c.m. energies between 1360 and 1760 MeV.[7] Our Listings give masses, widths, pole positions, and couplings for ten N and five Δ resonances, including an $N(1540)P_{13}$ and a $\Delta(1550)P_{31}$, which this analysis suggested for the first time.

NOVOSELLER 78[8] (Cal Tech) estimated resonance couplings to the inelastic channels by fitting partial-wave amplitudes with a resonant parametrization of the T matrix. Masses and widths of resonances were fixed to the results of elastic phase-shift analyses. Two solutions are given, one based on the $\pi N \rightarrow N\pi\pi$ amplitudes of the LBL-SLAC analysis (referred to in the Listings as a Breit-Wigner fit to HERNDON 75[4]), the other on a similar analysis that included the effects of one-pion exchange (referred to in the Listings as a Breit-Wigner fit to NOVOSELLER 78B[9]). The Listings give couplings for two N and three Δ resonances between 1650 and 1970 MeV.

BARNHAM 80[10] (Imperial College) estimated resonance parameters by a procedure similar to Method I of LONGACRE 75.[2] The $\pi N \rightarrow N\pi\pi$ amplitudes were obtained from an analysis of 44,000 $\pi^+ p \rightarrow p\pi^+\pi^0$ and $\pi^+ p \rightarrow n\pi^+\pi^+$ events with c.m. energies between 1400 and 1700 MeV; hence, it concerns only Δ resonances. It included the $\Delta(1232)\pi$, $N(1440)\pi$, and $N\rho$ intermediate states. The Listings give masses, widths, and couplings for four Δ resonances.

MANLEY 84 (VPI & SU)[11] is an analysis of 241,000 $\pi^- p \rightarrow n\pi^-\pi^+$, $\pi^- p \rightarrow p\pi^-\pi^0$, $\pi^+ p \rightarrow p\pi^+\pi^0$, and $\pi^+ p \rightarrow n\pi^+\pi^+$ events with c.m. energies between 1320 and 1930 MeV. It included the $\Delta(1232)\pi$, $N(1440)\pi$, $N(\pi\pi)_S$, and $N\rho$ intermediate states. Partial-wave amplitudes were fitted to a resonant parametrization of the T matrix to obtain smoothed Argand plots; however, resonance parameters were not published. The Listings give signs of couplings for eight N and eight Δ resonances, including a $\Delta(2000)F_{35}$, which this analysis suggested for the first time.

A compilation of the signs of various $\pi N \rightarrow N\pi\pi$ couplings determined from these analyses is given in our 1986 edition.[5] For further details of the analyses, see both our 1982 and 1986 editions.[1,5]

At this time, a new multichannel coupled resonance analysis based in part on the $\pi N \rightarrow N\pi\pi$ amplitudes of MANLEY 84 is underway.[13] This analysis parametrizes the amplitudes using a manifestly time-reversal-invariant and unitary S matrix, somewhat along the lines proposed by Novoseller.[14] The results of this analysis will be discussed in our 1992 edition.

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IV. Photoproduction and Compton scattering

(by R.L. Crawford, University of Glasgow)

Pion photoproduction: The $N\gamma$ couplings of the N and Δ resonances have been obtained in a large number of partial-wave analyses of single-pion photoproduction, $\gamma N \rightarrow \pi N$, on protons and neutrons. The couplings, $A_{1/2}$ and $A_{3/2}$, are related to the helicity amplitudes of the process, $A_{\ell\pm}$ and $B_{\ell\pm}$, by

$$\begin{aligned} A_{\ell\pm} &= \mp\alpha\, C_{N\pi}\, A_{1/2} \\ B_{\ell\pm} &= \pm 4\alpha[(2J-1)(2J+3)]^{-1/2}\, C_{N\pi}\, A_{3/2}\ , \end{aligned}$$

where

$$\alpha \equiv \left[\frac{1}{\pi}\frac{k}{q}\frac{1}{(2J+1)}\frac{M_N}{M_R}\frac{\Gamma_\pi}{\Gamma^2}\right]^{1/2} .$$

Here k and q are the photon and pion c.m. momenta; J is the angular momentum, M_R the mass, Γ the full width, and Γ_π the $N\pi$ partial width of the resonance; M_N is the nucleon mass; and $C_{N\pi}$ is the Clebsch-Gordan coefficient for the decay of the resonance into the relevant $N\pi$ charge state.

The large amount of pion photoproduction data, including many measurements from single and double polarization experiments, has permitted an accurate evaluation of the couplings for many of the resonances with masses below 2 GeV, and has given at least qualitative information about most of the others. However, most photoproduction analyses rely heavily upon $\pi N \to \pi N$ analyses for information on the existence, masses, and widths of the resonances. The only photoproduction analyses that give masses and widths as well as couplings are BERENDS 75, BERENDS 77, BARBOUR 78, and CRAWFORD 80. These results are of interest since they concern the charge +1 states of the resonances. In particular, the mass of the $\Delta(1232)^+$ seems to be as well determined as are the masses of the Δ^{++} and Δ^0, obtained from π^+p and π^-p scattering.

There are three main methods of analysis:

(a) The simple isobar model: This is the simplest form of energy-dependent partial-wave analysis (DPWA). The partial waves are parametrized as Breit-Wigner resonances plus smooth background. The Listings give results from FELLER 76, TAKEDA 80, and BRATASHEVSKIJ 80.

(b) Fixed-t dispersion relations (FTDR): The analyses in the Listings that use this technique are BARBOUR 78, ARAI 80, CRAWFORD 80, FUJII 81, and AWAJI 81.

(c) Energy-independent partial wave analysis (IPWA): The Listings give results from BERENDS 77 and CRAWFORD 83.

NOELLE 78 is a hybrid analysis using FTDR in a coupled-channel calculation. Further details of these methods may be found in our 1982 edition.[1]

Compton scattering: Two analyses, ISHII 80 and WADA 84, contribute measurements of the couplings obtained from Compton scattering on protons. Both are isobar analyses. In general, there is good agreement with results from photoproduction. The differences should not be taken seriously since the quality and quantity of the photoproduction data are much higher and constrain the values of the couplings more strongly than do the Compton scattering data.

Resonance couplings in the Listings: The Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition.[1]

The errors quoted for the couplings in the Listings are calculated in different ways in different analyses and therefore should be used with care. In general, it is likely that the systematic differences between the analyses caused by using different parametrization schemes are more indicative of the true uncertainties than are the quoted errors.

Probably the most reliable analyses are those from Glasgow (BARBOUR 78, CRAWFORD 80, and CRAWFORD 83) and those from Tokyo or based on the Tokyo analyses (ARAI 80, FUJII 81, and AWAJI 81). Table 3 gives a compilation of the couplings from these analyses (unchanged since our 1988 edition). The errors given are a combination of the statistical errors quoted in the analyses and the systematic differences between them. Two values are quoted for $A_{1/2}$ of the $\Delta(1620)\,S_{31}$ to take account of the surprisingly large spread in values obtained for it. This seems to be due to the different methods of treating the imaginary background in this partial wave. The second value given uses only the Glasgow analyses. These have always succeeded in getting stable and acceptable values for the mass and width of this resonance, and it seems reasonable to infer that the coupling obtained is accurate.

$N\gamma$ branching fractions: The Baryon Summary Table gives $N\gamma$ branching fractions for those resonances whose couplings are considered to have an unambiguous sign. The $N\gamma$ partial width Γ_γ is given by

$$\Gamma_\gamma = \frac{k^2}{\pi}\frac{2M_N}{(2J+1)M_R}\left[\,|A_{1/2}|^2 + |A_{3/2}|^2\right] ,$$

where M_N and M_R are the masses of the nucleon and the resonance, J is the resonance spin, and k is the photon c.m. decay momentum. The couplings $A_{1/2}$ and $A_{3/2}$ are taken from Table 3.

The E2/M1 ratio for the $\Delta(1232)P_{33}$: There is renewed interest in the ratio of electric to magnetic multipoles (E2/M1 ratio) for the photon couplings of the $\Delta(1232)P_{33}$, and two groups have used data from previous partial wave analyses to examine this ratio. Various parametrizations of the multipoles in terms of resonance plus background have been used. Results from TANABE 85 and DAVIDSON 86 are quoted in the Listings. Also given as PDG 86 is the average value from the $\Delta(1232)P_{33}$ couplings from the most reliable photoproduction partial wave analyses. Christillin and Dillon[2] also look at the E2/M1 ratio but do not give a specific value, although their results suggest that it should lie between zero and −0.02. They discuss the need for better data. Their papers comment on other analyses in relation to their own. The Particle Data Group value is consistent with the others that treat the $\Delta(1232)P_{33}$ multipoles in a more detailed way. Effectively, the couplings in the partial wave analyses are given by the ratio of the imaginary parts of the multipoles at the resonance energy and, as is pointed out by Christillin and Dillon, the result is the required ratio if the background phase is small.

Table 3. A compilation of measured $N\gamma$ decay couplings. Sources are given in the text.

(a) Proton-target couplings

Resonance	Heli-city	Couplings ($\mathrm{GeV}^{-1/2} \times 10^{-3}$)	Status
$N(1440)P_{11}$	1/2	-69 ± 7	good
$N(1520)D_{13}$	1/2	-22 ± 10	good
	3/2	$+167 \pm 10$	good
$N(1535)S_{11}$	1/2	$+73 \pm 14$	good
$N(1650)S_{11}$	1/2	$+48 \pm 16$	good
$N(1675)D_{15}$	1/2	$+19 \pm 12$	good, nonzero
	3/2	$+19 \pm 12$	good, nonzero
$N(1680)F_{15}$	1/2	-17 ± 10	good, nonzero
	3/2	$+127 \pm 12$	good
$N(1700)D_{13}$	1/2	-22 ± 13	good, small
	3/2	0 ± 19	fair, small
$N(1710)P_{11}$	1/2	$+5 \pm 16$	fair, small
$N(1720)P_{13}$	1/2	$+52 \pm 39$	poor
	3/2	-35 ± 24	fair
$N(1990)F_{17}$	1/2	$+24 \pm 30$	poor
	3/2	$+31 \pm 55$	bad
$\Delta(1232)P_{33}$	1/2	-141 ± 5	very good
	3/2	-258 ± 11	very good
$\Delta(1550)P_{31}$	1/2	$+16 \pm 16$	doubtful
$\Delta(1600)P_{33}$	1/2	-20 ± 29	poor, small
	3/2	$+1 \pm 22$	fair, small
$\Delta(1620)S_{31}$	1/2	$+19 \pm 16$	fair
	(1/2	$+30 \pm 10$	good — see text)
$\Delta(1700)D_{33}$	1/2	$+116 \pm 17$	good
	3/2	$+77 \pm 28$	fair
$\Delta(1900)S_{31}$	1/2	$+10 \pm ?$	?
$\Delta(1905)F_{35}$	1/2	$+27 \pm 13$	good
	3/2	-47 ± 19	fair
$\Delta(1910)P_{31}$	1/2	-12 ± 30	poor
$\Delta(1920)P_{33}$	1/2	$+40 \pm ?$	?
	3/2	$+23 \pm ?$	?
$\Delta(1930)D_{35}$	1/2	-30 ± 40	poor
	3/2	-10 ± 35	poor
$\Delta(1950)F_{37}$	1/2	-73 ± 14	good
	3/2	-90 ± 13	good

(continued)

(b) Neutron-target couplings

Resonance	Heli-city	Couplings ($\mathrm{GeV}^{-1/2} \times 10^{-3}$)	Status
$N(1440)P_{11}$	1/2	$+37 \pm 19$	fair
$N(1520)D_{13}$	1/2	-65 ± 13	good
	3/2	-144 ± 14	good
$N(1535)S_{11}$	1/2	-76 ± 32	fair
$N(1650)S_{11}$	1/2	-17 ± 37	poor
$N(1675)D_{15}$	1/2	-47 ± 23	fair
	3/2	-69 ± 19	fair
$N(1680)F_{15}$	1/2	$+31 \pm 13$	good
	3/2	-30 ± 14	good
$N(1700)D_{13}$	1/2	0 ± 56	bad
	3/2	-2 ± 44	bad
$N(1710)P_{11}$	1/2	-5 ± 23	fair, small
$N(1720)P_{13}$	1/2	-2 ± 26	fair, small
	3/2	-43 ± 94	very bad
$N(1990)F_{17}$	1/2	-49 ± 45	poor
	3/2	-122 ± 55	poor

$K\Lambda$ photoproduction: The Listings now give results from TANABE 89, an isobar analysis of $\gamma p \to \Lambda K^+$ that includes those resonances which have a non-negligible branching ratio to ΛK^+. These are the $N(1650)S_{11}$, the $N(1700)D_{13}$, the $N(1710)P_{11}$, the $N(1720)P_{13}$, and the $N(2190)G_{17}$. The mass of the D_{13} is set rather high at 1880 MeV in the analysis. The isobar contributions to the electric and magnetic multipoles are parametrized in the form

$$M_{\ell\pm} = \left\{ \frac{1}{k_R\, q_R\, \ell(\ell+1)}\, \frac{v_\ell(qR)}{v_\ell(q_R R)} \right\}^{1/2} \times \frac{M_R\, \Gamma\, \sqrt{X_P X_K}\, \exp(i\theta)}{(M_R^2 - s - iM_R\Gamma)}$$

$$E_{\ell\pm} = \left\{ \frac{1}{k_R\, q_R\, (\ell\pm1)(\ell\pm1+1)}\, \frac{v_\ell(qR)}{v_\ell(q_R R)} \right\}^{1/2} \times \frac{M_R\, \Gamma\, \sqrt{X_P X_K}\, \exp(i\theta)}{(M_R^2 - s - iM_R\Gamma)} .$$

Here k and q are the photon and kaon momenta, X_P and X_K are the branching ratios to γp and ΛK^+, $v_\ell(qR)$ is a barrier penetration factor, and θ is a phase angle. The Listings give $\sqrt{X_P X_K}$ and the phase angle θ.

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N(1440) P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**). In addition, results in this region from production experiments, which used to be listed separately as the next entry, have been entirely omitted. They too may be found in our 1982 edition.

N(1440) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1400 to 1480 OUR ESTIMATE			
1440±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1410±12	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1411	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1472	[1] BAKER 79	DPWA	$\pi^- p \to n\eta$
1417	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1460	BERENDS 77	IPWA	$\gamma N \to \pi N$
1380	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
1390	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

N(1440) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
120 to 350 OUR ESTIMATE Our best guess is 200 MeV.			
340±70	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
135±10	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
334	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
113	[1] BAKER 79	DPWA	$\pi^- p \to n\eta$
331	BARBOUR 78	DPWA	$\gamma N \to \pi N$
279	BERENDS 77	IPWA	$\gamma N \to \pi N$
200	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
200	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

N(1440) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1375±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1359	[4] ARNDT 85	DPWA	$\pi N \to \pi N$
1381 or 1379	[5] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$
1360 or 1333	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
180±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
200	[4] ARNDT 85	DPWA	$\pi N \to \pi N$
209 or 210	[5] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$
167 or 234	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

N(1440) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
−9±31	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
−51±7	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

N(1440) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	50–70 %
Γ_2	$N\eta$	
Γ_3	$N\pi\pi$	30–50 %
Γ_4	$\Delta\pi$	10–20 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	10–15 %
Γ_7	$N\rho$, S=1/2, P-wave	
Γ_8	$N\rho$, S=3/2, P-wave	
Γ_9	$N\,(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %
Γ_{10}	$p\gamma$	0.08–0.10 %
Γ_{11}	$p\gamma$, helicity=1/2	
Γ_{12}	$n\gamma$	0.01–0.06 %
Γ_{13}	$n\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

N(1440) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.5 to 0.7 OUR ESTIMATE			
0.68±0.04	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.51±0.05	HOEHLER 79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1440) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	[1] BAKER 79	DPWA	$\pi^- p \to n\eta$
+0.328	[6] FELTESSE 75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1440) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	[7] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
+0.41	[2,8] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.37	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1440) \to N\rho$, S=1/2, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0	MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.11	[2,8] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.23	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1440) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.0	MANLEY 84	IPWA	$\pi N \to N\pi\pi$
+0.18	[2,8] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1440) \to N\,(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.18	[2,8] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.23	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

N(1440) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1440) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.069 ±0.018	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
−0.063 ±0.008	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.069 ±0.004	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.066 ±0.004	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.079 ±0.009	BRATASHEV... 80	DPWA	$\gamma N \to \pi N$
−0.068 ±0.015	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.0584±0.0148	ISHII 80	DPWA	Compton scattering
−0.075 ±0.015	BARBOUR 78	DPWA	$\gamma N \to \pi N$
−0.087 ±0.006	FELLER 76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.129	[9] WADA 84	DPWA	Compton scattering
−0.125	[10] NOELLE 78		$\gamma N \to \pi N$
−0.076	BERENDS 77	IPWA	$\gamma N \to \pi N$

$N(1440) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.037±0.010	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.030±0.003	FUJII 81	DPWA	$\gamma N \to \pi N$
0.023±0.009	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.019±0.012	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.056±0.015	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.029±0.035	TAKEDA 80	DPWA	$\gamma N \to \pi N$
−0.059±0.016	BARBOUR 78	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.062	[10] NOELLE 78		$\gamma N \to \pi N$

$N(1440)$ FOOTNOTES

[1] BAKER 79 finds a coupling of the $N(1440)$ to the $N\eta$ channel near (but slightly below) threshold.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] ARNDT 85 finds a second P_{11} pole at $(1410, -80)$ MeV.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] An alternative which cannot be distinguished from this is to have a P_{13} resonance with $M = 1530$ MeV, $\Gamma = 79$ MeV, and elasticity $= +0.271$.

[7] MANLEY 84 considers this coupling sign to be well determined.

[8] LONGACRE 77 considers this coupling to be well determined.

[9] WADA 84 is inconsistent with other analyses; see the Note on N and Δ Resonances.

[10] Converted to our conventions using $M = 1486$ MeV, $\Gamma = 613$ MeV from NOELLE 78.

$N(1440)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KHAR)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, TOKY)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1520)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B). In addition, results in this region from production experiments, which used to be listed separately as the next entry, have been entirely omitted. They too may be found in our 1982 edition.

$N(1520)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1510 to 1530 OUR ESTIMATE			
1525 ± 10	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1519 ± 4	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1504	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1503	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1510	BERENDS 77	IPWA	$\gamma N \to \pi N$
1510	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
1520	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
100 to 140 OUR ESTIMATE	Our best guess is 125 MeV.		
120 ± 15	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
114 ± 7	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
124	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
183	BAKER 79	DPWA	$\pi^- p \to n\eta$
135	BARBOUR 78	DPWA	$\gamma N \to \pi N$
105	BERENDS 77	IPWA	$\gamma N \to \pi N$
110	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1510 ± 5	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1510	ARNDT 85	DPWA	$\pi N \to \pi N$
1514 or 1511	[3] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$
1508 or 1505	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
114 ± 10	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
122	ARNDT 85	DPWA	$\pi N \to \pi N$
146 or 137	[3] LONGACRE 78	IPWA	$\pi N \to N\pi\pi$
109 or 107	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
34 ± 2	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
-7 ± 3	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

$N(1520)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	50–60 %
Γ_2	$N\eta$	~ 0.1 %
Γ_3	$N\pi\pi$	40–50 %
Γ_4	$\Delta\pi$	20–30 %
Γ_5	$\Delta(1232)\pi$, S-wave	
Γ_6	$\Delta(1232)\pi$, D-wave	
Γ_7	$N\rho$	15–25 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N\,(\pi\pi)^{I=0}_{S\text{-wave}}$	<5 %
Γ_{12}	$p\gamma$	0.43–0.57 %
Γ_{13}	$p\gamma$, helicity=1/2	
Γ_{14}	$p\gamma$, helicity=3/2	
Γ_{15}	$n\gamma$	0.34–0.51 %
Γ_{16}	$n\gamma$, helicity=1/2	
Γ_{17}	$n\gamma$, helicity=3/2	

$N(1520)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.5 to 0.6 OUR ESTIMATE			
0.58 ± 0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.54 ± 0.03	HOEHLER 79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.02	BAKER 79	DPWA	$\pi^- p \to n\eta$
+0.011 or +0.058	FELTESSE 75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
− (large)	[4] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.26	[1,5] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.24	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1520) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
− (large)	[4] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.21	[1,5] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.30	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1520) \to N\rho$, S=3/2, S-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
− (large)	[4] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
−0.35	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.24	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1520) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.13	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.17	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1520) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on *N* and Δ Resonances preceding the Baryon Listings.

N(1520) → $p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.028 ±0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.007 ±0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.032 ±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.032 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.031 ±0.009	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
−0.019 ±0.007	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.0430±0.0063	ISHII	80	DPWA	Compton scattering
−0.016 ±0.008	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.005 ±0.005	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.012	WADA	84	DPWA	Compton scattering
−0.008	[6] NOELLE	78		$\gamma N \to \pi N$
−0.021	BERENDS	77	IPWA	$\gamma N \to \pi N$

N(1520) → $p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.156 ±0.022	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.168 ±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.178 ±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.162 ±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.166 ±0.005	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
0.167 ±0.010	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.1695±0.0014	ISHII	80	DPWA	Compton scattering
+0.157 ±0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.164 ±0.008	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.168	WADA	84	DPWA	Compton scattering
0.206	[6] NOELLE	78		$\gamma N \to \pi N$
+0.075	BERENDS	77	IPWA	$\gamma N \to \pi N$

N(1520) → $n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.066±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.067±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.076±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.071±0.011	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.056±0.011	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.050±0.014	TAKEDA	80	DPWA	$\gamma N \to \pi N$
−0.055±0.014	BARBOUR	78	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.060	[6] NOELLE	78		$\gamma N \to \pi N$

N(1520) → $n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.124±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.158±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.147±0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.148±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.144±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.118±0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
−0.141±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.127	[6] NOELLE	78		$\gamma N \to \pi N$

N(1520) FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] MANLEY 84 considers this coupling sign to be well determined.

[5] LONGACRE 77 considers this coupling to be well determined.

[6] Converted to our conventions using M = 1528 MeV, Γ = 187 MeV from NOELLE 78.

N(1520) REFERENCES

For early references, see Physics Letters **111B** (1982). For very early references, se
Rev. Mod. Phys. **37**, 633 (1965).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KHAR)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, TOKY)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

N(1535) S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

N(1535) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1520 to 1560 OUR ESTIMATE				
1550±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1526± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1513	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1511	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1500	BERENDS	77	IPWA	$\gamma N \to \pi N$
1547± 6	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1520	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1510	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1535) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 OUR ESTIMATE	Our best guess is 150 MeV.			
240±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
136	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
180	BAKER	79	DPWA	$\pi^- p \to n\eta$
132	BARBOUR	78	DPWA	$\gamma N \to \pi N$
57	BERENDS	77	IPWA	$\gamma N \to \pi N$
139±33	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
100	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1535) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1510±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1461	ARNDT	85	DPWA	$\pi N \to \pi N$
1496 or 1499	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1519± 4	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1525 or 1527	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
140	ARNDT	85	DPWA	$\pi N \to \pi N$
103 or 105	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
140±32	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135 or 123	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1535)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
116±46	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
20±21	BHANDARI 77	DPWA	Uses $N\eta$ cusp

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
31±92	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
13± 8	BHANDARI 77	DPWA	Uses $N\eta$ cusp

$N(1535)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–50 %
Γ_2	$N\eta$	45–55 %
Γ_3	$N\pi\pi$	~ 10 %
Γ_4	$\Delta\pi$	<5 %
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	~ 5 %
Γ_7	$N\rho$, S=1/2, S-wave	
Γ_8	$N\rho$, S=3/2, D-wave	
Γ_9	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	~ 5 %
Γ_{10}	$p\gamma$	0.1–0.2 %
Γ_{11}	$p\gamma$, helicity=1/2	
Γ_{12}	$n\gamma$	0.15–0.35 %
Γ_{13}	$n\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

$N(1535)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.35 to 0.50 OUR ESTIMATE			
0.50 ±0.10	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.38 ±0.04	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.297±0.026	BHANDARI 77	DPWA	Uses $N\eta$ cusp

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1535) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.33	BAKER 79	DPWA	$\pi^- p \to n\eta$
+0.48	FELTESSE 75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1535) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.00	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.06	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1535) \to N\rho$, S=1/2, S-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
− (small)	[4] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.10	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.09	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1535) \to N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (small)	[4] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.08	[1] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.09	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$N(1535)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1535) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.053 ±0.015	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.077 ±0.021	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.083 ±0.007	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.080 ±0.007	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.029 ±0.007	BRATASHEV... 80	DPWA	$\gamma N \to \pi N$
0.065 ±0.016	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
0.0704±0.0091	ISHII 80	DPWA	Compton scattering
+0.082 ±0.019	BARBOUR 78	DPWA	$\gamma N \to \pi N$
+0.070 ±0.004	FELLER 76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.055	WADA 84	DPWA	Compton scattering
0.046	[5] NOELLE 78		$\gamma N \to \pi N$
+0.034	BERENDS 77	IPWA	$\gamma N \to \pi N$

$N(1535) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.035±0.014	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.062±0.003	FUJII 81	DPWA	$\gamma N \to \pi N$
−0.075±0.019	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.075±0.018	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.098±0.026	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.011±0.017	TAKEDA 80	DPWA	$\gamma N \to \pi N$
−0.112±0.034	BARBOUR 78	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.048	[5] NOELLE 78		$\gamma N \to \pi N$

$N(1535)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] MANLEY 84 considers this coupling sign to be well determined.

[5] Converted to our conventions using M = 1548 MeV, Γ = 73 MeV from NOELLE 78.

$N(1535)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KHAR)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, TOKY)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
BHANDARI	77	PR D15 192	+Chao	(CMU) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

OTHER RELATED PAPERS

DAVIES	67B	NC 52A 1112	+Moorhouse	(GLAS, RHEL)

$N(1540)\ P_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: $*$

OMITTED FROM SUMMARY TABLE

Not seen in $\pi N \rightarrow \pi N$ analyses, and its existence is thus doubtful.

$N(1540)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1540	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1540)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
200	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1540)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1535 or 1482	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
207 or 314	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1540)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$\Delta(1232)\pi$, P-wave
Γ_3	$N\rho$, $S=1/2$, P-wave
Γ_4	$N\rho$, $S=3/2$, P-wave
Γ_5	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$
Γ_6	$p\gamma$, helicity=1/2
Γ_7	$p\gamma$, helicity=3/2

$N(1540)$ BRANCHING RATIOS

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)\ S_{31}$ coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1540) \rightarrow \Delta(1232)\pi$, P-wave $\qquad (\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
-0.11	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1540) \rightarrow N\rho$, $S=1/2$, P-wave $\qquad (\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
$+0.08$	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1540) \rightarrow N\rho$, $S=3/2$, P-wave $\qquad (\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.00	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1540) \rightarrow N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ $\qquad (\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.00	[1] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1540)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1540) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*	*TECN*	*COMMENT*
-0.014 ± 0.028	CRAWFORD 83	IPWA	$\gamma N \rightarrow \pi N$

$N(1540) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.009 ± 0.027	CRAWFORD 83	IPWA	$\gamma N \rightarrow \pi N$

$N(1540)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

$N(1540)$ REFERENCES

CRAWFORD 83 NP B211 1 +Morton (GLAS)
LONGACRE 77 NP B122 493 +Dolbeau (SACL) IJP
Also 76 NP B108 365 Dolbeau, Triantis, Neveu, Cadiet (SACL) IJP

$N(1650)\ S_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: $****$

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

$N(1650)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1620 to 1680 OUR ESTIMATE			
1650 ± 30	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
1670 ± 8	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1688	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
1672	MUSETTE 80	IPWA	$\pi^- p \rightarrow \Lambda K^0$
1680	SAXON 80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1680	BAKER 78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1694	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$
1700 ± 5	[1] BAKER 77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
1680	[1] BAKER 77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1700	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$
1675	KNASEL 75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1660	[3] LONGACRE 75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1650)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
100 to 200 OUR ESTIMATE	Our best guess is 150 MeV.		
150 ± 40	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
180 ± 20	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
183	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
179	MUSETTE 80	IPWA	$\pi^- p \rightarrow \Lambda K^0$
120	SAXON 80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
90	BAKER 78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
193	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$
130 ± 10	[1] BAKER 77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
90	[1] BAKER 77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
170	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$
170	KNASEL 75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
130	[3] LONGACRE 75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1650)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1640 ± 20	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1660	ARNDT 85	DPWA	$\pi N \rightarrow \pi N$
1648 or 1651	[4] LONGACRE 78	IPWA	$\pi N \rightarrow N\pi\pi$
1699 or 1698	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
150 ± 30	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
122	ARNDT 85	DPWA	$\pi N \rightarrow \pi N$
117 or 119	[4] LONGACRE 78	IPWA	$\pi N \rightarrow N\pi\pi$
174 or 173	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1650)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
16 ± 25	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
-58 ± 12	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$N(1650)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–65 %
Γ_2	$N\eta$	~ 1.5 %
Γ_3	ΛK	~ 8 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	20–35 %
Γ_6	$\Delta\pi$	<10 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$N\rho$	5–30 %
Γ_9	$N\rho$, S=1/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<15 %
Γ_{12}	$N(1440)\pi$, S-wave	
Γ_{13}	$p\gamma$	0.04–0.16 %
Γ_{14}	$p\gamma$, helicity=1/2	
Γ_{15}	$n\gamma$	0–0.17 %
Γ_{16}	$n\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

$N(1650)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.55 to 0.65 OUR ESTIMATE				
0.65 ± 0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.61 ± 0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09	[5] BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.22	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
-0.22	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.25	[6] BAKER	78	DPWA	See SAXON 80
-0.23 ± 0.01	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
-0.25	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
0.12	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.254	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.066 to 0.137	[7] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.20	KNASEL	75	DPWA	

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+ (large)	[8] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
$+0.29$	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
$+0.15$	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to N\rho$, S=1/2, S-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
–	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
$+0.17$	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
-0.16	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
large	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
$+0.29$	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
0.00	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
$+0.25$	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1650) \to N(1440)\pi$, S-wave $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	MANLEY	84	IPWA	$\pi N \to N\pi\pi$

$N(1650)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1650) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.033 ± 0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.050 ± 0.010	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.065 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.061 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.031 ± 0.017	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.048\pm0.017$	BARBOUR	78	DPWA	$\gamma N \to \pi N$
$+0.068\pm0.009$	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.091	WADA	84	DPWA	Compton scattering

$N(1650) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.008 ± 0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004 ± 0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
0.010 ± 0.020	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.008 ± 0.019	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.068 ± 0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.011 ± 0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
-0.045 ± 0.024	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1650)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \to N(1650) \to \Lambda K^+$ (E_{0+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
8.13	TANABE	89	DPWA

$p\gamma \to N(1650) \to \Lambda K^+$ phase angle θ (E_{0+} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-107.8	TANABE	89	DPWA

$N(1650)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] BAKER 79 fixed this coupling during fitting, but the negative sign relative to the $N(1535)$ is well determined.

[6] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions. Superseded by SAXON 80.

[7] The range given for DEANS 75 is from the four best solutions.

[8] MANLEY 84 considers this coupling sign to be well determined.

[9] LONGACRE 77 considers this coupling to be well determined.

$N(1650)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
MUSETTE	80	NC 57A 37		(BRUX) IJP

SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1675)\ D_{15}$

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**). In addition, results in this region from production experiments, which used to be listed separately in an entry following the $N(1700)$, have been entirely omitted. They too may be found in our 1982 edition.

$N(1675)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1660 to 1690 OUR ESTIMATE				
1675±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1679± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1685	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1670	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1680	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1650	[1] LONGACRE	77	IPWA	$\pi N \to N \pi\pi$
1660	[2] LONGACRE	75	IPWA	$\pi N \to N \pi\pi$

$N(1675)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
120 to 180 OUR ESTIMATE	Our best guess is 155 MeV.			
160±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
191	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
40	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
88	BAKER	79	DPWA	$\pi^- p \to n\eta$
192	BARBOUR	78	DPWA	$\gamma N \to \pi N$
130	[1] LONGACRE	77	IPWA	$\pi N \to N \pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N \pi\pi$

$N(1675)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1660±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1661	ARNDT	85	DPWA	$\pi N \to \pi N$
1663 or 1668	[3] LONGACRE	78	IPWA	$\pi N \to N \pi\pi$
1649 or 1650	[1] LONGACRE	77	IPWA	$\pi N \to N \pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
140±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
142	ARNDT	85	DPWA	$\pi N \to \pi N$
146 or 171	[3] LONGACRE	78	IPWA	$\pi N \to N \pi\pi$
127 or 127	[1] LONGACRE	77	IPWA	$\pi N \to N \pi\pi$

$N(1675)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
27±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−16±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1675)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–40 %
Γ_2	$N\eta$	~ 1 %
Γ_3	ΛK	~ 0.1 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	60–65 %
Γ_6	$\Delta\pi$	55–60 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$\Delta(1232)\pi$, G-wave	
Γ_9	$N\rho$	<10 %
Γ_{10}	$N\rho$, S=1/2, D-wave	
Γ_{11}	$N\rho$, S=3/2, D-wave	
Γ_{12}	$N\rho$, S=3/2, G-wave	
Γ_{13}	$N\ (\pi\pi)^{I=0}_{S\text{-wave}}$	<5 %
Γ_{14}	$N(1520)\pi$, P-wave	
Γ_{15}	$p\gamma$	~ 0.01 %
Γ_{16}	$p\gamma$, helicity=1/2	
Γ_{17}	$p\gamma$, helicity=3/2	
Γ_{18}	$n\gamma$	0.07–0.12 %
Γ_{19}	$n\gamma$, helicity=1/2	
Γ_{20}	$n\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$N(1675)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.35 to 0.40 OUR ESTIMATE				
0.38±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.07	BAKER	79	DPWA	$\pi^- p \to n\eta$
0.0 or +0.009	FELTESSE	75	DPWA	1488–1745 MeV

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.036	[4] SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
−0.034±0.006	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.003	[5] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)\ S_{31}$ coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+ (large)	[6] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
+0.46	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.50	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.5	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
− (small)	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
−0.15	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N\ (\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.03	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1675) \to N(1520)\pi$, P-wave $(\Gamma_1\Gamma_{14})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.15	MANLEY	84	IPWA	$\pi N \to N\pi\pi$

$N(1675)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1675) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.021±0.011	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.034±0.005	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.006±0.005	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.006±0.004	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.023±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.022±0.010	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.034±0.004	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1675) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.015±0.009	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.024±0.008	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.030±0.004	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.029±0.004	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.003±0.012	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.015±0.006	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.019±0.009	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1675) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.057±0.024	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.033±0.004	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.039±0.017	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.025±0.027	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.059±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.021±0.011	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
−0.066±0.020	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1675) \rightarrow n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.077±0.018	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.069±0.004	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.066±0.026	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.071±0.022	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.059±0.020	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.030±0.012	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
−0.073±0.014	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1675)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] SAXON 80 finds the coupling phase is near 90°.

[5] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] MANLEY 84 considers this coupling sign to be well determined.

[7] LONGACRE 77 considers this coupling to be well determined.

[8] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1675)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1680)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B). In addition, results in this region from production experiments, which used to be listed separately in an entry following the $N(1700)$, have been entirely omitted. They too may be found in our 1982 edition.

$N(1680)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670 to 1690 OUR ESTIMATE				
1680±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1684± 3	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1682	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1680	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1660	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1685	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1670	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1680)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110 to 140 OUR ESTIMATE	Our best guess is 125 MeV.			
120±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
128± 8	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
121	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
119	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
150	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
155	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
130	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1680)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1667±5	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1680	ARNDT	85	DPWA	$\pi N \rightarrow \pi N$
1668 or 1674	[3] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1656 or 1653	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	ARNDT	85	DPWA	$\pi N \rightarrow \pi N$
132 or 137	[3] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
145 or 143	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1680)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
31±2	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−14±3	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$N(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–65 %
Γ_2	$N\eta$	<1 %
Γ_3	ΛK	not seen
Γ_4	ΣK	
Γ_5	$N\pi\pi$	35–45 %
Γ_6	$\Delta\pi$	10–15 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$\Delta(1232)\pi$, F-wave	
Γ_9	$N\rho$	10–20 %
Γ_{10}	$N\rho$, $S=1/2$, F-wave	
Γ_{11}	$N\rho$, $S=3/2$, P-wave	
Γ_{12}	$N\rho$, $S=3/2$, F-wave	
Γ_{13}	$N\,(\pi\pi)^{I=0}_{S\text{-wave}}$	15–20 %
Γ_{14}	$p\gamma$	0.21–0.30 %
Γ_{15}	$p\gamma$, helicity=1/2	
Γ_{16}	$p\gamma$, helicity=3/2	
Γ_{17}	$n\gamma$	0.02–0.05 %
Γ_{18}	$n\gamma$, helicity=1/2	
Γ_{19}	$n\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$N(1680)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.55 to 0.65 OUR ESTIMATE			
0.62±0.05	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.65±0.02	HOEHLER 79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
not seen	BAKER 79	DPWA	$\pi^- p \to n\eta$

$\Gamma(N\eta)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.0005 or 0.001	[4] CARRERAS 70	MPWA	t pole + resonance
0.0004	[4] BOTKE 69	MPWA	t pole + resonance
0.003 ±0.002	[4] DEANS 69	MPWA	t pole + resonance

$\Gamma(N\eta)/\Gamma(N\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.027	HEUSCH 66	RVUE	π^0, η photoproduction

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

Coupling to ΛK not required in the analyses of BAKER 77, SAXON 80, or BELL 83.

VALUE	DOCUMENT ID	TECN	COMMENT
0.01	KNASEL 75	DPWA	$\pi^- p \to \Lambda K^0$
−0.009±0.009	DEVENISH 74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.001	[5] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
− (large)	[6] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.27	[1,7] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.25	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.38	[8] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (small)	[6] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
+0.07	[1,7] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.08	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.05	[8] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\rho$, $S=3/2$, P-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
− (large)	[6] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.23	[1,7] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.30	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.34	[8] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\rho$, $S=3/2$, F-wave — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
− (small)	MANLEY 84	IPWA	$\pi N \to N\pi\pi$
−0.15	[1,7] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1680) \to N\,(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	[6] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
+0.31	[1,7] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.42	[8] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$N(1680)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1680) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.017±0.018	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
−0.009±0.006	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.028±0.003	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.003	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.018±0.014	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.005±0.015	BARBOUR 78	DPWA	$\gamma N \to \pi N$
−0.009±0.002	FELLER 76	DPWA	$\gamma N \to \pi N$

$N(1680) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.132±0.010	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.115±0.008	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.115±0.003	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.122±0.003	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.141±0.014	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
+0.138±0.021	BARBOUR 78	DPWA	$\gamma N \to \pi N$
+0.121±0.010	FELLER 76	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.017±0.014	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.032±0.003	FUJII 81	DPWA	$\gamma N \to \pi N$
0.026±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.028±0.014	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.044±0.012	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
0.025±0.010	TAKEDA 80	DPWA	$\gamma N \to \pi N$
+0.037±0.010	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.033±0.013	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.023±0.005	FUJII 81	DPWA	$\gamma N \to \pi N$
−0.024±0.009	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.029±0.017	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.033±0.015	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.035±0.012	TAKEDA 80	DPWA	$\gamma N \to \pi N$
−0.038±0.018	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$N(1680)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] The parametrization used may be double counting.

[5] The range given is from 3 of 4 best solutions; not present in solution 1. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] MANLEY 84 considers this coupling sign to be well determined.

[7] LONGACRE 77 considers this coupling to be well determined.

[8] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1680)$ REFERENCES

For early references, see Physics Letters **111B** (1982). For very early references, see Rev. Mod. Phys. **37**, 633 (1965).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
CARRERAS	70	NP B16 35	+Donnachie	(DARE, MCHS)
BOTKE	69	PR 180 1417		(UCSB)
DEANS	69	PR 185 1797	+Wooten	(SFLA)
HEUSCH	66	PRL 17 1019	+Prescott, Dashen	(CIT)

$N(1700)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**). In addition, results in this region from production experiments, which used to be listed separately as the next entry, have been entirely omitted. They too may be found in our 1982 edition.

The various partial-wave analyses do not agree very well.

$N(1700)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1670 to 1730 OUR ESTIMATE				
1675±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1731±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1709	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1650	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1880	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
1690 to 1710	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1719	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1670±10	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1690	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1660	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1710	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
70 to 120 OUR ESTIMATE Our best guess is 100 MeV.				
90±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
110±30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
166	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
70	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
87	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
70 to 100	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
126	BARBOUR	78	DPWA	$\gamma N \to \pi N$
90±25	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
100	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
600	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1660±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1670	ARNDT	85	DPWA	$\pi N \to \pi N$
1710 or 1678	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1616 or 1613	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
90±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
80	ARNDT	85	DPWA	$\pi N \to \pi N$
607 or 567	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
577 or 575	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
6±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1700)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	~ 4 %
Γ_3	ΛK	~ 0.2 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	80–90 %
Γ_6	$\Delta\pi$	15–70 %
Γ_7	$\Delta(1232)\pi$, S-wave	
Γ_8	$\Delta(1232)\pi$, D-wave	
Γ_9	$N\rho$	<20 %
Γ_{10}	$N\rho$, S=1/2, D-wave	
Γ_{11}	$N\rho$, S=3/2, S-wave	
Γ_{12}	$N\rho$, S=3/2, D-wave	
Γ_{13}	$N\,(\pi\pi)^{I=0}_{S\text{-wave}}$	<70 %
Γ_{14}	$p\gamma$	~ 0.01 %
Γ_{15}	$p\gamma$, helicity=1/2	
Γ_{16}	$p\gamma$, helicity=3/2	
Γ_{17}	$n\gamma$	
Γ_{18}	$n\gamma$, helicity=1/2	
Γ_{19}	$n\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$N(1700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05 to 0.15 OUR ESTIMATE				
0.11±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1700) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.065	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1700) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.012	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.012	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
+0.026±0.019	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.04	[6] BAKER	78	DPWA	See SAXON 80
−0.03 ±0.004	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.03	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1700) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
<0.017	[7] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
small	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
0.00	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.16	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+ (small)	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
−0.12	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.14	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to N\rho$, $S=3/2$, S-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.07	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to N\,(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+ (small)	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
0.00	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.2	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1700) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.016 ± 0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.002 ± 0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.028 ± 0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.029 ± 0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.024 ± 0.019	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.033 ± 0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.014 ± 0.025	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1700) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.009 ± 0.012	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.029 ± 0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.002 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.014 ± 0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.017 ± 0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.014 ± 0.025	BARBOUR	78	DPWA	$\gamma N \to \pi N$
$0.0\ \ \pm0.014$	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1700) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.006 ± 0.024	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.002 ± 0.013	FUJII	81	DPWA	$\gamma N \to \pi N$
-0.052 ± 0.030	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.055 ± 0.030	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.052 ± 0.035	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.050\pm0.042$	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1700) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.033 ± 0.017	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.018 ± 0.018	FUJII	81	DPWA	$\gamma N \to \pi N$
-0.037 ± 0.036	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.035 ± 0.024	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.041 ± 0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.035\pm0.030$	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1700)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1700) \to \Lambda K^+$ (E_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.09	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1700) \to \Lambda K^+$ (M_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−7.09	TANABE	89	DPWA

$p\gamma \to N(1700) \to \Lambda K^+$ phase angle θ **(E_{2-} amplitude)**

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−35.9	TANABE	89	DPWA

$N(1700)$ FOOTNOTES

[1] The high mass found by BAKER 79 may be influenced by the $N(2080)$.

[2] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[3] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.

[7] The range given is from the four best solutions.

$N(1700)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1710)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**).

The various partial-wave analyses do not agree very well.

$N(1710)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1680 to 1740 OUR ESTIMATE				
1700 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
$1723\pm\ 9$	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1692	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1730	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1690	BAKER	79	DPWA	$\pi^- p \to n\eta$
1650 to 1680	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1721	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1625 ± 10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1650	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1720	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1670	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1710	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1710)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
90 to 130 OUR ESTIMATE	Our best guess is 110 MeV.			
90 ± 30	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
120 ± 15	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
540	BELL	83	DPWA	$\pi^- p \rightarrow \Lambda K^0$
200	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
550	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
97	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
90 to 150	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
167	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
160 ± 6	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
95	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
120	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
174	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
75	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1710)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1690 ± 20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1708 or 1712	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1720 or 1711	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 ± 20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
17 or 22	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
123 or 115	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1710)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-8 ± 2	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1 ± 5	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$N(1710)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	~ 25 %
Γ_3	ΛK	~ 15 %
Γ_4	ΣK	2–10 %
Γ_5	$N\pi\pi$	<50 %
Γ_6	$\Delta\pi$	10–20 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	5–35 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–35 %
Γ_{12}	$p\gamma$, helicity=1/2	
Γ_{13}	$n\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

$N(1710)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ $\qquad \Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.20 ± 0.04	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.12 ± 0.04	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow N\eta$ $\qquad (\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow \Lambda K$ $\qquad (\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.16	BELL	83	DPWA	$\pi^- p \rightarrow \Lambda K^0$
-0.14	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.12	[5] BAKER	78	DPWA	See SAXON 80
-0.05 ± 0.03	[1] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
-0.10	[1] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
0.10	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow \Sigma K$ $\qquad (\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.034	LIVANOS	80	DPWA	$\pi p \rightarrow \Sigma K$
0.075 to 0.203	[6] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow \Delta(1232)\pi$, P-wave $\qquad (\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$-$	MANLEY	84	IPWA	$\pi N \rightarrow N\pi\pi$
-0.17	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
$+0.20$	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow N\rho$, S=1/2, P-wave $\qquad (\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+$	MANLEY	84	IPWA	$\pi N \rightarrow N\pi\pi$
$+0.19$	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
-0.20	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow N\rho$, S=3/2, P-wave $\qquad (\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.31$	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1710) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ $\qquad (\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.26	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
-0.28	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1710)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1710) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.006 ± 0.018	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.028 ± 0.009	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
-0.009 ± 0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
-0.012 ± 0.005	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.015 ± 0.025	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
$+0.001 \pm 0.039$	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
$+0.053 \pm 0.019$	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1710) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.000 ± 0.018	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
-0.001 ± 0.003	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
0.005 ± 0.013	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.011 ± 0.021	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
-0.017 ± 0.020	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
-0.028 ± 0.045	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1710)$ $\gamma p \rightarrow \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(1710) \rightarrow \Lambda K^+$ $\qquad$ (M_{1-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-7.21	TANABE	89	DPWA

$p\gamma \rightarrow N(1710) \rightarrow \Lambda K^+$ phase angle θ $\qquad$ (M_{1-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
176.3	TANABE	89	DPWA

$N(1710)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.

[6] The range given for DEANS 75 is from the four best solutions.

$N(1710)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(TOKY)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAMB) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1720)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

$N(1720)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1690 to 1800 OUR ESTIMATE				
1700 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1710 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1785	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1690	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1710 to 1790	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1809	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1640 ± 10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1710	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1750	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1850	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1720	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1720)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125 to 250 OUR ESTIMATE Our best guess is 200 MeV.				
125 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
308	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
120	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
447	BAKER	79	DPWA	$\pi^- p \to n\eta$
300 to 400	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
285	BARBOUR	78	DPWA	$\gamma N \to \pi N$
200 ± 50	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
500	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
130	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
327	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
150	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1720)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1680 ± 30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1705	ARNDT	85	DPWA	$\pi N \to \pi N$
1716 or 1716	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1745 or 1748	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
120 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
80	ARNDT	85	DPWA	$\pi N \to \pi N$
124 or 126	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
135 or 123	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1720)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
-8 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
-3 ± 4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1720)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	~ 3.5 %
Γ_3	ΛK	~ 5 %
Γ_4	ΣK	2–5 %
Γ_5	$N\pi\pi$	<75 %
Γ_6	$\Delta\pi$	<15 %
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	<75 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N\,(\pi\pi)^{I=0}_{S\text{-wave}}$	<20 %
Γ_{12}	$p\gamma$	
Γ_{13}	$p\gamma$, helicity=1/2	
Γ_{14}	$p\gamma$, helicity=3/2	
Γ_{15}	$n\gamma$	
Γ_{16}	$n\gamma$, helicity=1/2	
Γ_{17}	$n\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$N(1720)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10 to 0.20 OUR ESTIMATE				
0.10 ± 0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14 ± 0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1720) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.08	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1720) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.09	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
-0.11	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.09	[5] BAKER	78	DPWA	See SAXON 80
-0.06 ± 0.02	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
-0.09	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1720) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.051 to 0.087	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(1720) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.17	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1720) \rightarrow N\rho$, S=1/2, P-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.26	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.40	[3] LONGACRE 75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1720) \rightarrow N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.15	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow N(1720) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.19	[2] LONGACRE 77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1720)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1720) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.044±0.066	CRAWFORD 83	IPWA	$\gamma N \rightarrow \pi N$
−0.004±0.007	AWAJI 81	DPWA	$\gamma N \rightarrow \pi N$
0.051±0.009	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.071±0.010	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.038±0.050	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
+0.111±0.047	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$

$N(1720) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.024±0.006	CRAWFORD 83	IPWA	$\gamma N \rightarrow \pi N$
−0.040±0.016	AWAJI 81	DPWA	$\gamma N \rightarrow \pi N$
−0.058±0.010	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.011±0.011	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.014±0.040	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
−0.063±0.032	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$

$N(1720) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.002±0.005	AWAJI 81	DPWA	$\gamma N \rightarrow \pi N$
−0.019±0.033	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.001±0.038	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.003±0.034	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
+0.007±0.020	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$

$N(1720) \rightarrow n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.015±0.019	AWAJI 81	DPWA	$\gamma N \rightarrow \pi N$
−0.139±0.039	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.134±0.044	ARAI 80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.018±0.028	CRAWFORD 80	DPWA	$\gamma N \rightarrow \pi N$
+0.051±0.051	BARBOUR 78	DPWA	$\gamma N \rightarrow \pi N$

$N(1720)$ $\gamma p \rightarrow \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(1720) \rightarrow \Lambda K^+$ (E_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
9.52	TANABE 89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \rightarrow N(1720) \rightarrow \Lambda K^+$ (M_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.18	TANABE 89	DPWA

$p\gamma \rightarrow N(1720) \rightarrow \Lambda K^+$ phase angle θ (E_{1+} amplitude)

VALUE (degrees)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
−103.4	TANABE 89	DPWA

$N(1720)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The overall phase of BAKER 78 copulings has been changed to agree with previous conventions.

[6] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(1720)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

TANABE 89 PR C39 741 +Kohno, Bennhold (MANZ)
Also 89 NC 102A 193 Kohno, Tanabe, Bennhold (MANZ)
ARNDT 85 PR D32 1085 +Ford, Roper (VPI)
BELL 83 NP B222 389 +Blissett, Broome, Daley, Hart, Lintern+ (RL) IJP
CRAWFORD 83 NP B211 1 +Morton (GLAS)
AWAJI 81 Bonn Conf. 352 +Kajikawa (NAGO)
Also 82 NP B197 365 Fujii, Hayashii, Iwata, Kajikawa+ (NAGO)
ARAI 80 Toronto Conf. 93 (TOKY)
Also 82 NP B194 251 Arai, Fujii (TOKY)
CRAWFORD 80 Toronto Conf. 107 (GLAS)
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL) IJP
SAXON 80 NP B162 522 +Baker, Bell, Blissett, Bloodworth+ (RHEL, BRIS) IJP
BAKER 79 NP B156 93 +Brown, Clark, Davies, Depagter, Evans+ (RHEL) IJP
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP
BAKER 78 NP B141 29 +Blissett, Bloodworth, Broome+ (RL, CAMB) IJP
BARBOUR 78 NP B141 253 +Crawford, Parsons (GLAS)
LONGACRE 78 PR D17 1795 +Lasinski, Rosenfeld, Smadja+ (LBL, SLAC)
BAKER 77 NP B126 365 +Blissett, Bloodworth, Broome, Hart+ (RHEL) IJP
LONGACRE 77 NP B122 493 +Dolbeau (SACL) IJP
Also 76 NP B108 365 Dolbeau, Triantis, Neveu, Cadiet (SACL) IJP
WINNIK 77 NP B128 66 +Toaff, Revel, Goldberg, Berny (HAIF) I
DEANS 75 NP B96 90 +Mitchell, Montgomery+ (SFLA, ALAH) IJP
KNASEL 75 PR D11 1 +Lindquist, Nelson+ (CHIC, WUSL, OSU, ANL) IJP
LONGACRE 75 PL 55B 415 +Rosenfeld, Lasinski, Smadja+ (LBL, SLAC) IJP

$N(1960)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $*$
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

A narrow peak in $\Sigma(1385)^- K^+$ diffractively produced by neutrons on quasi-free nucleons of carbon, aluminum, and copper. The spin-parity is one of $5/2^+$, $7/2^-$, etc.

$N(1960)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1956^{+8}_{-6}	ALEEV 84B	BIS2	$\Sigma(1385)^- K^+$

$N(1960)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
27±15	ALEEV 84B	BIS2	$\Sigma(1385)^- K^+$

$N(1960)$ REFERENCES

ALEEV 84B ZPHY C25 205 + (JINR, BERL, LEBD, MOSU, PRAG, SOFI, TBLI)

OTHER RELATED PAPERS

AMAGLOBELI 87 SJNP 45 632 +Dzhordzhadze, Kekelidze+ (JINR)
Translated from YAF 45 1020.
ALEEV 86 SJNP 44 652 + (BERL, JINR, MOSU, PRAG, SOFI, TBLI)
Translated from YAF 44 1010.

$N(1990)$ F_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

The various analyses do not agree very well with one another.

$N(1990)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2018	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1970 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2005 ± 150	HOEHLER	79	IPWA	$\pi N \to \pi N$
1999	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
295	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
350 ± 120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
350 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
216	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 ± 30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1990)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5 ± 4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-8 ± 4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1990)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$p\gamma$, helicity=1/2
Γ_7	$p\gamma$, helicity=3/2
Γ_8	$n\gamma$, helicity=1/2
Γ_9	$n\gamma$, helicity=3/2

$N(1990)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1990) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1990) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.01$	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
-0.021 ± 0.033	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1990) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.010 to 0.023	[1] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.06	LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 1)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(1990) \to N\pi\pi$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1990)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(1990) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.030 ± 0.029	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.001 ± 0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.040	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.086 ± 0.060	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004 ± 0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.004$	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.001	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.078 ± 0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.069	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.178	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.116 ± 0.045	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.072	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions.

$N(1990)$ REFERENCES

For early references, see Physics Letters 111B (1982).

MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$N(2000)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Older results have been retained simply because there is little information at all about this possible state.

$N(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1882 ± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2025	AYED	76	IPWA	$\pi N \to \pi N$
1970	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
2175	ALMEHED	72	IPWA	$\pi N \to \pi N$
1930	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
95 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
157	AYED	76	IPWA	$\pi N \to \pi N$
170	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
150	ALMEHED	72	IPWA	$\pi N \to \pi N$
112	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$p\gamma$

$N(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08	AYED	76	IPWA	$\pi N \to \pi N$
0.25	ALMEHED	72	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2000) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.022	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.05	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \to N(2000) \to \Lambda K$ $(\Gamma_5\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0022	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ FOOTNOTES

[1] Not seen in solution 1 of LANGBEIN 73.
[2] Value given is from solution 1 of DEANS 75; not present in solutions 2, 3, or 4.

$N(2000)$ REFERENCES

SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
AYED	76	CEA-N-1921 Thesis		(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP
ALMEHED	72	NP B40 157	+Lovelace	(LUND, RUTG) IJP
DEANS	72	PR D6 1906	+Jacobs, Lyons, Montgomery	(SFLA) IJP

$N(2080)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is some evidence for two resonances in this wave between 1800 and 2200 MeV (see CUTKOSKY 80). However, the solution of HOEHLER 79 is quite different.

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

$N(2080)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1920	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2060± 80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1900	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2081± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2080)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
320	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
180± 60	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower mass)
300±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher mass)
240	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
265± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2080)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower mass)
2050± 70	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher mass)

$-2 \times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
160±80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower mass)
200±80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher mass)

$N(2080)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
− 2±14	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower mass)
30±20	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher mass)

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
10± 5	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower mass)
0±52	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher mass)

$N(2080)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$p\gamma$, helicity=1/2
Γ_7	$p\gamma$, helicity=3/2
Γ_8	$n\gamma$, helicity=1/2
Γ_9	$n\gamma$, helicity=3/2
Γ_{10}	$p\gamma$

$N(2080)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.04	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower mass)
0.14±0.07	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher mass)
0.06±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2080) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2080) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.03	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2080) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.014 to 0.037	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $p\gamma \to N(2080) \to N\eta$ $(\Gamma_{10}\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0037	HICKS	73	MPWA	$\gamma p \to p\eta$

$N(2080)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(2080) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.020±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.026±0.052	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.017 ± 0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.128 ± 0.057	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.007 ± 0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.053 ± 0.083	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.053 ± 0.034	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.100 ± 0.141	DEVENISH	74	DPWA	$\gamma N \to \pi N$

$N(2080)$ FOOTNOTES

[1] CUTKOSKY 80 finds a lower mass D_{13} resonance, as well as one in this region. Both are listed here.

[2] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2080)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
Also	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
DEVENISH	74	PL 52B 227	+Lyth, Rankin	(DESY, LANC, BONN) IJP
HICKS	73	PR D7 2614	+Deans, Jacobs, Lyons+	(CMU, ORNL, SFLA) IJP

$N(2090)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

Any structure in the S_{11} wave above 1800 MeV is listed here. A few early results that are now obsolete have been omitted.

$N(2090)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2180 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1880 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
95 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2150 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1937 or 1949	[1] LONGACRE	78	IPWA	$\pi N \to N \pi \pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
139 or 131	[1] LONGACRE	78	IPWA	$\pi N \to N \pi \pi$

$N(2090)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 ± 20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2090)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΛK
Γ_3	$N\pi\pi$

$N(2090)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.18 ± 0.08	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.09 ± 0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i \Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2090) \to \Lambda K$ $(\Gamma_1 \Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2090)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$N(2090)$ REFERENCES

CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$N(2100)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$N(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2125 ± 75	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2050 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
200 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2100)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2120 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
240 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2100)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
11 ± 7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8 ± 6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2100)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$N(2100)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.12 ± 0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.10 ± 0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2100)$ REFERENCES

CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP

$N(2190)\ G_{17}$

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

$N(2190)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2120 to 2230 OUR ESTIMATE				
2200±70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2140±12	HOEHLER	79	IPWA	$\pi N \to \pi N$
2140±40	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2098	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
2180	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2140	BAKER	79	DPWA	$\pi^- p \to n\eta$
2117	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200 to 500 OUR ESTIMATE	Our best guess is 350 MeV.			
500±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
390± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
270± 50	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
238	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
80	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
319	BAKER	79	DPWA	$\pi^- p \to n\eta$
220	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2100±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2\times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
400±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2190)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
22±14	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−13±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2190)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	~ 14 %
Γ_2	$N\eta$	~ 3 %
Γ_3	ΛK	~ 0.3 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	
Γ_6	$N\rho$, S=3/2, D-wave	
Γ_7	$p\gamma$, helicity=1/2	
Γ_8	$p\gamma$, helicity=3/2	
Γ_9	$n\gamma$, helicity=1/2	
Γ_{10}	$n\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$N(2190)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
~ 0.14 OUR ESTIMATE				
0.12±0.06	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.16±0.04	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.052	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.02	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.02	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.014 to 0.019	[1] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to N(2190) \to N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
− (large)	MANLEY	84	IPWA	$\pi N \to N\pi\pi$

$N(2190)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$N(2190) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.055	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.180	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.042	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.085	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\mathrm{GeV}^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.126	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

For definitions, see Sec. IV of the Note on N and Δ Resonances preceding the $N(1440)$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (E_{4-} amplitude)

VALUE (units 10^{-3})	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.04	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (M_{4-} amplitude)

VALUE (units 10^{-3})	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−5.78	TANABE	89	DPWA

$p\gamma \to N(2190) \to \Lambda K^+$ phase angle θ (E_{4-} amplitude)

VALUE (degrees)	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−27.5	TANABE	89	DPWA

$N(2190)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2190)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
Also	84B	PRL 52 2122	Manley	(VPI)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$N(2200)$ D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The mass is not well determined. A few early results have been omitted.

$N(2200)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1900	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
2180 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1920	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2228 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2200)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
130	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
400 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
310 ± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2100 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
360 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0 ± 17	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
-20 ± 10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK

$N(2200)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10 ± 0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2200) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.066	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2200) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.03	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
-0.05	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2200)$ REFERENCES

BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP

$N(2220)$ H_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**).

$N(2220)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2150 to 2300 OUR ESTIMATE				
2230 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2205 ± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2300 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2050	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2220)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
300 to 500 OUR ESTIMATE	Our best guess is 400 MeV.			
500 ± 150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
365 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
450 ± 150	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2220)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2160 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
480 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2220)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
32 ± 20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
-32 ± 20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2220)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	~ 18 %
Γ_2	$N\eta$	~ 0.5 %
Γ_3	ΛK	~ 0.2 %

The above branching fractions are our estimates, not fits or averages.

$N(2220)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
~ 0.18 OUR ESTIMATE				
0.15 ± 0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.18 ± 0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.12 ± 0.04	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2220) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.034	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2220) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
not required	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2220)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2250)$ G_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$ Status: ∗∗∗∗

$N(2250)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2130 to 2270 OUR ESTIMATE				
2250 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2268 ± 15	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2250)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200 to 500 OUR ESTIMATE Our best guess is 300 MeV.				
480 ± 120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300 ± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
350 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2250)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2150 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$-2\times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
360 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2250)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
13 ± 7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
-15 ± 6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2250)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	~ 10 %
Γ_2	$N\eta$	~ 2 %
Γ_3	ΛK	~ 0.3 %

The above branching fractions are our estimates, not fits or averages.

$N(2250)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$\sim$ 0.10 OUR ESTIMATE				
0.10 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.10 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2250) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to N(2250) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
-0.02	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2250)$ REFERENCES

BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2600)$ $I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$ Status: ∗∗∗

$N(2600)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2580 to 2700 OUR ESTIMATE				
2577 ± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2700 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2600)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$300 OUR ESTIMATE Our best guess is 400 MeV.				
400 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
900 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	~ 5 %

$N(2600)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
$\sim$ 0.05 OUR ESTIMATE				
0.05 ± 0.01	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2600)$ REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2700)$ $K_{1,13}$

$I(J^P) = \frac{1}{2}(\frac{13}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$N(2700)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2612 ± 45	HOEHLER	79	IPWA	$\pi N \to \pi N$
3000 ± 100	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2700)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
350 ± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
900 ± 150	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2700)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$N(2700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.04 ± 0.01	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.07 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$N(2700)$ REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-1/2 resonances found in partial-wave analyses.

Our 1982 edition had an $N(3245)$, an $N(3690)$, and an $N(3755)$, each a narrow peak seen in a production experiment. Since nothing has been heard from them since the 1960's, we declare them to be dead. There was also an $N(3030)$, deduced from total cross-section and 180° elastic cross-section measurements; it is the KOCH 80 $L_{1,15}$ state below.

$N(\sim 3000)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2600	KOCH	80	IPWA	$\pi N \to \pi N$ D_{13}
3100	KOCH	80	IPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
3500	KOCH	80	IPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
3500 to 4000	KOCH	80	IPWA	$\pi N \to \pi N$ $N_{1,19}$ wave
3500±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
3800±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
4100±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{1,19}$ wave

$N(\sim 3000)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1300±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
1600±200	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
1900±300	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{1,19}$ wave

$N(\sim 3000)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$N(\sim 3000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.055±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$ $L_{1,15}$ wave
0.040±0.015	HENDRY	78	MPWA	$\pi N \to \pi N$ $M_{1,17}$ wave
0.030±0.015	HENDRY	78	MPWA	$\pi N \to \pi N$ $N_{1,19}$ wave

$N(\sim 3000)$ REFERENCES

KOCH	80	Toronto Conf. 3		(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND) IJP

Δ BARYONS
$(S = 0, I = 3/2)$

$\Delta^{++} = uuu$, $\Delta^{+} = uud$, $\Delta^{0} = udd$, $\Delta^{-} = ddd$

$\Delta(1232)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ****

Most of the results published before 1977 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**). In addition, results in this region from production experiments, which used to be listed separately as the next entry, have been entirely omitted. They too may be found in our 1982 edition.

$\Delta(1232)$ MASSES

MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1230 to 1234 OUR ESTIMATE				
1232±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1233±2	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(1232)^{++}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1230.9±0.3	KOCH	80B	IPWA	$\pi N \to \pi N$
1230.6±0.2	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1231.1±0.2	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

$\Delta(1232)^{+}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1234.9±1.4	MIROSHNIC...	79		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1231.6	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1231.2	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1231.8	BERENDS	75	IPWA	$\gamma p \to \pi N$

$\Delta(1232)^{0}$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1233.6±0.5	KOCH	80B	IPWA	$\pi N \to \pi N$
1232.5±0.3	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1233.8±0.2	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

$\Delta^0 - \Delta^{++}$ MASS DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.7±0.3	[1] PEDRONI	78	See the masses

$\Delta(1232)$ WIDTHS

MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
110 to 120 OUR ESTIMATE	Our best guess is 115 MeV.			
120±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
116±5	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(1232)^{++}$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
111.0±1.0	KOCH	80B	IPWA	$\pi N \to \pi N$
113.2±0.3	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
111.3±0.5	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

$\Delta(1232)^{+}$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
131.1±2.4	MIROSHNIC...	79		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
111.2	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
111.0	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1232)^{0}$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
113.0±1.5	KOCH	80B	IPWA	$\pi N \to \pi N$
121.3±0.4	ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
117.9±0.9	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

Δ^0 – Δ^{++} WIDTH DIFFERENCE

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
6.6 ± 1.0	PEDRONI	78	See the widths

$\Delta(1232)$ POLE POSITIONS

REAL PART, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1210 ± 1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1210	ARNDT	85	DPWA	$\pi N \to \pi N$

–IMAGINARY PART, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 ± 1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
50	ARNDT	85	DPWA	$\pi N \to \pi N$

REAL PART, $\Delta(1232)^{++}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1210.70 ± 0.16	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1209.6 ± 0.5	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1210.4 ± 0.17	[4] ZIDELL	78		
1210.5 to 1210.8	[5] VASAN	76B		Fit to CARTER 73

–IMAGINARY PART, $\Delta(1232)^{++}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
49.61 ± 0.12	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
50.4 ± 0.5	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
49.745 ± 0.14	[4] ZIDELL	78		
49.9 to 50.0	[5] VASAN	76B		Fit to CARTER 73

REAL PART, $\Delta(1232)^{+}$

VALUE (MeV)	DOCUMENT ID		COMMENT
1206.9 ± 0.9 to 1210.5 ± 1.8	MIROSHNIC...	79	Fit photoproduction
1208.0 ± 2.0	CAMPBELL	76	Fit photoproduction

–IMAGINARY PART, $\Delta(1232)^{+}$

VALUE (MeV)	DOCUMENT ID		COMMENT
55.6 ± 1.0 to 58.3 ± 1.1	MIROSHNIC...	79	Fit photoproduction
53.0 ± 2.0	CAMPBELL	76	Fit photoproduction

REAL PART, $\Delta(1232)^{0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1210.30 ± 0.36	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
1210.75 ± 0.6	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1209.5 ± 0.41	[4] ZIDELL	78		
1210.2	[5] VASAN	76B		Fit to CARTER 73

–IMAGINARY PART, $\Delta(1232)^{0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
54.0 ± 0.26	[2] ZIDELL	80	DPWA	$\pi N \to \pi N$ 0–350 MeV
52.8 ± 0.6	[3] VASAN	76B		Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •				
52.45 ± 0.2	[4] ZIDELL	78		
52.9 to 53.1	[5] VASAN	76B		Fit to CARTER 73

$\Delta(1232)$ ELASTIC POLE RESIDUES

ABSOLUTE VALUE, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
53 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE, MIXED CHARGES

VALUE	DOCUMENT ID		TECN	COMMENT
-0.82 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

ABSOLUTE VALUE, $\Delta(1232)^{++}$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
52.4 to 53.2	[3] VASAN	76B	Fit to CARTER 73
52.1 to 52.4	[5] VASAN	76B	Fit to CARTER 73

PHASE, $\Delta(1232)^{++}$

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-0.822 to -0.833	[3] VASAN	76B	Fit to CARTER 73
-0.823 to -0.830	[5] VASAN	76B	Fit to CARTER 73

ABSOLUTE VALUE, $\Delta(1232)^{0}$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
54.8 to 55.0	[3] VASAN	76B	Fit to CARTER 73
55.2 to 55.3	[5] VASAN	76B	Fit to CARTER 73

PHASE, $\Delta(1232)^{0}$

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-0.840 to -0.847	[3] VASAN	76B	Fit to CARTER 73
-0.848 to -0.856	[5] VASAN	76B	Fit to CARTER 73

$\Delta(1232)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	99.4 %
Γ_2	$N\gamma$	0.56–0.66 %
Γ_3	$N\gamma$, helicity=1/2	
Γ_4	$N\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$\Delta(1232)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.994 OUR ESTIMATE				
1.0	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1.0	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(1232)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1232) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.145 ± 0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.138 ± 0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.147 ± 0.001	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.145 ± 0.001	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.136 ± 0.006	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.142 ± 0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.141 ± 0.004	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.140	[6] NOELLE	78		$\gamma N \to \pi N$

$\Delta(1232) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($\text{GeV}^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.263 ± 0.026	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
-0.259 ± 0.006	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.264 ± 0.002	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
-0.261 ± 0.002	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
-0.247 ± 0.010	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.271 ± 0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$
-0.256 ± 0.003	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.247	[6] NOELLE	78		$\gamma N \to \pi N$

$\Delta(1232) \to N\gamma$, E_2/M_1 ratio

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.015 ± 0.002	DAVIDSON	86	FIT	$\gamma N \to \pi N$
-0.013 ± 0.005	PDG	86	FIT	$\gamma N \to \pi N$
$+0.037 \pm 0.004$	TANABE	85	FIT	$\gamma N \to \pi N$

$\Delta(1232)$ PHASE OF M1+(3/2) PHOTOPRODUCTION MULTIPOLE AMPLITUDE POLE RESIDUE

Information on the phase (and magnitude) of the M1+(3/2) multipole amplitude pole residue is contained implicitly in the paper of MIROSHNICHENKO 79. They find that the phase is consistent with being equal to that of the elastic pole residue.

$\Delta(1232)^{++}$ MAGNETIC MOMENT

See also HELLER 87.

VALUE (n.m.)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$+4.7$ to $+6.7$	NEFKENS	78	$\pi^+ p \to \pi^+ p \gamma$

$\Delta(1232)$ FOOTNOTES

[1] Using $\pi^{\pm}d$ as well, PEDRONI 78 determine $(M^{-} - M^{++}) + (M^{0} - M^{+})/3 = 4.6 \pm 0.2$ MeV.

[2] The accuracy claimed by ZIDELL 80 on the real part is considerably better than is allowed by uncertainties in the beam momentum.

[3] This VASAN 76B value is from fits to the coulomb-barrier-corrected CARTER 73 phase shift.

[4] ZIDELL 78 fits the nuclear phase shift without coulomb barrier corrections.

[5] This VASAN 76B value is from fits to the CARTER 73 nuclear phase shift without coulomb barrier corrections.

[6] Converted to our conventions using $M = 1232$ MeV, $\Gamma = 110$ MeV from NOELLE 78.

$\Delta(1232)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

HELLER	87	PR C35 718	+Kumano, Martinez, Moniz	(LANL, MIT, ILL)
DAVIDSON	86	PRL 56 804	+Mukhopadhyay, Wittman	(RPI)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	
ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
TANABE	85	PR C31 1876	+Ohta	(TOKY)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
KOCH	80B	NP A336 331	+Pietarinen	(KARL) IJP
ZIDELL	80	PR D21 1255	+Arndt, Roper	(VPI) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
MIROSHNIC...	79	SJNP 29 94 Translated from YAF 29 188.	Miroshnichenko, Nikiforov, Sanin+	(KHAR) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NEFKENS	78	PR D18 3911	+Arman, Ballagh, Glodis, Haddock+	(UCLA, CATH) IJP
NOELLE	78	PTP 60 778		(NAGO)
PEDRONI	78	NP A300 321	+Gabathuler, Domingo, Hirt+	(SIN, ISNG, KARL+) IJP
ZIDELL	78	LNC 21 140	+Arndt, Roper	(VPI) IJP
CAMPBELL	76	PR D14 2431	+Shaw, Ball	(BOIS, UCI, UTAH) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
VASAN	76B	NP B106 535		(CMU) IJP
Also	76	NP B106 526	Vasan	(CMU) IJP
BERENDS	75	NP B84 342	+Donnachie	(LEID, MCHS)
CARTER	73	NP B58 378	+Bugg, Carter	(CAVE, LOQM) IJP

$\Delta(1550)$ P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^{+})$ Status: *

OMITTED FROM SUMMARY TABLE

Not seen in $\pi N \to \pi N$ analyses, and its existence is thus doubtful.

$\Delta(1550)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1525	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1506	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1550	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1550)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
40	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
137	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
110	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1550)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1554 or 1553	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
105 or 104	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1550)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$\Delta(1232)\pi$, P-wave
Γ_3	$N\rho$, S=3/2, P-wave
Γ_4	$N\gamma$, helicity=1/2

$\Delta(1550)$ BRANCHING RATIOS

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1550) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.13 ± 0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
-0.11	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1550) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.17 ± 0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
-0.08	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1550)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1550) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.016 ± 0.016	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.013	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

$\Delta(1550)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

$\Delta(1550)$ REFERENCES

CRAWFORD	83	NP B211 1	+Morton	(GLAS)
BARNHAM	80	NP B168 243	+Glickman, Mier Jedrzejowicz+	(LOIC)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP

$\Delta(1600)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^{+})$ Status: **

OMITTED FROM SUMMARY TABLE

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**).

The various analyses are not in good agreement.

$\Delta(1600)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1690	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1600 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1522 ± 13	HOEHLER	79	IPWA	$\pi N \to \pi N$
1560	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1640	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
250	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
300 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220 ± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
180	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1581	ARNDT	85	DPWA	$\pi N \to \pi N$
1550 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1609 or 1610	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1541 or 1542	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
300	ARNDT	85	DPWA	$\pi N \to \pi N$
200 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
323 or 325	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
178 or 178	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
-15 ± 6	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
8 ± 8	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

$\Delta(1600)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK
Γ_3	$\Delta(1232)\pi$, P-wave
Γ_4	$\Delta(1232)\pi$, F-wave
Γ_5	$N\rho$, S=1/2, P-wave
Γ_6	$N\rho$, S=3/2, P-wave
Γ_7	$N\rho$, S=3/2, F-wave
Γ_8	$N(1440)\pi$, P-wave
Γ_9	$N\gamma$, helicity=1/2
Γ_{10}	$N\gamma$, helicity=3/2

$\Delta(1600)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.18 ± 0.04	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.21 ± 0.06	HOEHLER 79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1600) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.006 to 0.042	[4] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	[5] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
$+0.24\pm0.05$	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$
+0.34	[1,6] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.07	[1,6] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1600) \to N\rho$, S=1/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.10	[1,6] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1600) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.10	[1,6] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1600) \to N(1440)\pi$, P-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	[5] MANLEY 84	IPWA	$\pi N \to N\pi\pi$
$+0.23\pm0.04$	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$

$\Delta(1600)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1600) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
-0.039 ± 0.030	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
-0.046 ± 0.013	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.005 ± 0.020	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
0.000 ± 0.030	BARBOUR 78	DPWA	$\gamma N \to \pi N$
$0.0\ \ \pm0.020$	FELLER 76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-0.200	[7] WADA 84	DPWA	Compton scattering

$\Delta(1600) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
-0.013 ± 0.014	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.025 ± 0.031	AWAJI 81	DPWA	$\gamma N \to \pi N$
-0.009 ± 0.020	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
0.000 ± 0.045	BARBOUR 78	DPWA	$\gamma N \to \pi N$
$0.0\ \ \pm0.015$	FELLER 76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.023	WADA 84	DPWA	Compton scattering

$\Delta(1600)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[4] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[5] MANLEY 84 considers this coupling sign to be well determined.

[6] LONGACRE 77 considers this coupling to be well determined.

[7] WADA 84 is inconsistent with other analyses — see the Note on N and Δ Resonances.

$\Delta(1600)$ REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1620)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**).

$\Delta(1620)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1600 to 1650 OUR ESTIMATE			
$1620\ \pm20$	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
$1610\ \pm\ 7$	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1620	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$
$1712.8\pm\ 6.0$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
$1786.7\pm\ 2.0$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1657	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1662	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1580	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
1600	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
120 to 160 OUR ESTIMATE	Our best guess is 140 MeV.		
$140\ \pm20$	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
$139\ \pm18$	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
120	BARNHAM 80	IPWA	$\pi N \to N\pi\pi$
228.3 ± 18.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
$30.0\pm\ 6.4$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)
161	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
180	BARBOUR 78	DPWA	$\gamma N \to \pi N$
120	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
150	[3] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

Δ(1620) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1600±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1599	ARNDT	85	DPWA	$\pi N \to \pi N$
1583 or 1583	[4] LONGACRE	78	IPWA	$\pi N \to N \pi \pi$
1575 or 1572	[2] LONGACRE	77	IPWA	$\pi N \to N \pi \pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	ARNDT	85	DPWA	$\pi N \to \pi N$
143 or 149	[4] LONGACRE	78	IPWA	$\pi N \to N \pi \pi$
119 or 128	[2] LONGACRE	77	IPWA	$\pi N \to N \pi \pi$

Δ(1620) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−5±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−14±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1620) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	25–35 %
Γ_2	$N\pi\pi$	65–75 %
Γ_3	$\Delta\pi$	60–70 %
Γ_4	$\Delta(1232)\pi$, D-wave	
Γ_5	$N\rho$	10–20 %
Γ_6	$N\rho$, $S=1/2$, S-wave	
Γ_7	$N\rho$, $S=3/2$, D-wave	
Γ_8	$N(1440)\pi$, S-wave	
Γ_9	$N\gamma$	~ 0.03 %
Γ_{10}	$N\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1620) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.25 to 0.35 OUR ESTIMATE				
0.25±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.35±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.60	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
0.36	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the Δ(1620) S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
− (large)	[5] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
−0.33±0.06	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
−0.39	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.40	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to N\rho$, $S=1/2$, S-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+ (large)	[5] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
+0.40±0.10	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.08	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.28	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to N\rho$, $S=3/2$, D-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
− (small)	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
−0.13	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1620) \to N(1440)\pi$, S-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.11±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

Δ(1620) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

Δ(1620) → $N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.035±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.010±0.015	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.022±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.021±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.126±0.021	TAKEDA	80	DPWA	$\gamma N \to \pi N$
+0.034±0.028	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.005±0.016	FELLER	76	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.066	WADA	84	DPWA	Compton scattering

Δ(1620) FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances at somewhat higher masses than other analyses. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] MANLEY 84 considers this coupling sign to be well determined.

[6] LONGACRE 77 considers this coupling to be well determined.

Δ(1620) REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

Δ(1700) D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

Δ(1700) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1630 to 1740 OUR ESTIMATE				
1710 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1680 ±70	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1650	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
$1718.4^{+13.1}_{-13.0}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1622	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1629	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1600	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1680	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1700) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
190 to 300 OUR ESTIMATE	Our best guess is 250 MeV.			
280 ±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
230 ±80	HOEHLER	79	IPWA	$\pi N \to \pi N$

• • • We do not use the following data for averages, fits, limits, etc. • • •				
160	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
193.3±26.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
209	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
216	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
200	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
240	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

Δ(1700) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1675±25	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1668	ARNDT	85	DPWA	$\pi N \rightarrow \pi N$
1681 or 1672	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1600 or 1594	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
220±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
320	ARNDT	85	DPWA	$\pi N \rightarrow \pi N$
245 or 241	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
208 or 201	[2] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

Δ(1700) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
12±3	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−4±5	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(1700) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	80–90 %
Γ_4	$\Delta\pi$	50–90 %
Γ_5	$\Delta(1232)\pi$, S-wave	
Γ_6	$\Delta(1232)\pi$, D-wave	
Γ_7	$N\rho$	<35 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N\gamma$	0.14–0.33 %
Γ_{12}	$N\gamma$, helicity=1/2	
Γ_{13}	$N\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1700) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.12±0.03	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.20±0.03	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.002	LIVANOS	80	DPWA	$\pi p \rightarrow \Sigma K$
0.001 to 0.011	[5] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$

Note: Signs of couplings from $\pi N \rightarrow N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Delta(1232)\pi$, S-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	[6] MANLEY	84	IPWA	$\pi N \rightarrow N\pi\pi$
+0.18±0.04	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
+0.30	[2,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.24	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow \Delta(1232)\pi$, D-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	[6] MANLEY	84	IPWA	$\pi N \rightarrow N\pi\pi$
0.14±0.04	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$
+0.05	[2,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
+0.10	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=1/2, D-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.17±0.05	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=3/2, S-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	MANLEY	84	IPWA	$\pi N \rightarrow N\pi\pi$
+0.04	[2,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
−0.30	[3] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(1700) \rightarrow N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.07	BARNHAM	80	IPWA	$\pi N \rightarrow N\pi\pi$

Δ(1700) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1700) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.111±0.017	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.089±0.033	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.112±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.130±0.006	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.123±0.022	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.130±0.037	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.072±0.033	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1700) \rightarrow N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.107±0.015	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.060±0.015	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.047±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.050±0.007	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.102±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
+0.098±0.036	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.087±0.023	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

Δ(1700) FOOTNOTES

[1] Problems with CHEW 80 are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] MANLEY 84 considers this coupling sign to be well determined.

[7] LONGACRE 77 considers this coupling to be well determined.

Δ(1700) REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1900)\ S_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗∗∗

Δ(1900) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1850 to 2000 OUR ESTIMATE			
1890 ±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1908 ±30	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1918.5±23.0	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1803	CRAWFORD 80	DPWA	$\gamma N \to \pi N$

Δ(1900) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
130 to 300 OUR ESTIMATE	Our best guess is 150 MeV.		
170 ±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
140 ±40	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
93.5±54.0	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
137	CRAWFORD 80	DPWA	$\gamma N \to \pi N$

Δ(1900) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1870±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2029 or 2025	[1] LONGACRE 78	IPWA	$\pi N \to N \pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
180±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
164 or 163	[1] LONGACRE 78	IPWA	$\pi N \to N \pi\pi$

Δ(1900) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
9±4	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3±7	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(1900) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	not seen
Γ_3	$N\rho$, S=3/2, D-wave	
Γ_4	$N(1440)\pi$, S-wave	
Γ_5	$N\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1900) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE			
0.10±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.08±0.04	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.28	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1900) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.03	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.076	[2] DEANS 75	DPWA	$\pi N \to \Sigma K$
0.11	LANGBEIN 73	IPWA	$\pi N \to \Sigma K$ (sol. 1)
0.12	LANGBEIN 73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1900) \to N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
large	MANLEY 84	IPWA	$\pi N \to N \pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1900) \to N(1440)\pi$, S-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	MANLEY 84	IPWA	$\pi N \to N \pi\pi$

Δ(1900) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1900) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.004±0.016	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.029±0.008	AWAJI 81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.006 to −0.025	CRAWFORD 80	DPWA	$\gamma N \to \pi N$

Δ(1900) FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[2] The value given is from solution 1; the resonance is not present in solutions 2, 3, or 4.

Δ(1900) REFERENCES

For early references, see Physics Letters 111B (1982).

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$\Delta(1905)\ F_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

Δ(1905) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1890 to 1920 OUR ESTIMATE			
1910 ±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1905 ±20	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1960 ±40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1787.0^{+6.0}_{-5.7}$	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1880	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1892	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1830	[1] LONGACRE 75	IPWA	$\pi N \to N \pi\pi$

Δ(1905) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
250 to 400 OUR ESTIMATE	Our best guess is 300 MeV.		
400 ±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
260 ± 20	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
270 ± 40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$66.0^{+24.0}_{-16.0}$	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
193	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
159	BARBOUR 78	DPWA	$\gamma N \to \pi N$
220	[1] LONGACRE 75	IPWA	$\pi N \to N \pi\pi$

Δ(1905) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1830±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1830	ARNDT 85	DPWA	$\pi N \to \pi N$
1813 or 1808	[2] LONGACRE 78	IPWA	$\pi N \to N \pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
280±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
180	ARNDT	85	DPWA	$\pi N \to \pi N$
193 or 187	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

Δ(1905) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
16±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−19±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1905) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	<3 %
Γ_3	$N\pi\pi$	<75 %
Γ_4	$\Delta\pi$	~ 25 %
Γ_5	$\Delta(1232)\pi$, *P*-wave	
Γ_6	$\Delta(1232)\pi$, *F*-wave	
Γ_7	$N\rho$	<50 %
Γ_8	$N\rho$, S=3/2, *P*-wave	
Γ_9	$N\rho$, S=3/2, *F*-wave	
Γ_{10}	$N\rho$, S=1/2, *F*-wave	
Γ_{11}	$N\gamma$	0.01–0.05 %
Γ_{12}	$N\gamma$, helicity=1/2	
Γ_{13}	$N\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1905) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.08±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.15±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.015±0.003	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.013	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.021 to 0.054	[3] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, *P*-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+ (small)	MANLEY	84	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, *F*-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	[4] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
+0.17	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.06	[6] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.20	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1905) \to N\rho$, S=3/2, *P*-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.26	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.11 to +0.33	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.33	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1905) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on *N* and Δ Resonances preceding the Baryon Listings.

Δ(1905) → $N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.021±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.043±0.020	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.022±0.010	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.031±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.024±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.033±0.018	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1905) → $N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.056±0.028	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.025±0.023	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.029±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.045±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.072±0.035	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.055±0.019	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1905) FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[3] The range given for DEANS 75 is from the four best solutions.

[4] MANLEY 84 considers this coupling sign to be well determined and suggests that the large $N\rho$ decay seen in previous analyses is predominantly from a higher mass F_{35} resonance. See the Listings for the Δ(2000) F_{35}.

[5] A Breit-Wigner fit to the HERNDON 75 IPWA.

[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA.

[7] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 90°.

Δ(1905) REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
Also	84B	PRL 52 2122	Manley	(VPI)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

Δ(1910) P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**).

Δ(1910) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1850 to 1950 OUR ESTIMATE				
1910 ±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1888 ±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1715.2±21.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1778.4± 9.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1960.1±21.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$2121.4^{+13.0}_{-14.3}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1921	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1899	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1790	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

Baryon Full Listings

Δ(1910), Δ(1920)

Δ(1910) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
200 to 330 OUR ESTIMATE	Our best guess is 220 MeV.		
225 ±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
280 ±50	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
93.3±55.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
23.0±29.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
152.9±60.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
172.2±37.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
351	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
230	BARBOUR 78	DPWA	$\gamma N \to \pi N$
170	[2] LONGACRE 77	IPWA	$\pi N \to N \pi \pi$

Δ(1910) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1880±30	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1792 or 1801	[2] LONGACRE 77	IPWA	$\pi N \to N \pi \pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
200±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
172 or 165	[2] LONGACRE 77	IPWA	$\pi N \to N \pi \pi$

Δ(1910) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0±10	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
−20±4	CUTKOSKY 80	IPWA	$\pi N \to \pi N$

Δ(1910) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	15–25 %
Γ_2	ΣK	not seen
Γ_3	$N\pi\pi$	<75 %
Γ_4	$\Delta\pi$	small
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	small
Γ_7	$N\rho$, S=3/2, P-wave	
Γ_8	$N(1440)\pi$	large
Γ_9	$N(1440)\pi$, P-wave	
Γ_{10}	$N\gamma$, helicity=1/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1910) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.15 to 0.25 OUR ESTIMATE			
0.19±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.24±0.06	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.18	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
0.20	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
0.17	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
0.40	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
< 0.03	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.019	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.082 to 0.184	[3] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the Δ(1620) S_{31} coupling to Δ(1232)π.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.06	[2] LONGACRE 77	IPWA	$\pi N \to N \pi \pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.29	[2] LONGACRE 77	IPWA	$\pi N \to N \pi \pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.17	[4] NOVOSELLER 78	IPWA	$\pi N \to N \pi \pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1910) \to N(1440)\pi$, P-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+ (large)	[5] MANLEY 84	IPWA	$\pi N \to N \pi \pi$

Δ(1910) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

Δ(1910) → $N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
0.014±0.030	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.025±0.011	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.012±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.031±0.004	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.005±0.030	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.035±0.021	BARBOUR 78	DPWA	$\gamma N \to \pi N$

Δ(1910) FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] The range given for DEANS 75 is from the four best solutions.

[4] Evidence for this coupling is weak; see NOVOSELLER 78. This coupling assumes the mass is near 1820 MeV.

[5] MANLEY 84 finds this decay mode accounts for all the inelasticity.

Δ(1910) REFERENCES

For early references, see Physics Letters **111B** (1982).

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

Δ(1920) P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters **111B**).

Δ(1920) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1860 to 2160 OUR ESTIMATE			
1920 ±80	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1868 ±10	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1840 ±40	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
1955.0±13.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
$2065.0^{+13.6}_{-12.9}$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(1920) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
190 to 300 OUR ESTIMATE	Our best guess is 250 MeV.		
300 ±100	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
220 ± 80	HOEHLER 79	IPWA	$\pi N \to \pi N$

• • • We do not use the following data for averages, fits, limits, etc. • • •

200 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
88.3± 35.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
62.0± 44.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(1920) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1920) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−21±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−12±11	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1920) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	15–20 %
Γ_2	ΣK	~ 5 %
Γ_3	$\Delta(1232)\pi$, *P*-wave	
Γ_4	$N(1440)\pi$, *P*-wave	
Γ_5	$N\gamma$, helicity=1/2	
Γ_6	$N\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1920) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ $\qquad$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.20 OUR ESTIMATE				
0.20±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.18	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1920) \to \Sigma K$ $\qquad$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.052±0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.049	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.048 to 0.120	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1920) \to \Delta(1232)\pi$, *P*-wave $\qquad$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
0.3	[3] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.27	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1920) \to N(1440)\pi$, *P*-wave $\qquad$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+	MANLEY	84	IPWA	$\pi N \to N\pi\pi$

Δ(1920) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1920) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.040±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1920) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.023±0.017	AWAJI	81	DPWA	$\gamma N \to \pi N$

Δ(1920) FOOTNOTES

[1] CHEW 80 reports two P_{33} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] The range given for DEANS 75 is from the four best solutions.

[3] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −90°.

[4] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −90°.

Δ(1920) REFERENCES

For early references, see Physics Letters **111B** (1982).

CANDLIN 84 NP B238 477 +Lowe, Peach, Scotland+ (EDIN, RAL, LOWC)
MANLEY 84 PR D30 904 +Arndt, Goradia, Teplitz (VPI)
HOEHLER 83 Landolt-Boernstein 1/9B2 (KARL)
AWAJI 81 Bonn Conf. 352 +Kajikawa (NAGO)
Also 82 NP B197 365 Fujii, Hayashii, Iwata, Kajikawa+ (NAGO)
CHEW 80 Toronto Conf. 123 (LBL) IJP
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL) IJP
LIVANOS 80 Toronto Conf. 35 +Baton, Coutures, Kochowski, Neveu (SACL) IJP
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP
NOVOSELLER 78 NP B137 509 (CIT)
NOVOSELLER 78B NP B137 445 (CIT)
DEANS 75 NP B96 90 +Mitchell, Montgomery+ (SFLA, ALAH) IJP
HERNDON 75 PR D11 3183 +Longacre, Miller, Rosenfeld+ (LBL, SLAC)

Δ(1930) D_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

The various analyses are not in good agreement.

Δ(1930) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1890 to 1960 OUR ESTIMATE				
1940 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1901 ±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1910.0^{+15.0}_{-17.2}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2000	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
2024	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1930) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 350 OUR ESTIMATE	Our best guess is 250 MeV.			
320 ±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
195 ±60	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$74.8^{+17.0}_{-16.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
442	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
462	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1930) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1890±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1930) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
17±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−6±12	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1930) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	not seen
Γ_3	$N\pi\pi$	not seen
Γ_4	$N\gamma$, helicity=1/2	
Γ_5	$N\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

Δ(1930) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.14 ± 0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04 ± 0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1930) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.031	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.018 to 0.035	[1] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1930) \to N\pi\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	MANLEY	84	IPWA	$\pi N \to N\pi\pi$
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1930) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1930) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.009 ± 0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.030 ± 0.047	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
-0.062 ± 0.064	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.025 ± 0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
-0.033 ± 0.060	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
$+0.019\pm0.054$	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1930) FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions.

Δ(1930) REFERENCES

For early references, see Physics Letters **111B** (1982).

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1940)\ D_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

Δ(1940) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2058.1 ± 34.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1940 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1940) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
198.4 ± 45.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
200 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1940) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1915 or 1926	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190 or 186	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

Δ(1940) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
-6 ± 5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
6 ± 5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(1940) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK
Γ_3	$N\gamma$, helicity=1/2
Γ_4	$N\gamma$, helicity=3/2

Δ(1940) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.18	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.05 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(1940) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(1940) PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1940) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.036 ± 0.058	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.031 ± 0.012	AWAJI	81	DPWA	$\gamma N \to \pi N$

Δ(1940) FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$\Delta(1940)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$\Delta(1950)$ F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B). In addition, results in this region from production experiments, which used to be listed separately as the next entry, have been entirely omitted. They too may be found in our 1982 edition.

$\Delta(1950)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1910 to 1960 OUR ESTIMATE				
1950 ±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1913 ± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1925 ±20	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1855.0^{+11.0}_{-10.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1902	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1912	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1925	[1] LONGACRE	75	IPWA	$\pi N \to N \pi \pi$

$\Delta(1950)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200 to 340 OUR ESTIMATE	Our best guess is 240 MeV.			
340 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
224 ±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
330 ±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$157.2^{+22.0}_{-19.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
225	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
198	BARBOUR	78	DPWA	$\gamma N \to \pi N$
240	[1] LONGACRE	75	IPWA	$\pi N \to N \pi \pi$

$\Delta(1950)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1890±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1858	ARNDT	85	DPWA	$\pi N \to \pi N$
1924 or 1924	[2] LONGACRE	78	IPWA	$\pi N \to N \pi \pi$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
260±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
238	ARNDT	85	DPWA	$\pi N \to \pi N$
258 or 258	[2] LONGACRE	78	IPWA	$\pi N \to N \pi \pi$

$\Delta(1950)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
42±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−27±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–45 %
Γ_2	ΣK	not seen
Γ_3	$N\pi\pi$	<40 %
Γ_4	$\Delta\pi$	~ 30 %
Γ_5	$\Delta(1232)\pi$, *F*-wave	
Γ_6	$\Delta(1232)\pi$, *H*-wave	
Γ_7	$N\rho$	<10 %
Γ_8	$N\rho$, S=1/2, *F*-wave	
Γ_9	$N\rho$, S=3/2, *F*-wave	
Γ_{10}	$N(1680)\pi$, *P*-wave	
Γ_{11}	$N\gamma$	0.08–0.17 %
Γ_{12}	$N\gamma$, helicity=1/2	
Γ_{13}	$N\gamma$, helicity=3/2	

The above branching fractions are our estimates, not fits or averages.

$\Delta(1950)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.35 to 0.45 OUR ESTIMATE				
0.39±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1950) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.053±0.005	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022 to 0.040	[3] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1950) \to \Delta(1232)\pi$, *F*-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+ (large)	[4] MANLEY	84	IPWA	$\pi N \to N\pi\pi$
0.21	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.38	[6] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.32	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1950) \to N\rho$, S=3/2, *F*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.24	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.43	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
+0.24	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(1950) \to N(1680)\pi$, *P*-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.20	MANLEY	84	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ PHOTON DECAY AMPLITUDES

For the definition of the γN decay amplitudes, see Sec. IV of the Note on N and Δ Resonances preceding the Baryon Listings.

$\Delta(1950) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.068±0.007	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.091±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.083±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.067±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.058±0.013	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1950) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.094±0.016	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.101±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.100±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.082±0.017	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.075±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1950) FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N \pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[3] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[4] MANLEY 84 considers this coupling sign to be well determined.

[5] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −60°.

[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −60°.

[7] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near 120°.

[8] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 120°.

Δ(1950) REFERENCES

For early references, see Physics Letters **111B** (1982).

ARNDT	85	PR D32 1085	+Ford, Roper	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
Also	84B	PRL 52 2122	Manley	(VPI)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(TOKY)
Also	82	NP B194 251	Arai, Fujii	(TOKY)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

Δ(2000) F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2000) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 2000	MANLEY	84	IPWA	$\pi N \rightarrow N \pi\pi$
2200±125	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2000) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
400±125	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2000) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2150±100	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2000) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−14±13	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8±22	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2000) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\rho$, S=3/2, P-wave

Δ(2000) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.07±0.04	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(2000) \rightarrow N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+ (large)	[1] MANLEY	84	IPWA	$\pi N \rightarrow N \pi\pi$

Δ(2000) FOOTNOTES

[1] MANLEY 84 considers this coupling sign to be well determined. This resonance has not been seen in $\pi N \rightarrow \pi N$ analyses. Thus its coupling to the $N\pi$ channel is expected to be weak.

Δ(2000) REFERENCES

MANLEY	84	PR D30 904	+Arndt, Goradia, Teplitz	(VPI)
Also	84B	PRL 52 2122	Manley	(VPI)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

Δ(2150) S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Δ(2150) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2047.4± 27.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
2203.2± 8.4	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
2150 ±100	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2150) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
121.6± 62.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
120.5± 45.0	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
200 ±100	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2150) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2140±80	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200±80	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2150) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
−6±6	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

Δ(2150) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2150) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.41	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
0.37	[1] CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
0.08±0.02	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(2150) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CANDLIN	84	DPWA	$\pi^+ p \rightarrow \Sigma^+ K^+$

Δ(2150) FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

Δ(2150) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARL)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2200)\ G_{37}$

$I(J^P) = \frac{3}{2}(\frac{7}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

The various analyses are not in good agreement.

Δ(2200) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2200±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2215±60	HOEHLER	79	IPWA	$\pi N \to \pi N$
2280±80	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2280±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2200) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
450±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
400±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
400±150	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
400± 50	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2200) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2100±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
340±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2200) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
3±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−8±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2200) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2200) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.05±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2200) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.014±0.005	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2200) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2300)\ H_{39}$

$I(J^P) = \frac{3}{2}(\frac{9}{2}^+)$ Status: **

OMITTED FROM SUMMARY TABLE

Δ(2300) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2204.5± 3.4	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2217 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2450 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
32.3± 1.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
425 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300 ±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500 ±200	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2370±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
420±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2300) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−3±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2300) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2300) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.03±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\pi \to \Delta(2300) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.017	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(2350)$ D_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2350)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2400 ± 125	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
2305 ± 26	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2350)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
400 ± 150	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
300 ± 70	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2350)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2400 ± 125	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
400 ± 150	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2350)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
5 ± 17	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
-14 ± 10	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2350)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2350)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.20 ± 0.10	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
0.04 ± 0.02	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(2350) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.015	CANDLIN 84	DPWA	$\pi^+ p \rightarrow \Sigma^+ K^+$

$\Delta(2350)$ REFERENCES

CANDLIN 84 NP B238 477 +Lowe, Peach, Scotland+ (EDIN, RAL, LOWC)
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL)
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP

$\Delta(2390)$ F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2390)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2350 ± 100	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
2425 ± 60	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2390)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
300 ± 100	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
300 ± 80	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2390)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2350 ± 100	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$-2 \times$ IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
260 ± 100	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2390)$ ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0 ± 13	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
-12 ± 6	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$

$\Delta(2390)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2390)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.08 ± 0.04	CUTKOSKY 80	IPWA	$\pi N \rightarrow \pi N$
0.07 ± 0.04	HOEHLER 79	IPWA	$\pi N \rightarrow \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \rightarrow \Delta(2390) \rightarrow \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.015	CANDLIN 84	DPWA	$\pi^+ p \rightarrow \Sigma^+ K^+$

$\Delta(2390)$ REFERENCES

CANDLIN 84 NP B238 477 +Lowe, Peach, Scotland+ (EDIN, RAL, LOWC)
CUTKOSKY 80 Toronto Conf. 19 +Forsyth, Babcock, Kelly, Hendrick (CMU, LBL) IJP
Also 79 PR D20 2839 Cutkosky, Forsyth, Hendrick, Kelly (CMU, LBL)
HOEHLER 79 PDAT 12-1 +Kaiser, Koch, Pietarinen (KARL) IJP
Also 80 Toronto Conf. 3 Koch (KARL) IJP

Δ(2400) G_{39}

$I(J^P) = \frac{3}{2}(\frac{9}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2400) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2468± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2400) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
330±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
480±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
450±200	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2400) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
320±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2400) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
7±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−3±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2400) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2400) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.06±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.10±0.03	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(2400) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2400) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2420) $H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

In addition, results in this region from production experiments, which used to be listed separately as the next entry, have been entirely omitted. They too may be found in our 1982 edition.

Δ(2420) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2380 to 2450 OUR ESTIMATE				
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2416 ± 17	HOEHLER	79	IPWA	$\pi N \to \pi N$
2400 ± 60	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
2358.0± 9.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(2420) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
300 to 500 OUR ESTIMATE Our best guess is 300 MeV.				
450 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
340 ± 28	HOEHLER	79	IPWA	$\pi N \to \pi N$
460 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
202.2± 45.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(2420) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2360±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2 × IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
420±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2420) ELASTIC POLE RESIDUE

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
16±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
−9±11	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2420) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	

Δ(2420) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05 to 0.15 OUR ESTIMATE				
0.08±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.11±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\pi \to \Delta(2420) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.016	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2420) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	*79*	*PR D20 2839*	*Cutkosky, Forsyth, Hendrick, Kelly*	*(CMU, LBL)*
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2750) $I_{3,13}$

$I(J^P) = \frac{3}{2}(\frac{13}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2750) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2794 ± 80	HOEHLER 79	IPWA	$\pi N \to \pi N$
2650 ± 100	HENDRY 78	MPWA	$\pi N \to \pi N$

Δ(2750) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
350 ± 100	HOEHLER 79	IPWA	$\pi N \to \pi N$
500 ± 100	HENDRY 78	MPWA	$\pi N \to \pi N$

Δ(2750) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(2750) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.04 ± 0.015	HOEHLER 79	IPWA	$\pi N \to \pi N$
0.05 ± 0.01	HENDRY 78	MPWA	$\pi N \to \pi N$

Δ(2750) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2950) $K_{3,15}$

$I(J^P) = \frac{3}{2}(\frac{15}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2950) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2990 ± 100	HOEHLER 79	IPWA	$\pi N \to \pi N$
2850 ± 100	HENDRY 78	MPWA	$\pi N \to \pi N$

Δ(2950) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
330 ± 100	HOEHLER 79	IPWA	$\pi N \to \pi N$
700 ± 200	HENDRY 78	MPWA	$\pi N \to \pi N$

Δ(2950) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(2950) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.04 ± 0.02	HOEHLER 79	IPWA	$\pi N \to \pi N$
0.03 ± 0.01	HENDRY 78	MPWA	$\pi N \to \pi N$

Δ(2950) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARL) IJP
Also	80	Toronto Conf. 3	Koch	(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(~ 3000 Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-3/2 resonances found in partial-wave analyses.

Our 1982 edition also had a Δ(2850) and a Δ(3230). The evidence for them was deduced from total cross-section and 180° elastic cross-section measurements. The Δ(2850) has been resolved into the Δ(2750) $I_{3,13}$ and Δ(2950) $K_{3,15}$. The Δ(3230) is perhaps related to the $K_{3,13}$ of HENDRY 78 and to the $L_{3,17}$ of KOCH 80.

Δ(~ 3000) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3300	[1] KOCH 80	IPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
3500	[1] KOCH 80	IPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
2850 ± 150	HENDRY 78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
3200 ± 200	HENDRY 78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
3300 ± 200	HENDRY 78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
3700 ± 200	HENDRY 78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
4100 ± 300	HENDRY 78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

Δ(~ 3000) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
700 ± 200	HENDRY 78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
1000 ± 300	HENDRY 78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
1100 ± 300	HENDRY 78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
1300 ± 400	HENDRY 78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
1600 ± 500	HENDRY 78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

Δ(~ 3000) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(~ 3000) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.06 ± 0.02	HENDRY 78	MPWA	$\pi N \to \pi N$ $I_{3,11}$ wave
0.045 ± 0.02	HENDRY 78	MPWA	$\pi N \to \pi N$ $K_{3,13}$ wave
0.03 ± 0.01	HENDRY 78	MPWA	$\pi N \to \pi N$ $L_{3,17}$ wave
0.025 ± 0.01	HENDRY 78	MPWA	$\pi N \to \pi N$ $M_{3,19}$ wave
0.018 ± 0.01	HENDRY 78	MPWA	$\pi N \to \pi N$ $N_{3,21}$ wave

Δ(~ 3000) FOOTNOTES

[1] In addition, KOCH 80 reports some evidence for an S_{31} Δ(2700) and a P_{33} Δ(2800).

Δ(~ 3000) REFERENCES

KOCH	80	Toronto Conf. 3		(KARL) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Z BARYONS
$(S = +1)$

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has been reviewed more recently by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The present skepticism against baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

References

1. Particle Data Group, Rev. Mod. Phys. **48**, S188 (1976).
2. R.L. Kelly, in *Proceedings of the Meeting on Exotic Resonances* (Hiroshima, 1978), ed. I. Endo et al.
3. G.C. Oades, in *Low and Intermediate Energy Kaon-Nucleon Physics* (1981), ed. E. Ferrari and G. Violini.
4. K. Hashimoto, Phys. Rev. **C29**, 1377 (1984).
5. R.A. Arndt and L.D. Roper, Phys. Rev. **D31**, 2230 (1985).
6. Particle Data Group, Phys. Lett. **170B**, 289 (1986).

Λ BARYONS
$(S = -1, I = 0)$
$\Lambda^0 = uds$

Λ $I(J^P) = 0(\frac{1}{2}^+)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

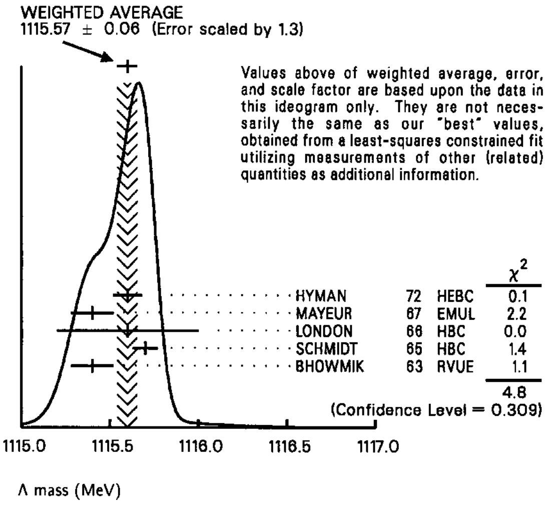
Λ MASS

The fit uses Λ, Σ^+, Σ^0, Σ^- mass and mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*
1115.63±0.05 OUR FIT		Error includes scale factor of 1.4.		
1115.57±0.06 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
1115.59±0.08	935	HYMAN	72	HEBC
1115.39±0.12	195	MAYEUR	67	EMUL
1115.6 ±0.4		LONDON	66	HBC
1115.65±0.07	488	[1] SCHMIDT	65	HBC
1115.44±0.12		[2] BHOWMIK	63	RVUE

[1] Since our final values for the Σ and Λ masses come from doing an overall fit to all measured masses and mass differences, we use the uncorrelated measurements from SCHMIDT 65 rather than those coming from the overall fit reported in that paper. Since there seems to be no convincing reason to ignore data using range measurements, we include here values depending on proton and pion ranges. The SCHMIDT 65 masses have been reevaluated using our April 1973 proton and $K^\pm$ and $\pi^\pm$ masses. P. Schmidt, private communication (1974).

[2] The mass has been raised 35 keV to take into account a 46 keV increase in the proton mass and an 11 keV decrease in the $\pi^\pm$ mass (note added 1967 edition, RMP 39, 1).



Λ – $\overline{\Lambda}$ MASS DIFFERENCE

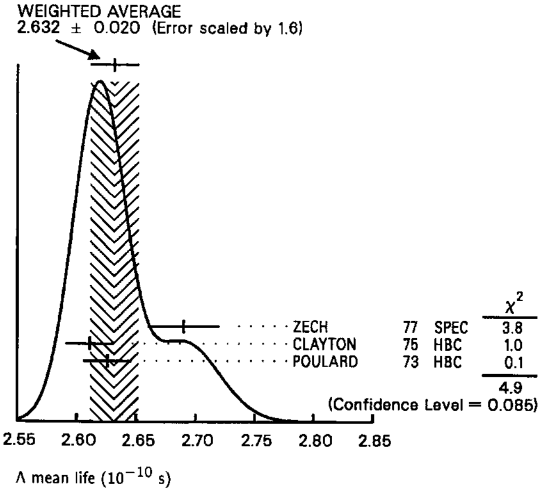
A test of *CPT*.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.00±0.12 OUR AVERAGE	Error includes scale factor of 2.1.			
−0.29±0.15	BADIER	67	HBC	2.4 GeV/*c* $\overline{p}p$
0.05±0.06	CHIEN	66	HBC	6.9 GeV/*c* $\overline{p}p$

Λ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted, and only the latest high-statistics measurements are used for the average.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.632±0.020 OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.			
2.69 ±0.03	53k	ZECH	77	SPEC	Neutral hyperon beam
2.611±0.020	34k	CLAYTON	75	HBC	0.96–1.4 GeV/*c* $K^- p$
2.626±0.020	36k	POULARD	73	HBC	0.4–2.3 GeV/*c* $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.69 ±0.05	6582	ALTHOFF	73B	OSPK	$\pi^+ n \to \Lambda K^+$
2.54 ±0.04	4572	BALTAY	71B	HBC	$K^- p$ at rest
2.535±0.035	8342	GRIMM	68	HBC	
2.47 ±0.08	2600	HEPP	68	HBC	
2.35 ±0.09	916	BURAN	66	HLBC	
$2.452^{+0.056}_{-0.054}$	2213	ENGELMANN	66	HBC	
2.59 ±0.09	794	HUBBARD	64	HBC	
2.59 ±0.07	1378	SCHWARTZ	64	HBC	
2.36 ±0.06	2239	BLOCK	63	HEBC	



$(\tau_\Lambda - \tau_{\overline{\Lambda}})\,/\,\tau_{\text{AVERAGE}}$, MEAN LIFE DIFFERENCE

A test of *CPT*.

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.044±0.085	BADIER 67	HBC	2.4 GeV/c $\overline{p}p$

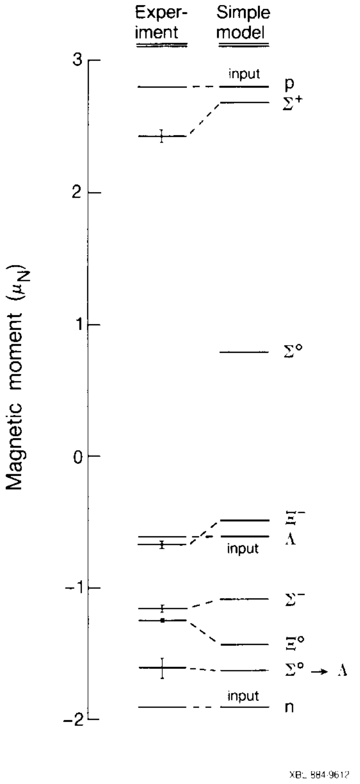
NOTE ON BARYON MAGNETIC MOMENTS

The figure shows the measured magnetic moments of the stable baryons. It also shows the predictions of the simplest quark model, using the measured p, n, and Λ moments as input. In this model, the moments are[1]

$$\begin{aligned} \mu_p &= (4\mu_u - \mu_d)/3 & \mu_n &= (4\mu_d - \mu_u)/3 \\ \mu_{\Sigma^+} &= (4\mu_u - \mu_s)/3 & \mu_{\Sigma^-} &= (4\mu_d - \mu_s)/3 \\ \mu_{\Xi^0} &= (4\mu_s - \mu_u)/3 & \mu_{\Xi^-} &= (4\mu_s - \mu_d)/3 \\ \mu_\Lambda &= \mu_s & \mu_{\Sigma^0} &= (2\mu_u + 2\mu_d - \mu_s)/3 \end{aligned}$$

and the $\Sigma^0 \to \Lambda$ transition moment is

$$\mu_{\Sigma^0\Lambda} = (\mu_d - \mu_u)/\sqrt{3}\ .$$



The quark moments that result from this simple model are $\mu_u = +1.852\,\mu_N$, $\mu_d = -0.972\,\mu_N$, and $\mu_s = -0.613\,\mu_N$. The corresponding effective quark masses, taking the quarks to be Dirac point particles, where $\mu = q\hbar/2m$, are 338, 322, and 510 MeV. As the figure shows, the model gives a good first approximation to the experimental moments. For efforts to make a better model, we refer to the literature.[2]

References

1. See, for example, D.H. Perkins, *Introduction to High Energy Physics* (Addison-Wesley, Reading, MA, 1987), or D. Griffiths, *Introduction to Elementary Particles* (Harper & Row, New York, 1987).
2. See, for example, J. Franklin, Phys. Rev. **D29**, 2648 (1984); H.J. Lipkin, Nucl. Phys. **B241**, 477 (1984); K. Suzuki, H. Kumagai, and Y. Tanaka, Europhys. Lett. **2**, 109 (1986); S.K. Gupta and S.B. Khadkikar, Phys. Rev. **D36**, 307 (1987); M.I. Krivoruchenko, Sov. Jour. Nucl. Phys. **45**, 109 (1987); L. Brekke and J.L. Rosner, Comments Nucl. Part. Phys. **18**, 83 (1988); K.-T. Chao, Phys. Rev. **D41**, 920 (1990); and references cited therein.

Λ MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments above. Measurements with an error $\geq 0.15\ \mu_N$ have been omitted.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.613 ±0.004 OUR AVERAGE				
−0.606 ±0.015	200k	COX 81	SPEC	
−0.6138±0.0047	3M	SCHACHIN... 78	SPEC	
−0.59 ±0.07	350k	HELLER 77	SPEC	
−0.57 ±0.05	1.2M	BUNCE 76	SPEC	
−0.66 ±0.07	1300	DAHL-JENSEN 71	EMUL	200 kG field

Λ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-16} *e*-cm)	*CL%*	*DOCUMENT ID*	*TECN*
< 1.5	95	[3] PONDROM 81	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<100	95	[4] BARONI 71	EMUL
<500	95	GIBSON 66	EMUL

[3] PONDROM 81 measures $(-3.0 \pm 7.4) \times 10^{-17}$ *e*-cm.

[4] BARONI 71 measures $(-5.9 \pm 2.9) \times 10^{-15}$ *e*-cm

Λ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\pi^-$	(64.1 ±0.5) %
Γ_2	$n\pi^0$	(35.7 ±0.5) %
Γ_3	$n\gamma$	(1.02±0.33) × 10^{-3}
Γ_4	$p\pi^-\gamma$	[a] (8.5 ±1.4) × 10^{-4}
Γ_5	$pe^-\overline{\nu}_e$	(8.34±0.14) × 10^{-4}
Γ_6	$p\mu^-\overline{\nu}_\mu$	(1.57±0.35) × 10^{-4}

[a] See the Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 24 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 13.6 for 20 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100			
x_3	−9	2		
x_5	46	−46	−4	
x_6	0	0	0	0
	x_1	x_2	x_3	x_5

Λ BRANCHING RATIOS

$\Gamma(p\pi^-)/\Gamma(N\pi)$ $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.642±0.005 OUR FIT				
0.640±0.005 OUR AVERAGE				
0.646±0.008	4572	BALTAY 71B	HBC	$K^- p$ at rest
0.635±0.007	6736	DOYLE 69	HBC	$\pi^- p \to \Lambda K^0$
0.643±0.016	903	HUMPHREY 62	HBC	
0.65 ±0.05		COLUMBIA 60	HBC	
0.627±0.031		CRAWFORD 59B	HBC	

$\Gamma(n\pi^0)/\Gamma(N\pi)$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID	TECN
0.358±0.005 OUR FIT			
0.304±0.025 OUR AVERAGE			
0.35 ±0.05		BROWN 63	HLBC
0.291±0.034	75	CHRETIEN 63	HLBC
0.28 ±0.08		BAGLIN 60	HLBC
0.43 ±0.14		CRAWFORD 59B	HBC
0.23 ±0.09		EISLER 57	HLBC

$\Gamma(n\gamma)/\Gamma(n\pi^0)$ Γ_3/Γ_2

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.9 ±0.9 OUR FIT				
2.86±0.74±0.57	24	BIAGI 86	SPEC	SPS hyperon beam

$\Gamma(p\pi^-\gamma)/\Gamma(p\pi^-)$ Γ_4/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.32±0.22	72	BAGGETT 72C	HBC	$\pi^- < 95$ MeV/c

$\Gamma(pe^-\overline{\nu}_e)/\Gamma(p\pi^-)$ Γ_5/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.301±0.019 OUR FIT				
1.301±0.019 OUR AVERAGE				
1.335±0.056	7111	BOURQUIN 83	SPEC	SPS hyperon beam
1.313±0.024	10k	WISE 80	SPEC	
1.23 ±0.11	544	LINDQUIST 77	SPEC	$\pi^- p \to K^0\Lambda$
1.27 ±0.07	1089	KATZ 73	HBC	
1.31 ±0.06	1078	ALTHOFF 71	OSPK	
1.17 ±0.13	86	[5] CANTER 71	HBC	$K^- p$ at rest
1.20 ±0.12	143	[6] MALONEY 69	HBC	
1.17 ±0.18	120	[6] BAGLIN 64	FBC	K^- freon 1.45 GeV/c
1.23 ±0.20	150	[6] ELY 63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.32 ±0.15	218	[5] LINDQUIST 71	OSPK	See LINDQUIST 77

[5] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ assuming the authors used $\Gamma(p\pi^-)/\Gamma_{\text{total}}$ = 2/3.

[6] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ because $\Gamma(pe^-\nu)/\Gamma(p\pi^-)$ is the directly measured quantity.

$\Gamma(p\mu^-\overline{\nu}_\mu)/\Gamma(N\pi)$ $\Gamma_6/(\Gamma_1+\Gamma_2)$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
1.57±0.35 OUR FIT				
1.57±0.35 OUR AVERAGE				
1.4 ±0.5	14	BAGGETT 72B	HBC	$K^- p$ at rest
2.4 ±0.8	9	CANTER 71B	HBC	$K^- p$ at rest
1.3 ±0.7	3	LIND 64	RVUE	
1.5 ±1.2	2	RONNE 64	FBC	

Λ DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings. Some early results have been omitted.

α_- FOR $\Lambda \to p\pi^-$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.642±0.013 OUR AVERAGE				
0.584±0.046	8500	ASTBURY 75	SPEC	
0.649±0.023	10325	CLELAND 72	OSPK	
0.67 ±0.06	3520	DAUBER 69	HBC	From Ξ decay
0.645±0.017	10130	OVERSETH 67	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN 63	CNTR	Λ from $\pi^- p$

ϕ ANGLE FOR $\Lambda \to p\pi^-$ $(\tan\phi = \beta\ /\ \gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
− 6.5± 3.5 OUR AVERAGE				
− 7.0± 4.5	10325	CLELAND 72	OSPK	Λ from $\pi^- p$
− 8.0± 6.0	10130	OVERSETH 67	OSPK	Λ from $\pi^- p$
13.0±17.0	1156	CRONIN 63	OSPK	Λ from $\pi^- p$

$\alpha_0\ /\ \alpha_- = \alpha(\Lambda \to n\pi^0)\ /\ \alpha(\Lambda \to p\pi^-)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.01 ±0.07 OUR AVERAGE				
1.000±0.068	4760	[7] OLSEN 70	OSPK	$\pi^+ n \to \Lambda K^+$
1.10 ±0.27		CORK 60	CNTR	

[7] OLSEN 70 compares proton and neutron distributions from Λ decay.

$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})]\ /\ [\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$

Zero if *CP* is conserved.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.03±0.06 OUR AVERAGE				
+0.01±0.10	770	TIXIER 88	DM2	$J/\psi \to \Lambda\overline{\Lambda}$
−0.07±0.09	4063	BARNES 87	CNTR	$\overline{p}p \to \overline{\Lambda}\Lambda$ LEAR
−0.02±0.14	10k	[8] CHAUVAT 85	CNTR	$pp, \overline{p}p$ ISR

[8] CHAUVAT 85 actually gives $\alpha_+(\overline{\Lambda})/\alpha_-(\Lambda) = -1.04 \pm 0.29$. Assumes polarization is same in $\overline{p}p \to \overline{\Lambda}\,X$ and $pp \to \Lambda\,X$. Tests of this assumption, based on *C*-invariance and fragmentation, are satisfied by the data.

$g_A\ /\ g_V$ FOR $\Lambda \to pe^-\overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the Note on Baryon Decay Parameters in the neutron Listings. The measurements all assume that the form factor $g_2 = 0$. See also the footnote on DWORKIN 90.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.718±0.015 OUR AVERAGE				
−0.719±0.016±0.012	37k	[9] DWORKIN 90	SPEC	$e\nu$ angular corr.
−0.70 ±0.03	7111	BOURQUIN 83	SPEC	$\Xi \to \Lambda\pi^-$
−0.734±0.031	10k	[10] WISE 81	SPEC	$e\nu$ angular correl.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.63 ±0.06	817	ALTHOFF 73	OSPK	Polarized Λ

[9] The tabulated result assumes the weak-magnetism coupling $w \equiv g_W(0)/g_V(0)$ to be 0.97, as given by the CVC hypothesis and as assumed by the other listed measurements. However, DWORKIN 90 *measures* w to be 0.15 ± 0.30, and then $g_A/g_V = -0.731 \pm 0.016$.

[10] This experiment measures only the absolute value of g_A/g_V.

REFERENCES FOR Λ

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

DWORKIN	90	PR D41 780	+Cox, Dukes, Overseth+	(MICH, WISC, RUTG, MINN)
TIXIER	88	PL B212 523	+Ajaltouni, Falvard, Jousset+	(DM2 Collab.)
BARNES	87	PL B199 147	+	(CMU, SACL, LANL, VIEN, FREI, ILL, UPPS+)
BIAGI	86	ZPHY C30 201	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
CHAUVAT	85	PL 163B 273	+Erhan, Hayes+	(CERN, UDCF, UCLA, SACL)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEID, LALO, RL, STRB)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
PONDROM	81	PR D23 814	+Handler, Sheaff, Cox+	(WISC, MICH, RUTG, MINN)
WISE	81	PL 98B 123	+Jensen, Kreisler, Lomanno, Poster+	(MASA, BNL)
WISE	80	PL 91B 165	+Jensen, Kreisler, Lomanno, Poster+	(MASA, BNL)
SCHACHIN...	78	PRL 41 1348	Schachinger, Bunce, Cox+	(MICH, RUTG, WISC)
HELLER	77	PL 68B 480	+Overseth, Bunce, Dydak+	(MICH, WISC, HEID)
LINDQUIST	77	PR D16 2104	+Swallow, Sumner+	(EFI, OSU, ANL)
Also	76	JP G2 L211	Lindquist, Swallow+	(EFI, WUSL, OSU, ANL)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEID)
BUNCE	76	PRL 36 1113	+Handler, March, Martin+	(WISC, MICH, RUTG)
ASTBURY	75	NP B99 30	+Gallivan, Jafar+	(LOIC, CERN, ETH, SACL)
CLAYTON	75	NP B95 130	+Bacon, Butterworth, Waters+	(LOIC, RHEL)
ALTHOFF	73	PL 43B 237	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
ALTHOFF	73B	NP B66 29	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
KATZ	73	Maryland Thesis		(UMD)
POULARD	73	PL 46B 135	+Givernaud, Borg	(SACL)
BAGGETT	72B	ZPHY 252 362	+Baggett, Eisele, Filthuth, Frehse+	(HEID)
BAGGETT	72C	PL 42B 379	+Baggett, Eisele, Filthuth, Frehse, Hepp+	(HEID)
CLELAND	72	NP B40 221	+Conforto, Eaton, Gerber+	(CERN, GEVA, LUND)
HYMAN	72	PR D5 1063	+Bunnell, Derrick, Fields, Katz+	(ANL, CMU)
ALTHOFF	71	PL 37B 531	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
BALTAY	71B	PR D4 670	+Bridgewater, Cooper, Habibi+	(COLU, BING)
BARONI	71	LNC 2 1256	+Petrera, Romano	(ROMA)
CANTER	71	PRL 26 868	+Cole, Lee-Franzini, Loveless+	(STON, COLU)
CANTER	71B	PRL 27 59	+Cole, Lee-Franzini, Loveless+	(STON, COLU)
DAHL-JENSEN	71	NC 3A 1	+	(CERN, ANKA, LAUS, MPIM, ROMA)
LINDQUIST	71	PRL 27 612	+Sumner+	(EFI, WUSL, OSU, ANL)
OLSEN	70	PRL 24 843	+Pondrom, Handler, Limon, Smith+	(WISC, MICH)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
DOYLE	69	UCRL 18139 Thesis		(LRL)
MALONEY	69	PRL 23 425	+Sechi-Zorn	(UMD)
GRIMM	68	NC 54A 187		(HEID)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
BADIER	67	PL 25B 152	+Bonnet, Briandet, Sadoulet	(EPOL)
MAYEUR	67	U.Libr.Brux.Bul. 32	+Tompa, Wickens	(BELG, LOUC)
OVERSETH	67	PRL 19 391	+Roth	(MICH, PRIN)
BURAN	66	PL 20 318	+Eivindson, Skjeggestad, Tofte+	(OSLO)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
ENGELMANN	66	NC 45A 1038	+Filthuth, Alexander+	(HEID, REHO)
GIBSON	66	NC 45A 882	+Green	(BRIS)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
SCHMIDT	65	PR 140B 1328		(COLU)
BAGLIN	64	NC 35 977	+Bingham+	(EPOL, CERN, LOUC, RHEL, BERG)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
LIND	64	PR 135B 1483	+Binford, Good, Stern	(WISC)
RONNE	64	PL 11 357	+	(CERN, EPOL, LOUC, BERG+)
SCHWARTZ	64	UCRL 11360 Thesis		(LRL)
BHOWMIK	63	NC 28 1494	+Goyal	(DELH)
BLOCK	63	PR 130 766	+Gessaroli, Ratti+	(NWES, BGNA, SYRA, ORNL)
BROWN	63	PR 130 769	+Kadyk, Trilling, Roe+	(LRL, MICH)
CHRETIEN	63	PR 131 2208	+	(BRAN, BROW, HARV, MIT)
CRONIN	63	PR 129 1795	+Overseth	(PRIN)
ELY	63	PR 131 868	+Gidal, Kalmus, Oswald, Powell+	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)
BAGLIN	60	NC 18 1043	+Bloch, Brisson, Hennessy+	(EPOL)
COLUMBIA	60	Rochester Conf. 726	Schwartz+	(COLU)
CORK	60	PR 120 1000	+Kerth, Wenzel, Cronin+	(LRL, PRIN, BNL)
CRAWFORD	59B	PRL 2 266	+Cresti, Douglass, Good, Ticho+	(LRL)
EISLER	57	NC 5 1700	+Plano, Samios, Schwartz+	(COLU, BNL)

NOTE ON Λ AND Σ RESONANCES

I. Introduction

In the Listing of the $\Lambda(1405)$, there is a new note by R.H. Dalitz on the status of that resonance. Otherwise, there are no new results on Λ and Σ resonances for this edition. The field remains at a standstill. It can only be revived if a kaon factory is built. What follows is the review from our 1986 edition: it summarizes "recent" progress and problems. For another brief overview, see Tripp.[1]

Table 1 is an attempt to evaluate the status, both overall and channel by channel, of each Λ and Σ resonance in the full Baryon Listings; the evaluations are of course partly subjective. A blank indicates there is no evidence at all; either the relevant couplings are small or the resonance does not really exist. The main Baryon Summary Table includes only the established resonances (overall status 3 or 4 stars). A number of the 1- and 2-star entries may eventually disappear, but there are certainly many resonances yet to be discovered underlying the established ones.

None of the Λ's and Σ's proposed since the mid 1970's couple strongly to the main 2-body decay channels $N\overline{K}$, $\Lambda\pi$, and $\Sigma\pi$, and thus they seldom appear in cross sections or invariant mass distributions. However, when the reactions $\overline{K}N \to \overline{K}N$, $\overline{K}N \to \Lambda\pi$, and $\overline{K}N \to \Sigma\pi$ are analyzed, some of the partial-wave amplitudes traverse small, more-or-less resonance-like circles. The question in each case is: Is this really a resonance, or is it an idle meander? Is the effect even real, or is it the result of imperfect data and analysis?

II. Formation experiments

(by G.P. Gopal, Rutherford Appleton Laboratory)

Partial-wave analyses have been made mainly for the $N\overline{K}$, $\Lambda\pi$, and $\Sigma\pi$ channels, but there are also a few results for the ΞK, $\Lambda\omega$, and some quasi-2-body channels. Early analyses usually covered only the range of a single bubble chamber experiment. Although the amplitudes from analyses in neighboring mass ranges often did not join smoothly, they did give fairly reliable information about the strongly coupled resonances. More recent analyses have used the Breit-Wigner forms of the dominant resonances as input to provide constraints in determining the overall amplitudes and thus in learning about the less prominent resonances. Besides covering wider ranges, some of the more ambitious of the analyses at the lower energies have treated several channels simultaneously, so that unitarity constraints are automatically satisfied and only a single mass and width is obtained for each resonance.

In the mid and late 1970's, much new data became available. Results from several large K^-p bubble chamber experiments were published,[2–5] and other bubble chamber experiments studied K^-n reactions[6] and K^0_Lp reactions.[7] Counter experiments measured the $K^-p \to \overline{K}^0n$ total and differential cross sections at low energies,[8] the K^-p polarizations down to 1630 MeV for the first time,[9] the K^-p polarizations from 1700 to 1900 MeV with an order of magnitude increase in statistics,[10] the K^-n elastic angular distributions from 1600 to 1800 MeV[11] and from 1900 to 2300 MeV,[12] and the 180° K^-p and 0° $\Sigma^-\pi^+$ differential cross sections from 1550 to 1900 MeV.[13]

Table 1. The status of the Λ and Σ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —			
Particle	$L_{I \cdot 2J}$	Overall status	$N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	P_{01}	****		F		$N\pi$(weakly)
$\Lambda(1405)$	S_{01}	****	****	o	****	
$\Lambda(1520)$	D_{03}	****	****	r	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	P_{01}	***	***	b	**	
$\Lambda(1670)$	S_{01}	****	****	i	****	$\Lambda\eta$
$\Lambda(1690)$	D_{03}	****	****	d	****	$\Lambda\pi\pi, \Sigma\pi\pi$
$\Lambda(1800)$	S_{01}	***	***	d	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(1810)$	P_{01}	***	***	e	**	$N\overline{K}^*$
$\Lambda(1820)$	F_{05}	****	****	n	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	D_{05}	****	***	F	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	P_{03}	****	****	o	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(2000)$		*		r	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2020)$	F_{07}	*	*	b	*	
$\Lambda(2100)$	G_{07}	****	****	i	***	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2110)$	F_{05}	***	**	d	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2325)$	D_{03}	*	*	d		$\Lambda\omega$
$\Lambda(2350)$		***	***	e	*	
$\Lambda(2585)$		**	**	n		
$\Sigma(1193)$	P_{11}	****				$N\pi$(weakly)
$\Sigma(1385)$	P_{13}	****		****	****	
$\Sigma(1480)$		*	*	*	*	
$\Sigma(1560)$		**		**	**	
$\Sigma(1580)$	D_{13}	**	*	*		
$\Sigma(1620)$	S_{11}	**	**	*	*	
$\Sigma(1660)$	P_{11}	***	***	*	**	
$\Sigma(1670)$	D_{13}	****	****	****	****	several others
$\Sigma(1690)$		**	*	**	*	$\Lambda\pi\pi$
$\Sigma(1750)$	S_{11}	***	***	**	*	$\Sigma\eta$
$\Sigma(1770)$	P_{11}	*				
$\Sigma(1775)$	D_{15}	****	****	****	***	several others
$\Sigma(1840)$	P_{13}	*	*	**	*	
$\Sigma(1880)$	P_{11}	**	**	**		$N\overline{K}^*$
$\Sigma(1915)$	F_{15}	****	***	****	***	$\Sigma(1385)\pi$
$\Sigma(1940)$	D_{13}	***	*	***	**	quasi-2-body
$\Sigma(2000)$	S_{11}	*		*		$N\overline{K}^*, \Lambda(1520)\pi$
$\Sigma(2030)$	F_{17}	****	****	****	**	several others
$\Sigma(2070)$	F_{15}	*	*		*	
$\Sigma(2080)$	P_{13}	**		**		
$\Sigma(2100)$	G_{17}	*		*	*	
$\Sigma(2250)$		***	***	*	*	
$\Sigma(2455)$		**	*			
$\Sigma(2620)$		**	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				multi-body

****	Good, clear, and unmistakable.
***	Good, but in need of clarification or not absolutely certain.
**	Not established; needs confirmation.
*	Evidence weak; could disappear.

More recently, there have been new measurements of K^-n elastic scattering between 1600 and 1740 MeV.[14] Also, new total and differential cross-section data on K^-p, $\overline{K}^0n$, $\Sigma^{\pm}\pi^{\mp}$, and $\Lambda\pi^0$ between 1437 and 1486 MeV have became available.[15] They clearly show the onset of P-wave amplitudes by 1450 MeV, which brings into question analyses of low energy data that assumed only S waves were significant. Finally, there are new $\Sigma^{\pm}\pi^{\mp}$ differential cross-section and polarization distributions in a region where data were sparse, from 1650 to 1715 MeV.[16]

We now compare the more recent analyses with each other and with the data. Some of the data have yet to be incorporated into any analysis.

The $N\overline{K}$ channel: The most recent analysis[17] is an update of the old Rutherford Lab-Imperial College (RLIC 77) analysis.[18] As before, it is a conventional energy-dependent analysis with the added constraint that the masses and widths of the resonances had to be consistent with those determined in the inelastic channels analyzed previously — $\Lambda\pi, \Sigma\pi$, $\Lambda(1520)\pi$, $\Sigma(1385)\pi$, and $N\overline{K}^{*}(892)$. The analysis also goes closer to threshold, covering 1470 to 2170 MeV. It does not include the data from a number of the more recent experiments mentioned above. As before, angular distributions (a total of 5110 data points) were fit directly. The new amplitudes differ little from the RLIC 77 amplitudes. However, the $K^{-}n$ data removed some of the uncertainties in the Σ resonances.

The LBL-Mt. Holyoke-CERN analysis[19] covers the narrower range of 1500 to 1940 MeV and also includes most of the new data. It is an energy-dependent analysis using a unitary background parametrized in terms of scattering lengths. The cusp effects at the $\Lambda\eta$ and $\Sigma\eta$ thresholds are included by introducing a square-root singularity in the energy variation of the widths of the appropriate resonances. This group's own high-statistics charge-exchange data[8] (which do not agree with bubble chamber measurements) all but kill the less well-established resonances.

The University College, London (UCL) K-matrix energy-dependent analysis[20] covers from 1540 to 2000 MeV. The $N\overline{K}$ amplitudes are consistent with those of the other analyses over most of this range. However, at the low end there are major differences, due to the absence of constraints from the Λ(1520), which lies just outside the range covered. The $K^{-}n$ angular distributions and $K^{-}p$ polarization measurements are not fit very well.

The above analyses, all below 2200 MeV, are complemented by the College de France-Saclay (CdF-S) energy-dependent analysis[5] covering from 2070 to 2440 MeV. Besides the conventional polynomial parametrization of the background amplitudes, also tried is a parametrization using constraints imposed by the duality hypothesis (that s-channel backgrounds come exclusively from the t-channel Pomeron exchange amplitude). With 30 fewer free parameters, the results are consistent with the conventional approach.

The $\Sigma\pi$ channel: There is very little agreement, particularly about the lower partial waves, between the two multichannel analyses.[18,20] The low-energy $K^{0}_{L}p \to \Sigma^{0}\pi^{+}$ data[7] are better explained by the RLIC 77 amplitudes than by the UCL amplitudes. At the high end, there is good continuity between the RLIC 77 amplitudes and those from the single-channel analysis of the CdF-S collaboration[5] covering from 2070 to 2440 MeV. The Λ(1520) and Λ(2110) resonances, which lie outside the range covered by the UCL analysis, clearly provide strong constraints.

The $\Lambda\pi$ channel: This isospin-1 channel has been the subject of many energy-dependent and -independent analyses (for example, RLIC 77,[18] UCL,[20] Baillon-Litchfield,[21] de Bellefon-Berthon,[22] and Van Horn[23]). However, even the widespread use of the method of Barrelet zeroes has not helped to resolve the Σ spectrum — probably because most Σ resonances simply do not couple strongly to the $N\overline{K}$ initial state.

Quasi-2-body channels: The Rutherford Lab-Imperial College group has made energy-dependent analyses of the $\Lambda(1520)\pi$, $\Sigma(1385)\pi$, and $N\overline{K}^{*}(892)$ channels over the widest ranges for which data are available. The data were extracted from the appropriate 3-particle final states by making 4-variable fits to an incoherent superposition of quasi-2-body final states and 3-particle Lorentz-invariant phase space. The quality of the fits suggests a maximum model-dependent systematic uncertainty of 10%. The $\Lambda\omega$ channel has been analyzed from threshold to 2440 MeV by the CdF-S collaboration.[5]

Sign conventions for resonance couplings: In terms of the isospin-0 and -1 elastic scattering amplitudes A_0 and A_1, the amplitude for $K^{-}p \to \overline{K}^{0}n$ scattering is $\pm(A_1 - A_0)/2$, where the sign depends on conventions used in conjunction with the Clebsch-Gordan coefficients (such as, is the baryon or the meson the "first" particle). If this reaction is partial-wave analyzed and if the overall phase is chosen so that, say, the $\Sigma(1775)D_{15}$ amplitude at resonance points along the positive imaginary axis (points "up"), then any Σ at resonance will point "up" and any Λ at resonance will point "down" (along the negative imaginary axis). Thus the phase at resonance determines the isospin. The above ignores background amplitudes in the resonating partial waves.

That is the basic idea. In a similar but somewhat more complicated way, the phases of the $\overline{K}N \to \Lambda\pi$ and $\overline{K}N \to \Sigma\pi$ amplitudes for a resonating wave help determine the SU(3) multiplet to which the resonance belongs. Again, a convention has to be adopted for some overall arbitrary phases: which way is "up"? Our convention is that of Levi-Setti[24] and is shown in Figure 1, which also compares experimental results with theoretical predictions for the signs of several resonances. In the Listings, a + or − sign in front of a measurement of an inelastic resonance coupling indicates the sign (the *absence* of a sign means that the sign is not determined, *not* that it is positive). For more details, see Appendix II of our 1982 edition.[25]

Argand plots: Figure 2 shows some representative Argand plots of partial-wave amplitudes. For the $N\overline{K}$ channel we show the amplitudes from RLIC 77[18] and from LBL-Mt. Holyoke-CERN,[19] and for the $\Lambda\pi$ and $\Sigma\pi$ channels we show those from RLIC 77[18] and from UCL.[20]

Errors on masses and widths: The errors quoted on resonance parameters from partial-wave analyses are often only statistical, and the parameters can change by more than these errors when a different parametrization of the waves is used. Furthermore, the different analyses use more or less the same data, so it is not really appropriate to treat the different determinations of the resonance parameters as independent or to average them together. In any case, the spread of the masses, widths, and branching fractions from the different analyses is certainly a better indication of the uncertainties than are the quoted errors. In the Baryon Summary Table, usually a range reflecting the spread of the values is given rather than a particular value with error.

For three states, the Λ(1520), the Λ(1820), and the Σ(1775), there is enough information to make an overall fit to the various branching fractions. It is then necessary to use the quoted errors, but the errors obtained from the fit should not be taken seriously.

III. Production experiments

Partial-wave analyses of course separate partial waves, whereas a peak in a cross section or an invariant mass distribution usually cannot be disentangled from background and analyzed for its quantum numbers; and more than one resonance may be contributing to the peak. Results from partial-wave analyses and from production experiments are generally kept separate in the Listings, and in the Baryon Summary Table results from production experiments are used only for the low-mass states. The Σ(1385) and Λ(1405) of course lie below the $\overline{K}N$ threshold and nearly everything about them is learned from production experiments; and production and formation experiments agree quite well in the case of Λ(1520) and results have been combined. There is some disagreement between production and formation experiments in the 1600–1700 MeV region: see the Note on the Σ(1670).

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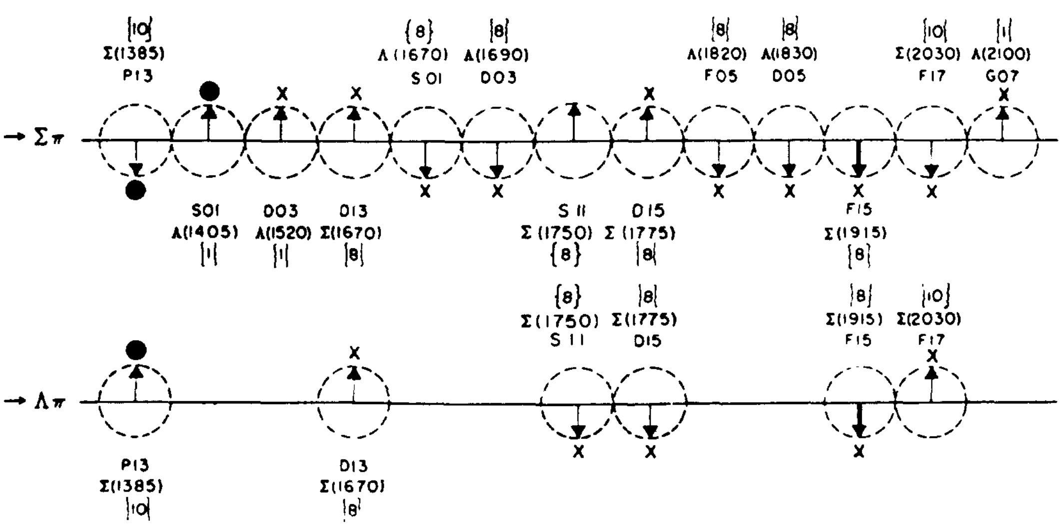


Figure 1. The signs of the imaginary parts of resonating amplitudes in the $\overline{K}N \rightarrow \Lambda\pi$ and $\Sigma\pi$ channels. The signs of the Σ(1385) and Λ(1405), marked with a •, are set by convention, and then the others are determined relative to them. The signs required by the SU(3) assignments of the resonances are shown with an arrow, and the experimentally determined signs are shown with an ×.

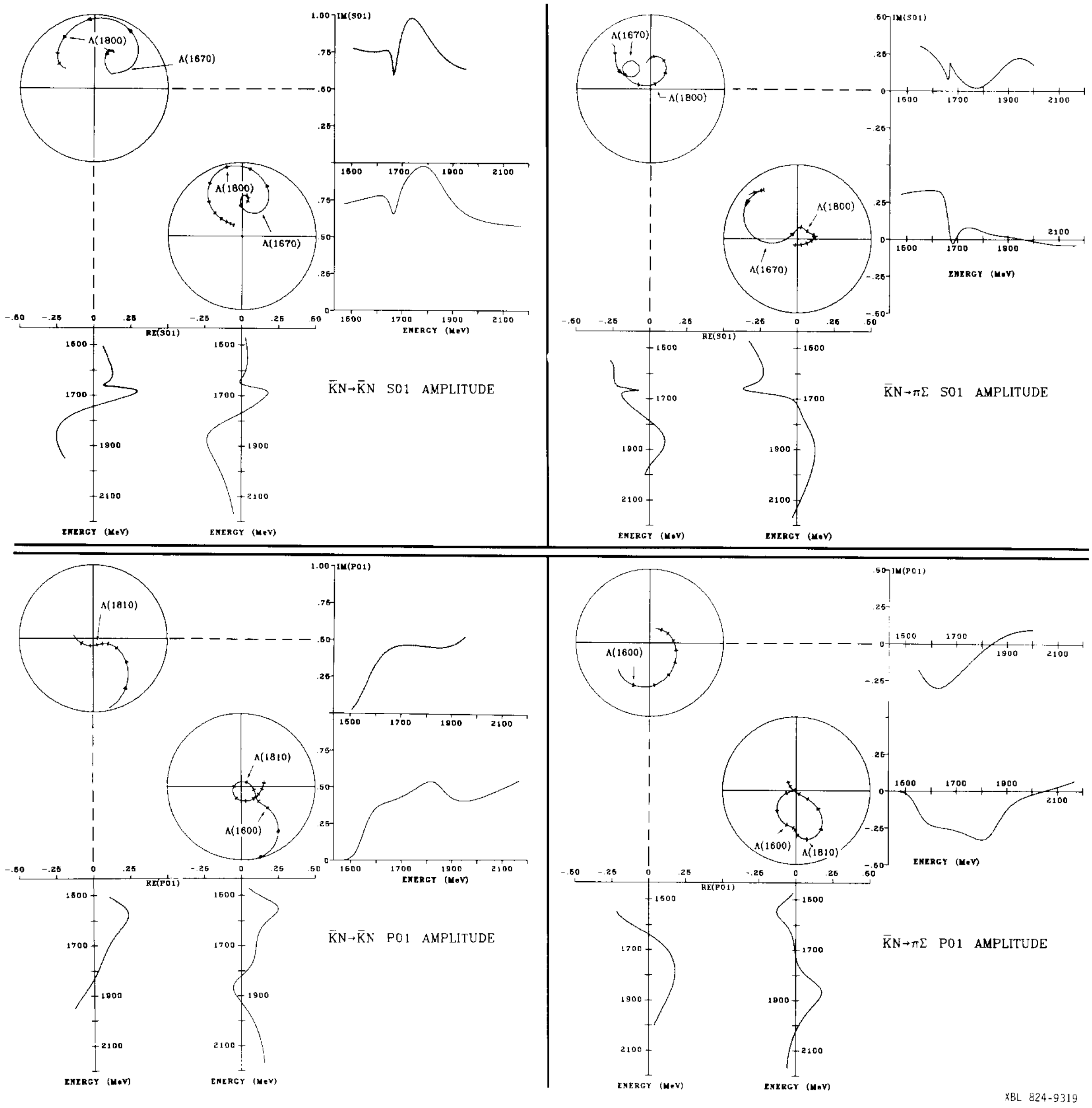


Figure 2(a). The $L_{I \cdot 2J} = S_{01}$ and P_{01} partial-wave amplitudes for $\overline{K}N$ scattering in the elastic and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plots for the elastic amplitudes are from ALSTON 78, and the upper plots for the $\Sigma\pi$ amplitudes are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions [the $S_{01}\Lambda(1405)$ is of course below threshold and is not shown]. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.

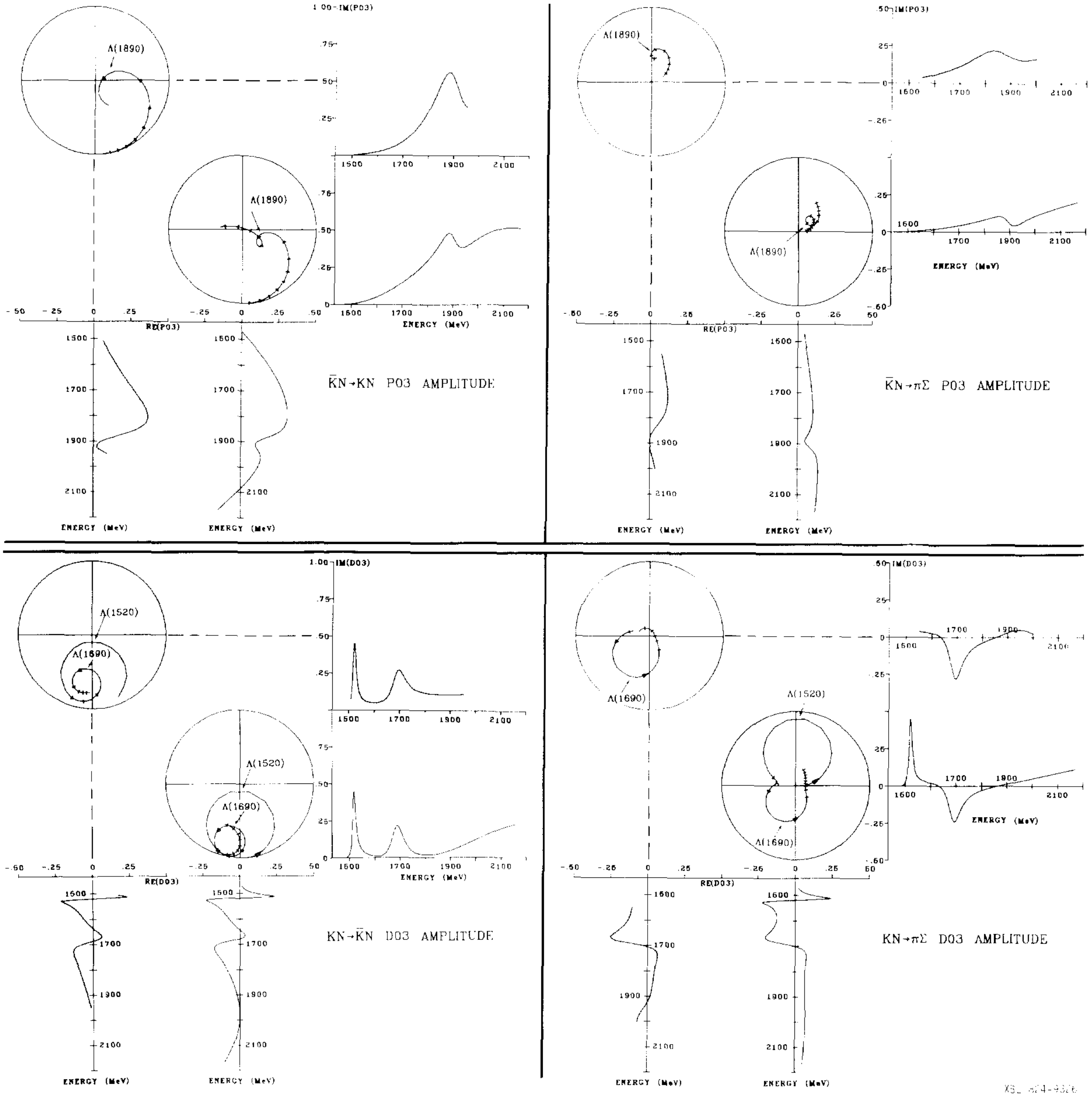


Figure 2(b). The $L_{I \cdot 2J} = P_{03}$ and D_{03} partial-wave amplitudes for $\overline{K}N$ scattering in the elastic and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plots for the elastic amplitudes are from ALSTON 78, and the upper plots for the $\Sigma\pi$ amplitudes are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.

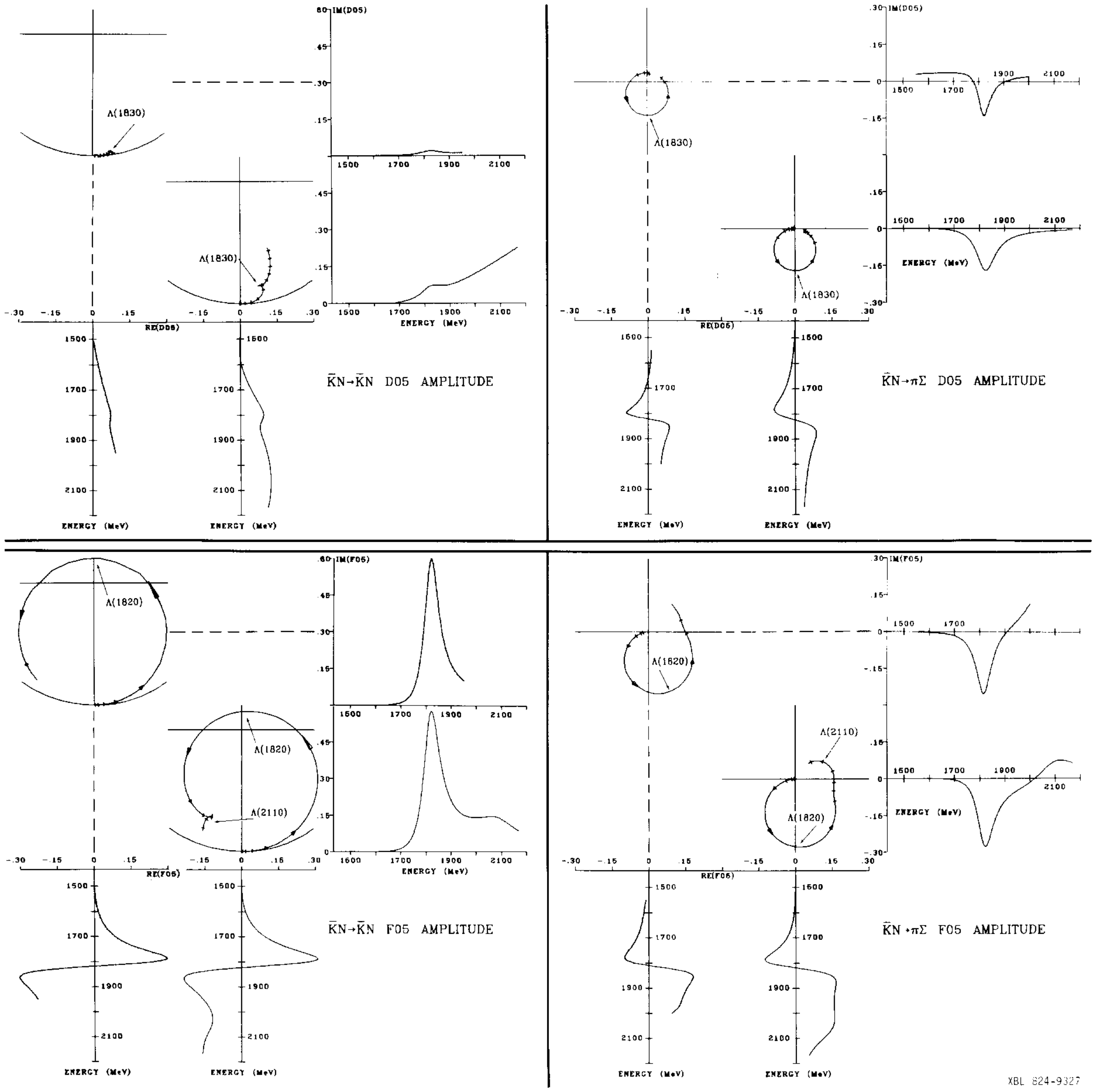


Figure 2(c). The $L_{I\cdot 2J} = D_{05}$ and F_{05} partial-wave amplitudes for $\overline{K}N$ scattering in the elastic and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plots for the elastic amplitudes are from ALSTON 78, and the upper plots for the $\Sigma\pi$ amplitudes are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.

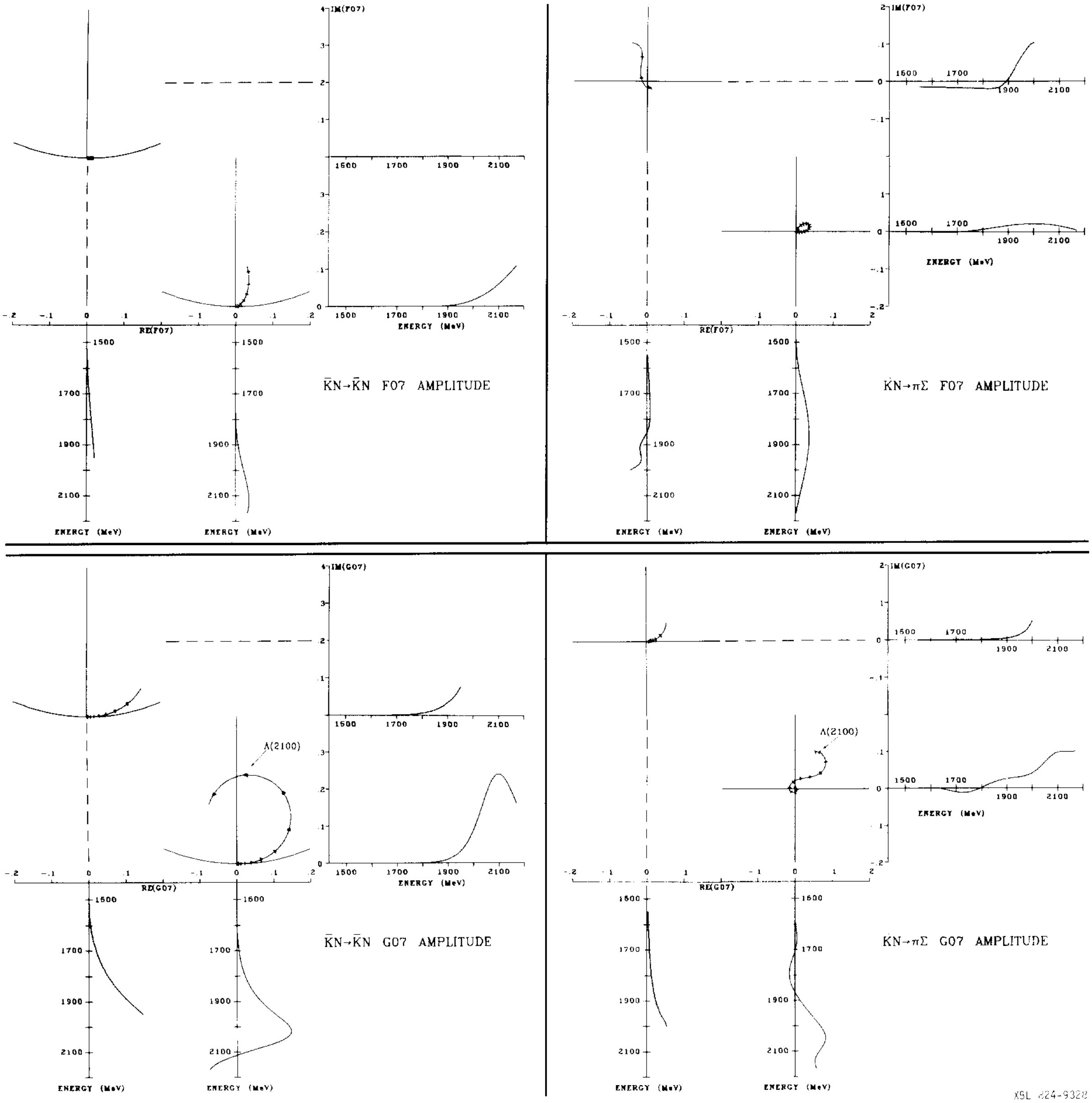
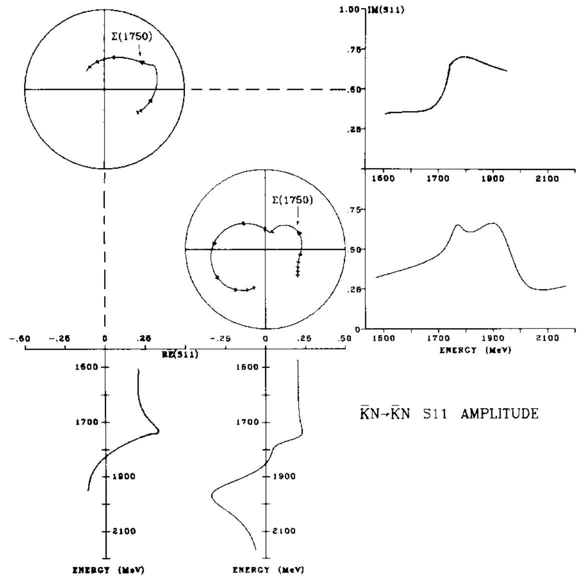
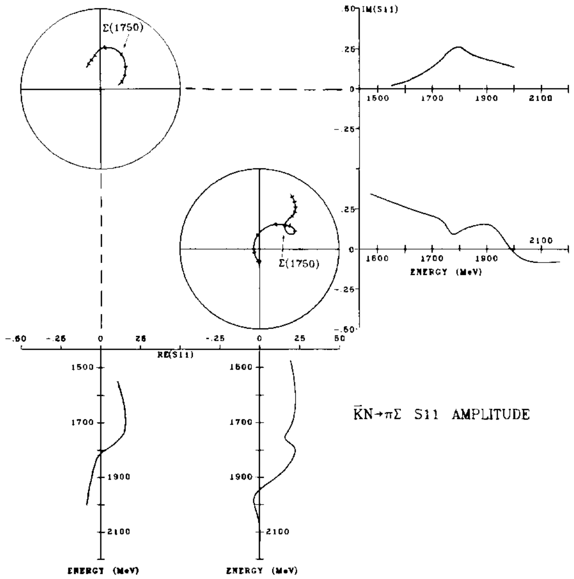


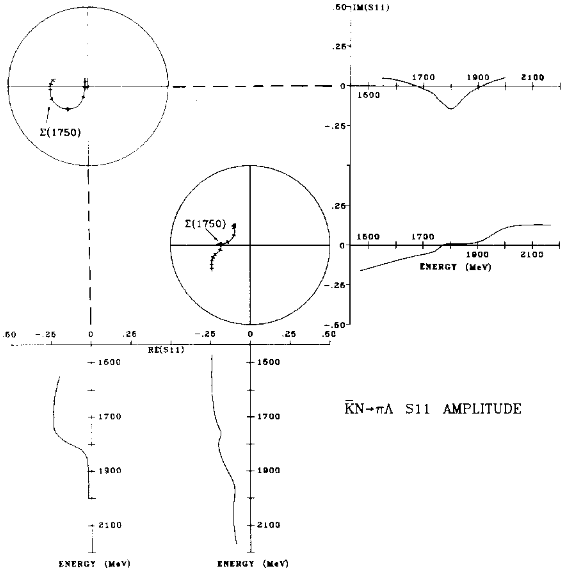
Figure 2(d). The $L_{I \cdot 2J} = F_{07}$ and G_{07} partial-wave amplitudes for $\overline{K}N$ scattering in the elastic and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plots for the elastic amplitudes are from ALSTON 78, and the upper plots for the $\Sigma\pi$ amplitudes are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonance is shown at its nominal position. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.



$\overline{K}N \to \overline{K}N$ S11 AMPLITUDE

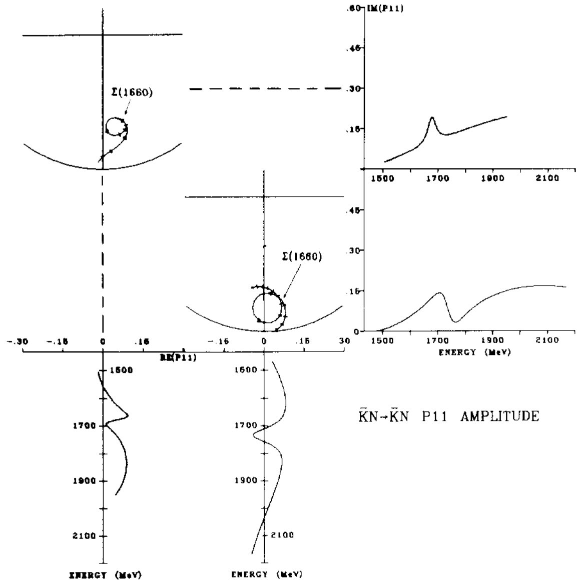


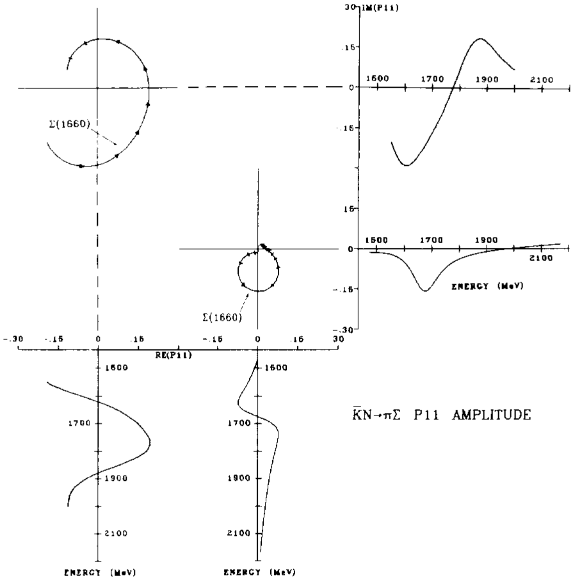
$\overline{K}N \to \pi\Sigma$ S11 AMPLITUDE



$\overline{K}N \to \pi\Lambda$ S11 AMPLITUDE

Figure 2(e). The $L_{I\cdot 2J} = S_{11}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonance is shown at its nominal position. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.





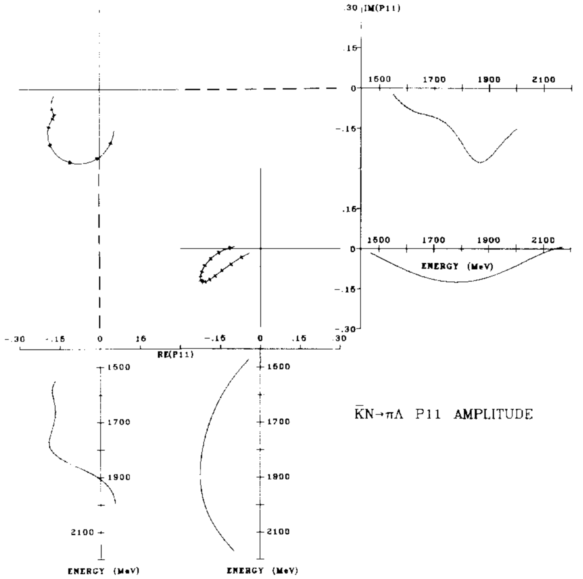
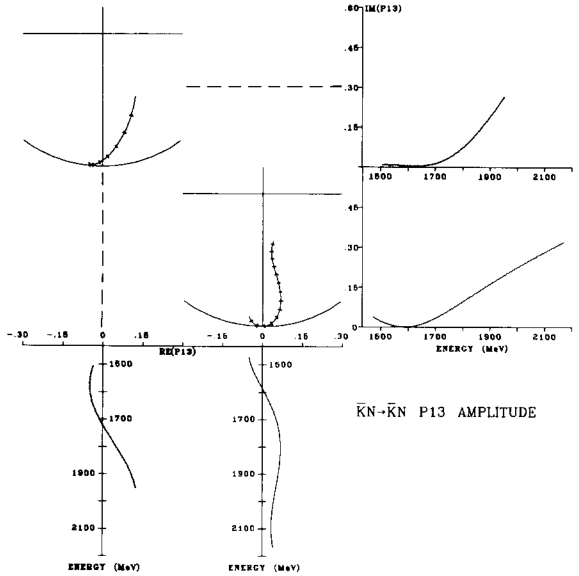
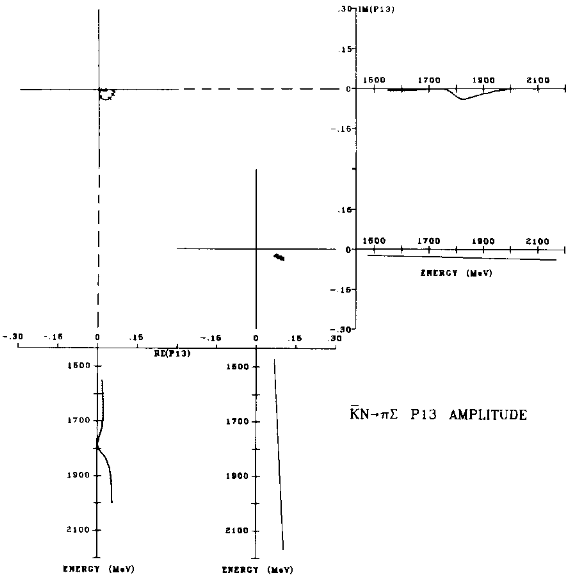


Figure 2(f). The $L_{I \cdot 2J} = P_{11}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonance is shown at its nominal position. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.


$\overline{K}N \to \overline{K}N$ P13 AMPLITUDE


$\overline{K}N \to \pi\Sigma$ P13 AMPLITUDE

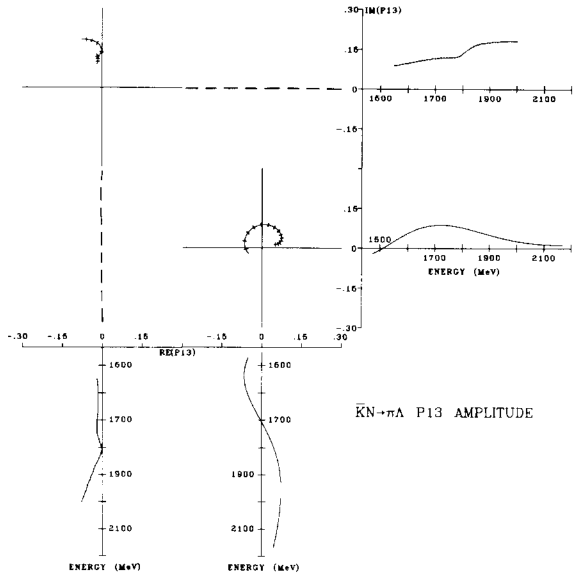
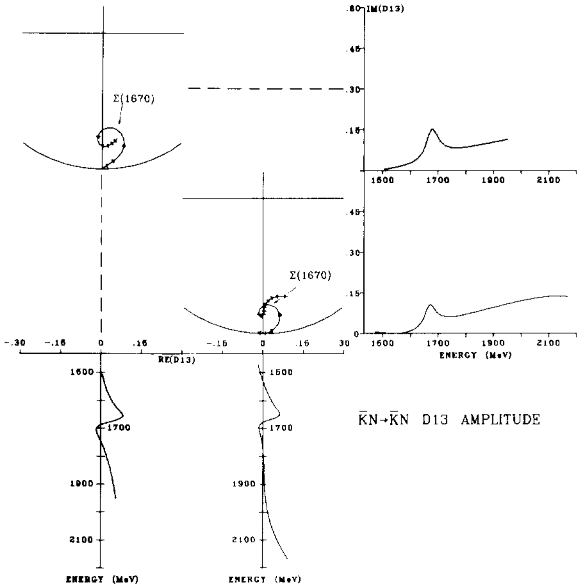
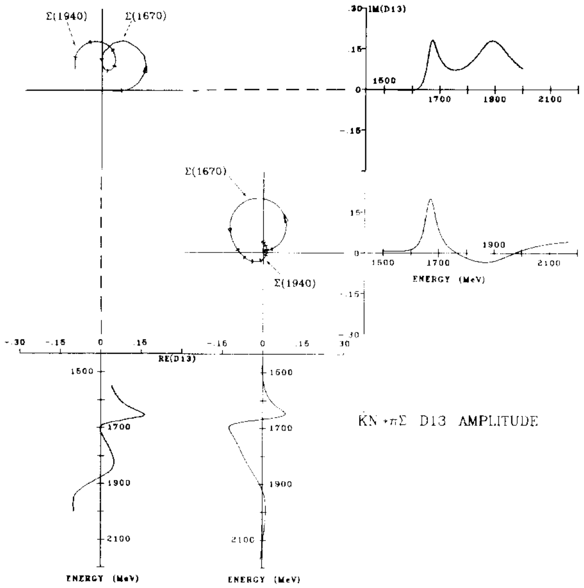

$\overline{K}N \to \pi\Lambda$ P13 AMPLITUDE

Figure 2(g). The $L_{I \cdot 2J} = P_{13}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV [the $\Sigma(1385)$ is of course below threshold and is not shown]. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.





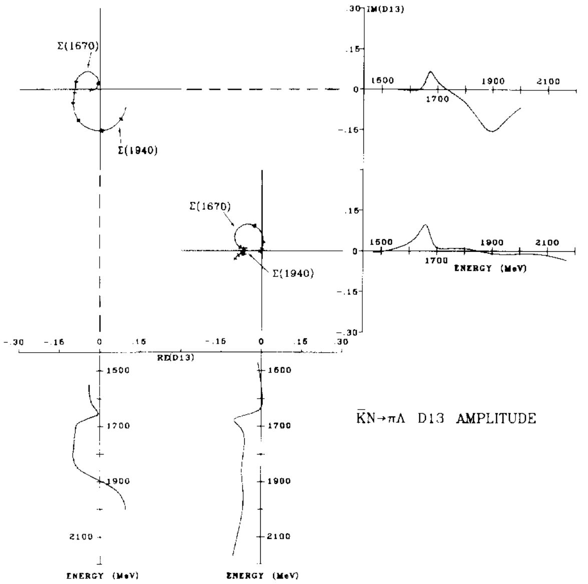
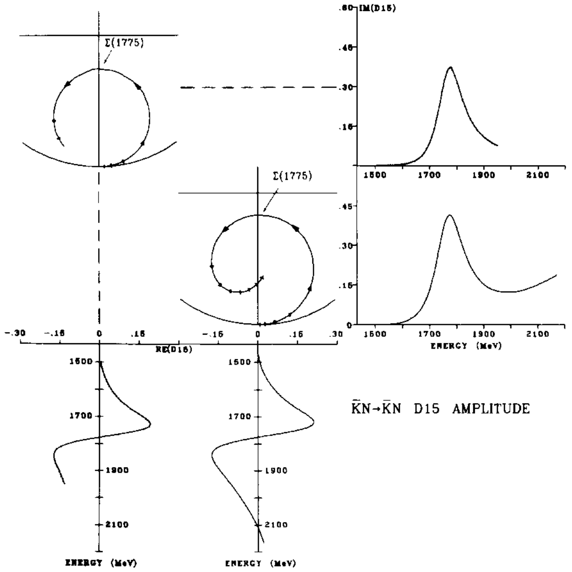
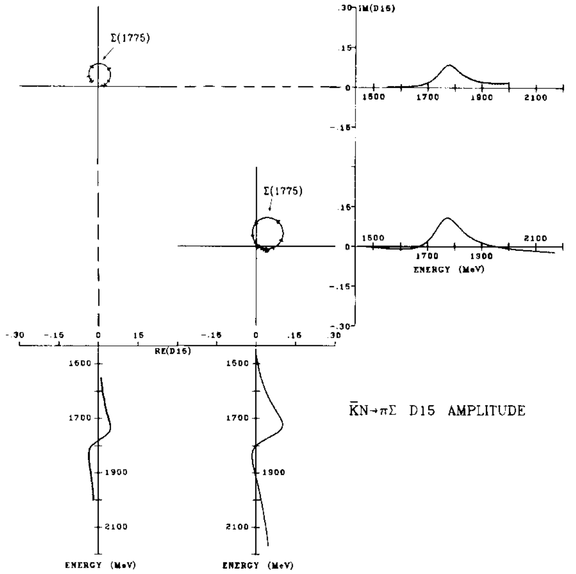


Figure 2(h). The $L_{I\cdot 2J} = D_{13}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonances are shown at their nominal positions. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.





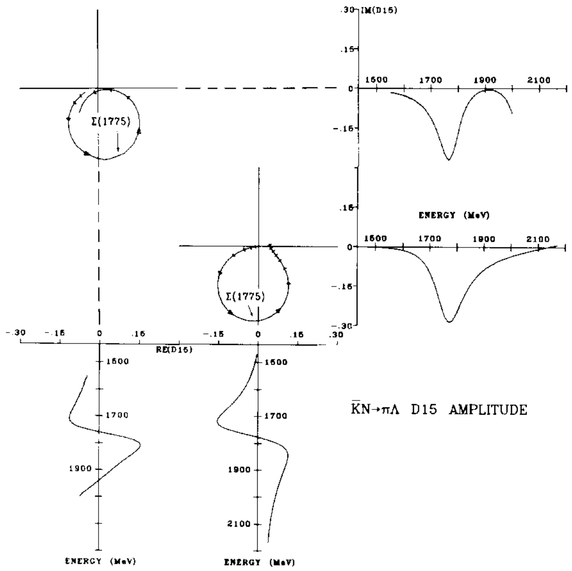
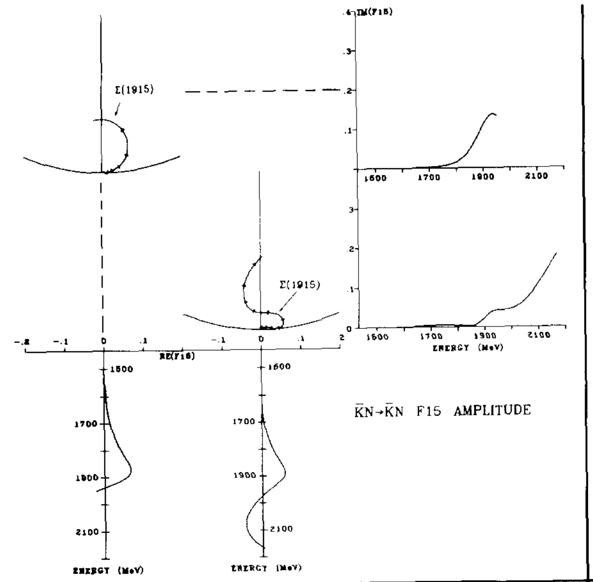
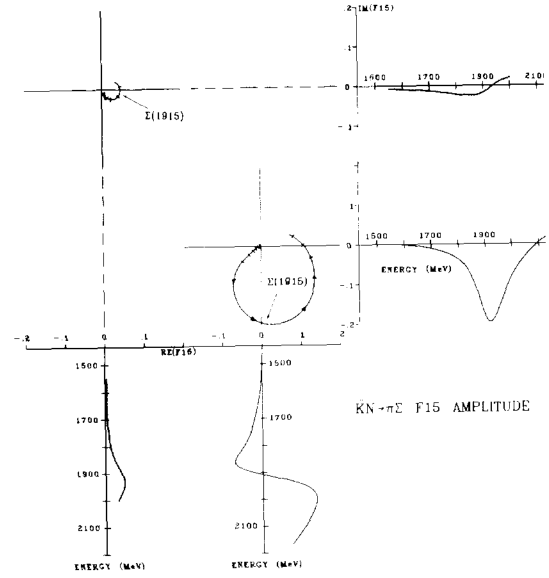


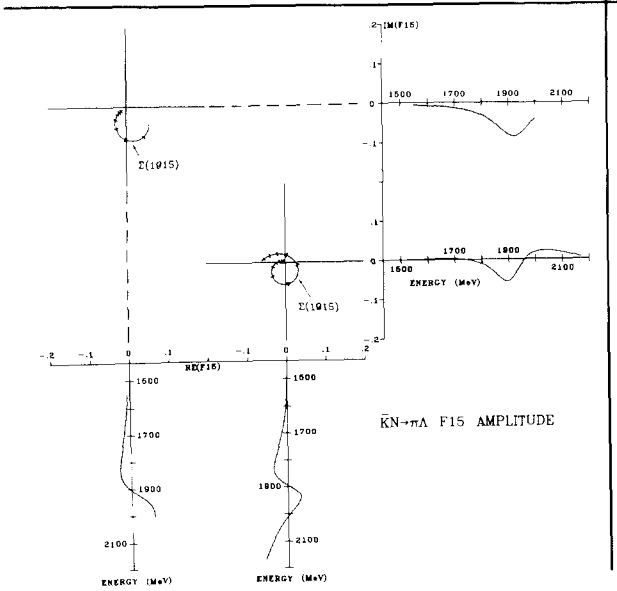
Figure 2(i). The $L_{I \cdot 2J} = D_{15}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonance is shown at its nominal position. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.



K̄N→K̄N F15 AMPLITUDE



K̄N→πΣ F15 AMPLITUDE



K̄N→πΛ F15 AMPLITUDE

Figure 2(j). The $L_{I\cdot 2J} = F_{15}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonance is shown at its nominal position. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.

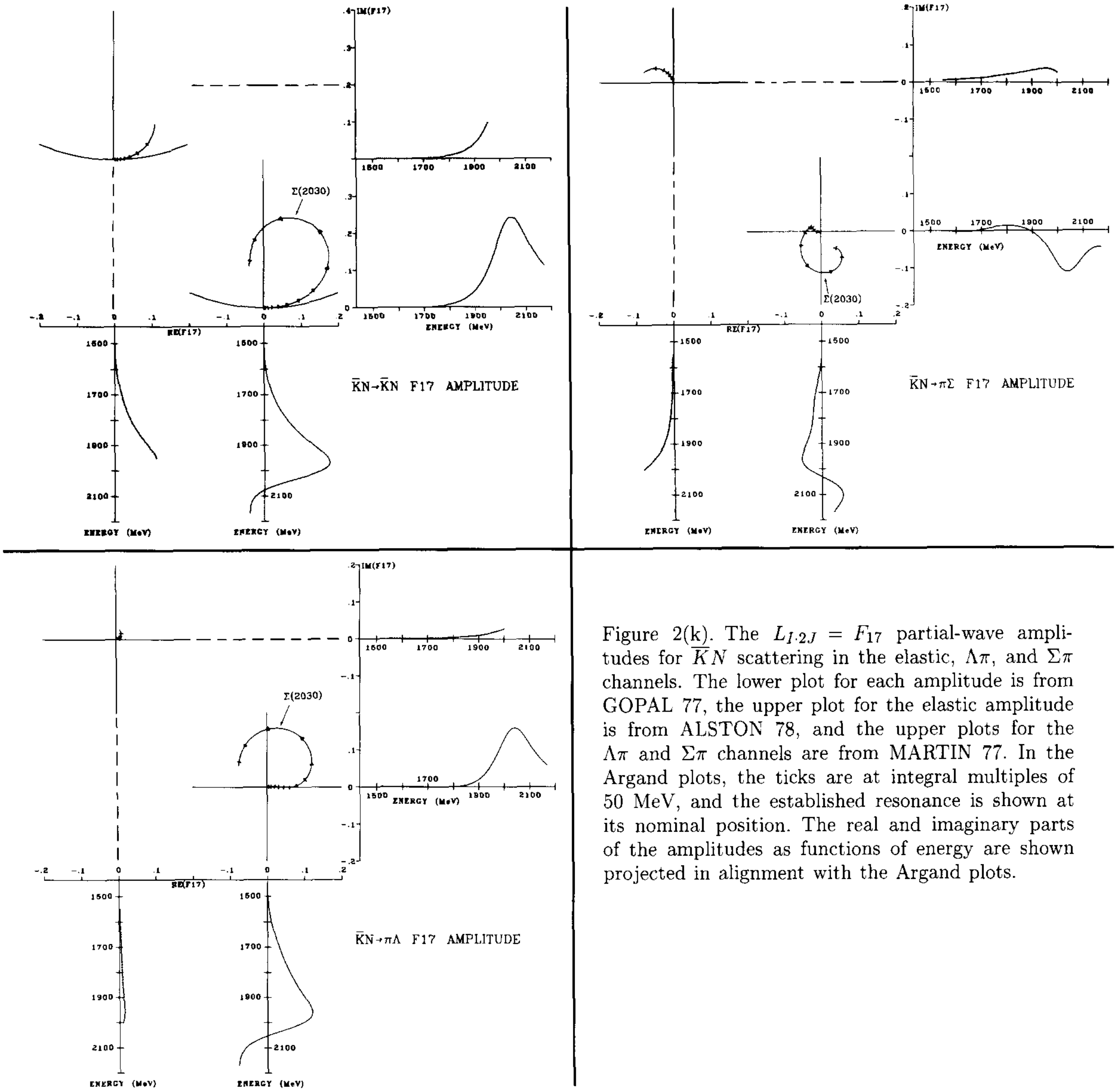


Figure 2(k). The $L_{I \cdot 2J} = F_{17}$ partial-wave amplitudes for $\overline{K}N$ scattering in the elastic, $\Lambda\pi$, and $\Sigma\pi$ channels. The lower plot for each amplitude is from GOPAL 77, the upper plot for the elastic amplitude is from ALSTON 78, and the upper plots for the $\Lambda\pi$ and $\Sigma\pi$ channels are from MARTIN 77. In the Argand plots, the ticks are at integral multiples of 50 MeV, and the established resonance is shown at its nominal position. The real and imaginary parts of the amplitudes as functions of energy are shown projected in alignment with the Argand plots.

$\Lambda(1405)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

NOTE ON THE $\Lambda(1405)$

(by R.H. Dalitz, Oxford University)

It is generally accepted that the $\Lambda(1405)$ is a well-established $J^P = 1/2^-$ resonance. It is assigned to the lowest $L = 1$ supermultiplet of the 3-quark system and paired with the $J^P = 3/2^-$ $\Lambda(1520)$. Lying about 30 MeV below the $N\overline{K}$ threshold, the $\Lambda(1405)$ can be observed directly only as a resonance bump in the $(\Sigma\pi)^0$ subsystem in final states of production experiments. It was first reported by ALSTON 61B in the reaction $K^-p \rightarrow \Sigma\pi\pi\pi$ at 1.15 GeV/c and has since been seen in at least eight other experiments, so that there is no doubt about its existence.

Only two production experiments have had statistics adequate for a detailed analysis: THOMAS 73, with about 400 $\Sigma^\pm\pi^\mp$ events from $\pi^-p \rightarrow K^0(\Sigma\pi)^0$ at 1.69 GeV/c; and HEMINGWAY 85, with 766 $\Sigma^+\pi^-$ and 1106 $\Sigma^-\pi^+$ events from $K^-p \rightarrow (\Sigma\pi\pi)^+\pi^-$ at 4.2 GeV/c, after selection on $1600 \leq M(\Sigma\pi\pi)^+ \leq 1720$ MeV and momentum transfer ≤ 1.0 (GeV/c)^2 to purify the $\Lambda(1405) \rightarrow (\Sigma\pi)^0$ sample. The mass and width estimates from these two experiments are in agreement, with masses around 1395–1400 MeV and widths around 60 MeV (the mass 1391 ± 1 MeV quoted by Hemingway is from the best Breit-Wigner fit, which is an unacceptable fit to the data).

The Byers-Fenster tests on these data give only $J \geq 1/2$ and no parity determination. Neither spin nor parity have yet been determied *directly* by experiment. The early indications for $J^P = 1/2^-$ came from the analysis of low-energy $N\overline{K}$ scattering and reaction data in a constant-scattering-length approach (see KIM 65, SAKITT 65, and earlier references cited therein), because $\mathrm{Re}\,A(I = 0)$ was found to be large and negative. The first multichannel energy-dependent K-matrix analysis (KIM 67) strengthened the case for a Λ resonance of mass about 1400–1420 MeV strongly coupled to the $I = 0$ S-wave $N\overline{K}$ system.

THOMAS 73 and HEMINGWAY 85 both found the $\Lambda(1405)$ bump to be asymmetric and not well-fitted by a Breit-Wigner resonance function with constant parameters. This asymmetry involves a rapid fall in intensity as the $N\overline{K}$ threshold energy is approached from below, readily interpreted as due to a strong coupling of the $\Lambda(1405)$ to the S-wave $N\overline{K}$ channel (see DALITZ 81). This striking S-shaped cusp behavior at a new threshold is characteristic of an S-wave coupling; the other below-threshold strangeness -1 resonance, the $\Sigma(1385)$, has no such asymmetry because its $N\overline{K}$ coupling is P-wave. For the $\Lambda(1405)$, this asymmetry is the *sole direct evidence* that $J^P = 1/2$.

Following the early work cited above, a considerable literature has developed on proper procedures for phenomenological extrapolation below the $N\overline{K}$ threshold, partly in order to strengthen the evidence for the spin-parity of the $\Lambda(1405)$ and partly to provide an estimate for the amplitude $f(N\overline{K})$ in the unphysical domain below the $N\overline{K}$ threshold, which is needed for evaluation of the dispersion relation for $N\overline{K}$ and NK forward scattering amplitudes. These procedures are based on the analysis of the low-energy formation data ($N\overline{K}$ total and partial S-wave cross sections for $\overline{K}$ laboratory momenta in the range 100–300 MeV/c; for recent reviews, see MILLER 84, BARRETT 89). In most recent work, the $(\Sigma\pi)^0$ production spectrum is included in the data fitted (see, e.g., CHAO 73).

It is now accepted that the data can be fitted phenomenologically only with an S-wave pole in the reaction amplitudes below $N\overline{K}$ threshold, but there is still controversy about the physical origin of this pole. For a review on this topic, see DALITZ 81 and DALITZ 82. Two extreme possibilities are: (a) an $L = 1$ unitary-flavor-singlet 3-quark baryon state, coupled with the S-wave meson-baryon systems; or (b) an unstable $N\overline{K}$ bound state, analogous to the (stable) deuteron in the NN system. If (a) holds, we have to understand why the $\Lambda(1405)$ mass is so much lower than that of its partner, the $\Lambda(1520)$, since this requires very large spin-orbit splittings in the QCD-inspired nonrelativistic quark model. Such splittings are considered to be excluded on other grounds (see ISGUR 80, CAPSTICK 86, and CAPSTICK 89). If (b) holds, another $(I, J^P) = (0, 1/2^-)$ resonance is needed to replace the $\Lambda(1405)$ in the $L = 1$ supermultiplet, and this resonance must lie close to the $\Lambda(1520)$, a region already well-explored by $N\overline{K}$ experiments with no evidence at all of any such resonance. Intermediate structures are possible; for example, the Cloudy Bag Model allows the configurations (a) and (b) to mix and finds (VEIT 84, VEIT 85, JENNINGS 86) the intensity of configuration (a) in the $\Lambda(1405)$ to be only 14%. Such models naturally predict a second $1/2^-$ Λ state close to the $\Lambda(1520)$.

There are difficulties even in the determination of the mass and width of the resonance from the $(\Sigma\pi)^0$ data. This mass spectrum is usually interpreted using the "Watson approximation," which states that the production rate $R(\Sigma\pi)$ of the final $(\Sigma\pi)^0$ state has a mass dependence proportional to $(\sin^2\delta_{\Sigma\pi})/q$, q being the $\Sigma\pi$ c.m. momentum, in a $\Sigma\pi$ mass range where $\delta_{\Sigma\pi}$ is not far from $\pi/2$ and only the $\Sigma\pi$ channel is open, i.e. between the $\Sigma\pi$ and the $N\overline{K}$ thresholds. It is more useful to consider the product $q\,R(\Sigma\pi)$, since it is proportional to $\sin^2\delta_{\Sigma\pi}$. It is then convenient to define the mass M to be the mass value at which $\sin^2\delta_{\Sigma\pi} = 1$. The width Γ may be determined from the rate at which $\delta_{\Sigma\pi}$ goes through $\pi/2$, or from the FWHM; this is a matter of convention. The determination of M and Γ from the data suffers from the following difficulties:

(i) The absolute value of $\delta_{\Sigma\pi}$ is not directly determined. Only $\sin^2\delta_{\Sigma\pi}$ can be determined, and that only after $R(\Sigma\pi)$ is scaled to give $\sin^2\delta_{\Sigma\pi} = 1$ at the peak for the best fit to the data. Thus the bump must be *assumed* to arise from a resonance. This might not always be the case, but for the

$\Lambda(1405)$ this assumption is supported by the analysis of the low-energy $N\overline{K}$ data and its extrapolation below the $N\overline{K}$ threshold.

(ii) The form of the best fit to the $M(\Sigma\pi)$ bump has considerable uncertainty, even with data as good as Hemingway's. For a c.m. energy E below a strong S-wave threshold, the general form for $\delta_{\Sigma\pi}$ is

$$q\cot\delta_{\Sigma\pi} = \frac{1+\kappa\alpha}{\gamma+\kappa(\alpha\gamma-\beta^2)}\ ,$$

where α, β, and γ are the (generally energy-dependent) $NN, N\Sigma$, and $\Sigma\Sigma$ elements of the $I = 0$ S-wave K-matrix for the $(\Sigma\pi, N\overline{K})$ system, and κ is the magnitude of the (imaginary) c.m. momentum k_K for the $N\overline{K}$ system below threshold. The elements (α, β, γ) are real functions of E; they have no branch cuts at the $\Sigma\pi$ and $N\overline{K}$ thresholds, but they are permitted to have poles in E along the real E axis. The determination of $\delta_{\Sigma\pi}$ from the shape of the $M(\Sigma\pi)$ distribution thus requires the determination of three real functions. Even if they are assumed to be constant over the resonance region, it is clear that the available data cannot provide their determination, especially if data below 1370 MeV are ruled out as being outside the range where the Watson approximation is valid. We note that $\delta_{\Sigma\pi}$ reaches the value $\pi/2$ when $\kappa = -1/\alpha$.

The plot of $q\,R(\Sigma\pi)$ for Hemingway's $\Sigma^+\pi^-$ data has three almost equal bins centered on 1395, 1405, and 1415 MeV. A good fit by eye, giving an S cusp at 1432 MeV and fitting the low-energy data down to 1360 MeV, would suggest that $M \approx 1405$ MeV is a reasonable estimate. However, it should be emphasized that the strong asymmetry of the $q\,R(\Sigma\pi)$ distribution gives rise to very considerable uncertainty in the determination of the location of the peak of this distribution; we are accustomed to fitting distributions that are symmetric, where the location of the axis of symmetry can be determined rather accurately. After some trials, it appears possible to draw curves giving acceptable fits to the data with peak values lying anywhere in the range 1400 to 1410 MeV. There is therefore considerable uncertainty in the mass; a reasonable assessment is $M = 1405$ MeV. The FWHM gives $\Gamma = 60$ to 70 MeV.

Accepting the close connection of $\delta_{\Sigma\pi}$ with the low-energy $N\overline{K}$ data, it becomes attractive to analyze these two sets of data together, for there is a large body of accurate data for the laboratory momentum range $100 \leq k_K \leq 300$ MeV/c (see MILLER 84). The two sets of data span c.m. energies from 1370 MeV to 1490 MeV, and it would be unreasonable to expect the K-matrix elements to be energy independent over such a broad range. In fact, for the $I = 0$ channels, a linear energy dependence for K^{-1} has been adopted routinely ever since the work of KIM 67, and it is essential when the $q\,R(\Sigma\pi)$ data and the low-energy $N\overline{K}$ data are fitted together. However, $q\,R(\Sigma\pi)$ is not always well-fitted in this way; the value obtained for M varies a good deal from one type of fit to another. This is not surprising since the $\Sigma\pi$ mass spectrum contributes only 9 data points in a total of about 200. The conclusion is that the value obtained for the $\Lambda(1405)$ from such an overall fit does not necessarily represent an improvement on estimates obtained from the $q\,R(\Sigma\pi)$ data alone; the value obtained may be a function of the representation used (K-matrix, relativistic—separable or non-separable—potentials, etc.) to describe these interactions over the full range of energy.

The present status of the $\Lambda(1405)$ thus depends considerably on theoretical arguments about what assumptions are most reasonable, a somewhat unsatisfactory basis for a four-star rating. Nevertheless, there is no known reason to doubt its existence and its quantum numbers. A measurement of the energy-level shift and width for the 1s level of kaonic hydrogen (also for kaonic deuterium) would give a valuable check on our present analyses of the $(\Sigma\pi, N\overline{K})$ amplitudes, since $k_K \approx 0$ for the K^-p atom corresponds to an energy roughly midway between those for the two sets of data. The three measurements of $(\Delta E - i\Gamma/2)$ for kaonic hydrogen in the literature are inconsistent with one another and require $\mathrm{Re}[A(I=0)+A(I=1)]$ to have a sign opposite that given by the current values from $N\overline{K}$ reaction data (see BATTY 89). An accurate measurement of $(\Delta E - i\Gamma/2)$ for kaonic hydrogen is urgently needed. Processes where the $\Lambda(1405)$ is indirectly involved, e.g., as an intermediate state in $K^-p \to \Sigma^0\gamma$ and $\Lambda\gamma$ (see WHITEHOUSE 89), are now being investigated and may ultimately give valuable information on the $\Lambda(1405)$ parameters.

To settle the nature of the $\Lambda(1405)$ will require much further research, both experimental and theoretical. Higher-statistics experiments on the production and decay of the $\Lambda(1405)$ are needed, but good K^- beams for this work are not available, and the experiments will not be possible until a kaon factory is built. Not all of the low-energy $N\overline{K}$ reaction cross sections are sufficiently well determined, especially those involving $\overline{K}^0p$ interactions, which have not been studied for 20 years. Kaonic hydrogen stands out as one area where suitable K^- beams are still available; measurements on it could be made now and might greatly clarify our understanding of the $(\Sigma\pi, N\overline{K})$ system.

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1400 to 1410 OUR ESTIMATE				
1391± 1	700	[1] HEMINGWAY 85	HBC	K^-p 4.2 GeV/c
~ 1405	400	[2] THOMAS 73	HBC	π^-p 1.69 GeV/c
1405	120	BARBARO-... 68B	DBC	K^-d 2.1–2.7 GeV/c
1400± 5	67	BIRMINGHAM 66	HBC	K^-p 3.5 GeV/c
1382± 8		ENGLER 65	HDBC	π^-p, π^+d 1.68 GeV/c
1400±24		MUSGRAVE 65	HBC	$\overline{p}p$ 3–4 GeV/c
1410		ALEXANDER 62	HBC	π^-p 2.1 GeV/c
1405		ALSTON 62	HBC	K^-p 1.2–0.5 GeV/c
1405		ALSTON 61B	HBC	K^-p 1.15 GeV/c

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1411	[3] MARTIN 81		K-matrix fit
1406	[4] CHAO 73	DPWA	0–range fit (sol. B)
1421	MARTIN 70	RVUE	Constant K-matrix
1416 ±4	MARTIN 69	HBC	Constant K-matrix
1403 ±3	KIM 67	HBC	K-matrix fit
1407.5±1.2	[5] KITTEL 66	HBC	0–effective-range fit
1410.7±1.0	KIM 65	HBC	0–effective-range fit
1409.6±1.7	[5] SAKITT 65	HBC	0–effective-range fit

$\Lambda(1405)$ WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
45 to 65 OUR ESTIMATE				
32± 1	700	[1] HEMINGWAY 85	HBC	$K^- p$ 4.2 GeV/c
45 to 55	400	[2] THOMAS 73	HBC	$\pi^- p$ 1.69 GeV/c
35	120	BARBARO-... 68B	DBC	$K^- d$ 2.1–2.7 GeV/c
50±10	67	BIRMINGHAM 66	HBC	$K^- p$ 3.5 GeV/c
89±20		ENGLER 65	HDBC	
60±20		MUSGRAVE 65	HBC	
35± 5		ALEXANDER 62	HBC	
50		ALSTON 62	HBC	
20		ALSTON 61B	HBC	

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
30	[3] MARTIN 81		K-matrix fit
55	[4,6] CHAO 73	DPWA	0–range fit (sol. B)
20	MARTIN 70	RVUE	Constant K-matrix
29 ±6	MARTIN 69	HBC	Constant K-matrix
50 ±5	KIM 67	HBC	K-matrix fit
34.1±4.1	[5] KITTEL 66	HBC	
37.0±3.2	KIM 65	HBC	
28.2±4.1	[5] SAKITT 65	HBC	

$\Lambda(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma\pi$	100 %
Γ_2	$N\overline{K}$	

$\Lambda(1405)$ BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ Γ_2/Γ_1

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<3	95	HEMINGWAY 85	HBC	$K^- p$ 4.2 GeV/c

$\Lambda(1405)$ FOOTNOTES

[1] HEMINGWAY 85 finds the $\Sigma\pi$ mass distribution is asymmetric and a Breit-Wigner fit is poor.

[2] THOMAS 73 data is fit by CHAO 73 (see next section).

[3] The MARTIN 81 fit includes the $K^{\pm} p$ forward scattering amplitudes and the dispersion relations they must satisfy.

[4] See also the accompanying paper of THOMAS 73.

[5] Data of SAKITT 65 are used in the fit by KITTEL 66.

[6] An asymmetric shape, with $\Gamma/2 = 41$ MeV below resonance, 14 MeV above.

$\Lambda(1405)$ REFERENCES

HEMINGWAY 85 NP B253 742 (CERN) J
MARTIN 81 NP B179 33 (DURH)
CHAO 73 NP B56 46 +Kraemer, Thomas, Martin (RHEL, CMU, LOUC)
THOMAS 73 NP B56 15 +Engler, Fisk, Kraemer (CMU) J
MARTIN 70 NP B16 479 +Ross (DURH)
MARTIN 69 PR 183 1352 +Sakitt (LOUC, BNL)
Also 69B PR 183 1345 Martin, Sakitt (LOUC, BNL)
BARBARO-... 68B PRL 21 573 Barbaro-Galtieri, Chadwick+ (LRL, SLAC)
KIM 67 PRL 19 1074 (YALE)
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
KITTEL 66 PL 21 349 +Otter, Wacek (VIEN)
ENGLER 65 PRL 15 224 +Fisk, Kraemer, Meltzer, Westgard+ (CMU, BNL) IJ
KIM 65 PRL 14 29 (COLU)
MUSGRAVE 65 NC 35 735 +Petmezas+ (BIRM, CERN, EPOL, LOIC, SACL)
SAKITT 65 PR 139B 719 +Day, Glasser, Seeman, Friedman+ (UMD, LRL)
ALEXANDER 62 PRL 8 447 +Kalbfleisch, Miller, Smith (LRL) I
ALSTON 62 CERN Conf. 311 +Alvarez, Ferro-Luzzi+ (LRL) I
ALSTON 61B PRL 6 698 +Alvarez, Eberhard, Good+ (LRL) I

OTHER RELATED PAPERS

BARRETT 89 NC 102A 179 (SURR)
BATTY 89 NC 102A 255 +Gal (RAL, HEBR)
CAPSTICK 89 Excited Baryons '88, p. 32 (GUEL)
LOWE 89 NC 102A 167 (BIRM)
WHITEHOUSE 89 PRL 63 1352 + (BIRM, BOST, BRCO, BNL, CASE, BUDA, TRIU)
SIEGEL 88 PR C38 2221 +Weise (REGE)
WORKMAN 88 PR D37 3117 +Fearing (TRIU)
SCHNICK 87 PRL 58 1719 +Landau (ORST)
CAPSTICK 86 PR D34 2809 +Isgur (TNTO)
JENNINGS 86 PL B176 229 (TRIU)
MALTMAN 86 PR D34 1372 +Isgur (LANL, TNTO)
ZHONG 86 PL B171 471 +Thomas, Jennings, Barrett (ADLD, TRIU, SURR)
BURKHARDT 85 NP A440 653 +Lowe, Rosenthal (NOTT, BIRM, WMIU)
DAREWYCH 85 PR D32 1765 +Koniuk, Isgur (YORK, TNTO)
VEIT 85 PR D31 1033 +Jennings, Thomas, Barrett (TRIU, ADLD, SURR)
KIANG 84 PR C30 1638 +Kumar, Nogami, VanDijk (DALH, MCMS)
MILLER 84 (LOUC)
Conf. Intersections between Particle and Nuclear Physics, p. 783
VANDIJK 84 PR D30 937 (MCMS)
VEIT 84 PL 137B 415 +Jennings, Barrett, Thomas (TRIU, SURR, CERN)
DALITZ 82 +McGinley, Belyea, Anthony (OXF)
Heidelberg Conf., p. 201
DALITZ 81 +McGinley (OXF)
Low and Intermediate Energy Kaon-Nucleon Physics, p.381
MARTIN 81B Low and Intermediate Energy Kaon-Nucleon Phys., p. 97 (DURH)
OADES 77 NC 42A 462 +Rasche (AARH, ZURI)
SHAW 73 Purdue Conf. 417 (UCI)
BARBARO-... 72 LBL-555 Barbaro-Galtieri (LBL)
DOBSON 72 PR D6 3256 +McElhaney (HAWA)
RAJASEKA... 72 PR D5 610 Rajasekaran (TATA)
CLINE 71 PRL 26 1194 +Laumann, Mapp (WISC)
MARTIN 71 PL 35B 62 +Martin, Ross (DURH, LOUC, RHEL)
DALITZ 67 PR 153 1617 +Wong, Rajasekaran (OXF, BOMB)
DONALD 66 PL 22 711 +Edwards, Lys, Nisar, Moore (LIVP)
KADYK 66 PRL 17 599 +Oren, Goldhaber, Goldhaber, Trilling (LRL)
ABRAMS 65 PR 139B 454 +Sechi-Zorn (UMD)

$\Lambda(1520)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

Discovered by FERRO-LUZZI 62; the elaboration in WATSON 63 is the classic paper on the Breit-Wigner analysis of a multichannel resonance.

The measurements of the mass, width, and elasticity published before 1975 are now obsolete and have been omitted. They were last listed in our 1982 edition (Physics Letters 111B).

Production and formation experiments agree quite well, so they are listed together here.

$\Lambda(1520)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1519.5 ±1.0 OUR ESTIMATE				
1519.50±0.18 OUR AVERAGE				
1517.3 ±1.5	300	BARBER 80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
1519 ±1		GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1517.8 ±1.2	5k	BARLAG 79	HBC	$K^- p$ 4.2 GeV/c
1520.0 ±0.5		ALSTON-... 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1519.7 ±0.3	4k	CAMERON 77	HBC	$K^- p$ 0.96–1.36 GeV/c
1519 ±1		GOPAL 77	DPWA	$\overline{K}N$ multichannel
1519.4 ±0.3	2000	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Lambda(1520)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
15.6 ±1.0 OUR ESTIMATE				
15.59±0.27 OUR AVERAGE				
16.3 ±3.3	300	BARBER 80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
16 ±1		GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
14 ±3	677	[1] BARLAG 79	HBC	$K^- p$ 4.2 GeV/c
15.4 ±0.5		ALSTON-... 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
16.3 ±0.5	4k	CAMERON 77	HBC	$K^- p$ 0.96–1.36 GeV/c
15.0 ±0.5		GOPAL 77	DPWA	$\overline{K}N$ multichannel
15.5 ±1.6	2000	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Lambda(1520)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	45 ± 1%
Γ_2	$\Sigma\pi$	42 ± 1%
Γ_3	$\Lambda\pi\pi$	10 ± 1%
Γ_4	$\Sigma(1385)\pi$	
Γ_5	$\Sigma(1385)\pi$ ($\rightarrow \Lambda\pi\pi$)	
Γ_6	$\Lambda(\pi\pi)_{S\text{-wave}}$	
Γ_7	$\Sigma\pi\pi$	0.9 ± 0.1%
Γ_8	$\Lambda\gamma$	0.8 ± 0.2%
Γ_9	$\Sigma^0\gamma$	

CONSTRAINED FIT INFORMATION

An overall fit to 9 branching ratios uses 24 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 16.5 for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−63				
x_3	−32	−33			
x_7	−4	−3	−1		
x_8	−9	−8	−4	0	
x_9	−24	−21	−10	−1	−2
	x_1	x_2	x_3	x_7	x_8

Λ(1520) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ — Γ_1/Γ

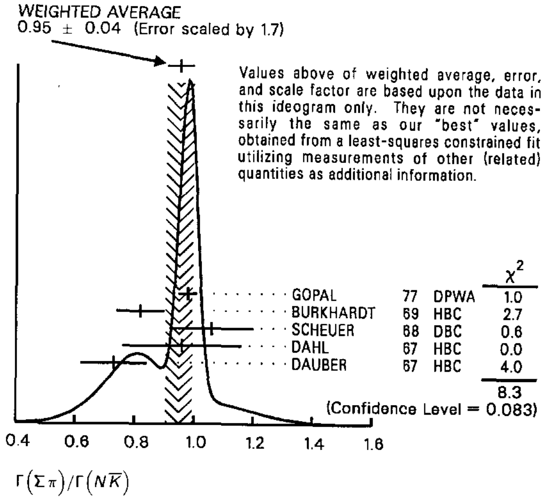
VALUE	DOCUMENT ID	TECN	COMMENT
0.45 ±0.01 OUR ESTIMATE			
0.448±0.007 OUR FIT Error includes scale factor of 1.2.			
0.455±0.011 OUR AVERAGE			
0.47 ±0.02	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.45 ±0.03	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
0.448±0.014	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.47 ±0.01	GOPAL 77	DPWA	See GOPAL 80
0.42	MAST 76	HBC	$K^- p \to \overline{K}^0 n$

$\Gamma(\Sigma\pi)/\Gamma_{\rm total}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.42 ±0.01 OUR ESTIMATE			
0.421±0.007 OUR FIT Error includes scale factor of 1.2.			
0.423±0.011 OUR AVERAGE			
0.426±0.014	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.418±0.017	BARBARO-... 69B	HBC	$K^- p$ 0.28–0.45 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.46	KIM 71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(N\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.940±0.026 OUR FIT Error includes scale factor of 1.3.			
0.95 ±0.04 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.			
0.98 ±0.03	[2] GOPAL 77	DPWA	$\overline{K}N$ multichannel
0.82 ±0.08	BURKHARDT 69	HBC	$K^- p$ 0.8–1.2 GeV/c
1.06 ±0.14	SCHEUER 68	DBC	$K^- N$ 3 GeV/c
0.96 ±0.20	DAHL 67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.73 ±0.11	DAUBER 67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.06 ±0.12	BERTHON 74	HBC	Quasi-2-body σ
1.72 ±0.78	MUSGRAVE 65	HBC	



$\Gamma(\Lambda\pi\pi)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.10 ±0.01 OUR ESTIMATE			
0.095±0.005 OUR FIT Error includes scale factor of 1.2.			
0.096±0.008 OUR AVERAGE Error includes scale factor of 1.6.			
0.091±0.006	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.11 ±0.01	[3] MAST 73B	IPWA	$K^- p \to \Lambda\pi\pi$

$\Gamma(\Lambda\pi\pi)/\Gamma(N\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.213±0.012 OUR FIT Error includes scale factor of 1.2.			
0.202±0.021 OUR AVERAGE			
0.22 ±0.03	BURKHARDT 69	HBC	$K^- p$ 0.8–1.2 GeV/c
0.19 ±0.04	SCHEUER 68	DBC	$K^- N$ 3 GeV/c
0.17 ±0.05	DAHL 67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.21 ±0.18	DAUBER 67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.27 ±0.13	BERTHON 74	HBC	Quasi-2-body σ
0.2	KIM 71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
4.42±0.25 OUR FIT Error includes scale factor of 1.2.			
3.9 ±0.6 OUR AVERAGE			
3.9 ±1.0	UHLIG 67	HBC	$K^- p$ 0.9–1.0 GeV/c
3.3 ±1.1	BIRMINGHAM 66	HBC	$K^- p$ 3.5 GeV/c
4.5 ±1.0	ARMENTEROS65C	HBC	

$\Gamma(\Sigma(1385)\pi)/\Gamma_{\rm total}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.041±0.005	CHAN 72	HBC	$K^- p \to \Lambda\pi\pi$

$\Gamma(\Sigma(1385)\pi\ (\to \Lambda\pi\pi))/\Gamma(\Lambda\pi\pi)$ — Γ_5/Γ_3

The $\Lambda\pi\pi$ mode is largely due to $\Sigma(1385)\pi$. Only the values of $(\Sigma(1385)\pi)$ / $(\Lambda 2\pi)$ given by MAST 73B and CORDEN 75 are based on real 3-body partial-wave analyses. The discrepancy between the two results is essentially due to the different hypotheses made concerning the shape of the $(\pi\pi)_{S\text{-wave}}$ state.

VALUE	DOCUMENT ID	TECN	COMMENT
0.58±0.22	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.82±0.10	[4] MAST 73B	IPWA	$K^- p \to \Lambda\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.39±0.10	[5] BURKHARDT 71	HBC	$K^- p \to (\Lambda\pi\pi)\pi$

$\Gamma(\Lambda(\pi\pi)_{S\text{-wave}})/\Gamma(\Lambda\pi\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID	TECN	COMMENT
0.20±0.08	CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{\rm total}$ — Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.009 ±0.001 OUR ESTIMATE			
0.0086±0.0005 OUR FIT			
0.0086±0.0005 OUR AVERAGE			
0.007 ±0.002	[6] CORDEN 75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.0085±0.0006	[7] MAST 73	MPWA	$K^- p \to \Sigma\pi\pi$
0.010 ±0.0015	BARBARO-... 69B	HBC	$K^- p$ 0.28–0.45 GeV/c

$\Gamma(\Lambda\gamma)/\Gamma_{\rm total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.008 ±0.002 OUR ESTIMATE				
0.0079±0.0014 OUR FIT				
0.0080±0.0014	238	MAST 68B	HBC	Using $\Gamma(N\overline{K})/\Gamma_{\rm total}$=0.45

$\Gamma(\Sigma^0\gamma)/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0195±0.0034 OUR FIT			
0.02 ±0.0035	[8] MAST 68B	HBC	Not measured; see note

Λ(1520) FOOTNOTES

[1] From the best-resolution sample of $\Lambda\pi\pi$ events only.

[2] The $\overline{K}N \to \Sigma\pi$ amplitude at resonance is +0.46 ± 0.01.

[3] Assumes $\Gamma(N\overline{K})/\Gamma_{\rm total}$ = 0.46 ± 0.02.

[4] Both $\Sigma(1385)\pi$ DS_{03} and $\Sigma(\pi\pi)$ DP_{03} contribute.

[5] The central bin (1514–1524 MeV) gives 0.74 ± 0.10; other bins are lower by 2-to-5 standard deviations.

[6] Much of the $\Sigma\pi\pi$ decay proceeds via $\Sigma(1385)\pi$.

[7] Assumes $\Gamma(N\overline{K})/\Gamma_{\rm total}$ = 0.46.

[8] Calculated from $\Gamma(\Lambda\gamma)/\Gamma_{\rm total}$, assuming SU(3). Needed to constrain the sum of all the branching ratios to be unity.

Λ(1520) REFERENCES

BARBER	80D	ZPHY C7 17	+Dainton, Lee, Marshall+	(DARE, LANC, SHEF)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
BARLAG	79	NP B149 220	+Blokzijl, Jongejans+	(AMST, CERN, NIJM, OXF)
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MAST	76	PR D14 13	+Alston-Garnjost, Bangerter+	(LBL)
CORDEN	75	NP B84 306	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
MAST	73	PR D7 3212	+Bangerter, Alston-Garnjost+	(LBL) IJP
MAST	73B	PR D7 5	+Bangerter, Alston-Garnjost+	(LBL) IJP
CHAN	72	PRL 28 256	+Button-Shafer, Hertzbach, Kofler+	(MASA, YALE)
BURKHARDT	71	NP B27 64	+Filthuth, Kluge+	(HEID, CERN, SACL)

KIM 71 PRL 27 356 (HARV) IJP
Also 70 Duke Conf. 161 Kim (HARV) IJP
BARBARO-... 69B Lund Conf. 352 Barbaro-Galtieri, Bangerter, Mast, Tripp (LRL)
Also 70 Duke Conf. 95 Tripp (LRL)
BURKHARDT 69 NP B14 106 +Filthuth, Kluge+ (HEID, EFI, CERN, SACL)
MAST 68B PRL 21 1715 +Alston-Garnjost, Bangerter, Galtieri+ (LRL)
SCHEUER 68 NP B8 503 +Merrill, Verglas, DeWitt+ (SABRE Collab.)
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL)
DAUBER 67 PL 24B 525 +Malamud, Schlein, Slater, Stork (UCLA)
UHLIG 67 PR 155 1448 +Charlton, Condon, Glasser, Yodh+ (UMD, NRL)
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
ARMENTEROS 65C PL 19 338 +Ferro-Luzzi+ (CERN, HEID, SACL)
MUSGRAVE 65 NC 35 735 +Petmezas+ (BIRM, CERN, EPOL, LOIC, SACL)
WATSON 63 PR 131 2248 +Ferro-Luzzi, Tripp (LRL) IJP
FERRO-LUZZI 62 PRL 8 28 +Tripp, Watson (LRL) IJP

Λ(1600) P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

See also the Λ(1810) P_{01}. There are quite possibly two P_{01} states in this region.

Λ(1600) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1560 to 1700 OUR ESTIMATE			
1568±20	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1703±100	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1573±25	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1596±6	KANE 74	DPWA	$K^- p \to \Sigma\pi$
1620±10	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1572 or 1617	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1646±7	[2] CARROLL 76	DPWA	Isospin-0 total σ
1570	KIM 71	DPWA	K-matrix analysis

Λ(1600) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
50 to 250 OUR ESTIMATE Our best guess is 150 MeV.			
116±20	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
593±200	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
147±50	GOPAL 77	DPWA	$\overline{K}N$ multichannel
175±20	KANE 74	DPWA	$K^- p \to \Sigma\pi$
60±10	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
247 or 271	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
20	[2] CARROLL 76	DPWA	Isospin-0 total σ
50	KIM 71	DPWA	K-matrix analysis

Λ(1600) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–30 %
Γ_2	$\Sigma\pi$	10–60 %

The above branching fractions are our estimates, not fits or averages.

Λ(1600) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.15 to 0.30 OUR ESTIMATE			
0.23±0.04	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.14±0.05	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
0.25±0.15	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.24±0.04	GOPAL 77	DPWA	See GOPAL 80
0.30 or 0.29	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(1600) $\to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.16±0.04	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.33±0.11	KANE 74	DPWA	$K^- p \to \Sigma\pi$
0.28±0.09	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.39 or −0.39	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$

Λ(1600) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] A total cross-section bump with $(J+1/2)\,\Gamma_{el} / \Gamma_{\text{total}} = 0.04$.

Λ(1600) REFERENCES

GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEID, MPIM) IJP
KANE 74 LBL-2452 (LBL) IJP
LANGBEIN 72 NP B47 477 +Wagner (MPIM) IJP
KIM 71 PRL 27 356 (HARV) IJP

Λ(1670) S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition (Physics Letters 111B).

Λ(1670) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1660 to 1680 OUR ESTIMATE			
1670.8±1.7	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
1667 ±5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1671 ±3	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ±5	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1675 ±2	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
1679 ±1	KANE 74	DPWA	$K^- p \to \Sigma\pi$
1665 ±5	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1664	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

Λ(1670) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
25 to 50 OUR ESTIMATE Our best guess is 35 MeV.			
34.1±3.7	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
29 ±5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
29 ±5	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
45 ±10	GOPAL 77	DPWA	$\overline{K}N$ multichannel
46 ±5	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
40 ±3	KANE 74	DPWA	$K^- p \to \Sigma\pi$
19 ±5	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
12	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

Λ(1670) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–25 %
Γ_2	$\Sigma\pi$	20–60 %
Γ_3	$\Lambda\eta$	15–35 %
Γ_4	$\Sigma(1385)\pi$	

The above branching fractions are our estimates, not fits or averages.

Λ(1670) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.15 to 0.25 OUR ESTIMATE			
0.18±0.03	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.17±0.03	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.20±0.03	GOPAL 77	DPWA	See GOPAL 80
0.15	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(1670) $\to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.26±0.02	KOISO 85	DPWA	$K^- p \to \Sigma\pi$
−0.31±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.29±0.03	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
−0.23±0.03	LONDON 75	HLBC	$K^- p \to \Sigma^0\pi^0$
−0.27±0.02	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.13	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(1670) $\to \Lambda\eta$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.20±0.05	BAXTER 73	DPWA	$K^- p \to$ neutrals

• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24	KIM	71	DPWA	K-matrix analysis
0.26	ARMENTEROS	69C	HBC	
0.20 or 0.23	BERLEY	65	HBC	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1670) \rightarrow \Sigma(1385)\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.18 ± 0.05	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

Λ(1670) FOOTNOTES

[1] MARTIN 77 obtains identical resonance parameters from a T-matrix pole and from a Breit-Wigner fit.

Λ(1670) REFERENCES

KOISO 85 NP A433 619 +Sai, Yamamoto, Kofler (TOKY, MASA)
GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEID, MPIM) IJP
LONDON 75 NP B85 289 +Yu, Boyd+ (BNL, CERN, EPOL, ORSA, TORI)
KANE 74 LBL-2452 (LBL) IJP
PREVOST 74 NP B69 246 +Barloutaud+ (SACL, CERN, HEID)
BAXTER 73 NP B67 125 +Buckingham, Corbett, Dunn+ (OXF) IJP
KIM 71 PRL 27 356 (HARV) IJP
Also 70 Duke Conf. 161 Kim (HARV) IJP
ARMENTEROS 69C Lund Paper 229 +Baillon+ (CERN, HEID, SACL) IJP
Values are quoted in LEVI-SETTI 69.
BERLEY 65 PRL 15 641 +Connolly, Hart, Rahm, Stonehill+ (BNL) IJP

$\boxed{\Lambda(1690)\ D_{03}}$

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition (Physics Letters 111B).

Λ(1690) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1685 to 1695 OUR ESTIMATE				
1695.7±2.6	KOISO	85	DPWA	$K^- p \rightarrow \Sigma\pi$
1690 ±5	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1692 ±5	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1690 ±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1690 ±3	HEPP	76B	DPWA	$K^- N \rightarrow \Sigma\pi$
1689 ±1	KANE	74	DPWA	$K^- p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1687 or 1689	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1692 ±4	CARROLL	76	DPWA	Isospin-0 total σ

Λ(1690) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 70 OUR ESTIMATE	Our best guess is 60 MeV.			
67.2± 5.6	KOISO	85	DPWA	$K^- p \rightarrow \Sigma\pi$
61 ± 5	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
64 ±10	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
60 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
82 ± 8	HEPP	76B	DPWA	$K^- N \rightarrow \Sigma\pi$
60 ± 4	KANE	74	DPWA	$K^- p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62 or 62	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
38	CARROLL	76	DPWA	Isospin-0 total σ

Λ(1690) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–30 %
Γ_2	$\Sigma\pi$	20–40 %
Γ_3	$\Lambda\pi\pi$	~ 25 %
Γ_4	$\Sigma\pi\pi$	~ 20 %
Γ_5	$\Lambda\eta$	
Γ_6	$\Sigma(1385)\pi$, S-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(1690) BRANCHING RATIOS

The sum of all the quoted branching ratios is more than 1.0. The two-body ratios are from partial-wave analyses, and thus probably are more reliable than the three-body ratios, which are determined from bumps in cross sections. Of the latter, the $\Sigma\pi\pi$ bump looks more significant. (The error given for the $\Lambda\pi\pi$ ratio looks unreasonably small.) Hardly any of the $\Sigma\pi\pi$ decay can be via Σ(1385), for then seven times as much $\Lambda\pi\pi$ decay would be required. See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.3 OUR ESTIMATE				
0.23±0.03	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.22±0.03	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24±0.03	GOPAL	77	DPWA	See GOPAL 80
0.28 or 0.26	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1690) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.34 ± 0.02	KOISO	85	DPWA	$K^- p \rightarrow \Sigma\pi$
-0.25 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.29 ± 0.03	HEPP	76B	DPWA	$K^- N \rightarrow \Sigma\pi$
-0.28 ± 0.03	LONDON	75	HLBC	$K^- p \rightarrow \Sigma^0\pi^0$
-0.28 ± 0.02	KANE	74	DPWA	$K^- p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.30 or -0.28	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1690) \rightarrow \Lambda\eta$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00±0.03	BAXTER	73	DPWA	$K^- p \rightarrow$ neutrals

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1690) \rightarrow \Lambda\pi\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.25±0.02	[2] BARTLEY	68	HDBC	$K^- p \rightarrow \Lambda\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1690) \rightarrow \Sigma\pi\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.21	ARMENTEROS	68C	HDBC	$K^- N \rightarrow \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1690) \rightarrow \Sigma(1385)\pi$, S-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.27\pm0.04$	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

Λ(1690) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit. Another D_{03} Λ at 1966 MeV is also suggested by MARTIN 77, but is very uncertain.

[2] BARTLEY 68 uses only cross-section data. The enhancement is not seen by PREVOST 71.

Λ(1690) REFERENCES

KOISO 85 NP A433 619 +Sai, Yamamoto, Kofler (TOKY, MASA)
GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76B PL 65B 487 +Braun, Grimm, Strobele+ (CERN, HEID, MPIM) IJP
LONDON 75 NP B85 289 +Yu, Boyd+ (BNL, CERN, EPOL, ORSA, TORI)
KANE 74 LBL-2452 (LBL) IJP
PREVOST 74 NP B69 246 +Barloutaud+ (SACL, CERN, HEID)
BAXTER 73 NP B67 125 +Buckingham, Corbett, Dunn+ (OXF) IJP
PREVOST 71 Amsterdam Conf. (CERN, HEID, SACL)
ARMENTEROS 68C NP B8 216 +Baillon+ (CERN, HEID, SACL) I
BARTLEY 68 PRL 21 1111 +Chu, Dowd, Greene+ (TUFT, FSU, BRAN) I

Λ(1800) S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

This is the second resonance in the S_{01} wave, the first being the Λ(1670).

Λ(1800) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1720 to 1850 OUR ESTIMATE				
1841±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1725±20	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1825±20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1830±20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1767 or 1842	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1780	KIM	71	DPWA	K-matrix analysis
1872±10	BRICMAN	70B	DPWA	$\overline{K}N \rightarrow \overline{K}N$

Λ(1800) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
200 to 400 OUR ESTIMATE Our best guess is 300 MeV.				
228±20	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
185±20	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
230±20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
70±15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
435 or 473	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
40	KIM	71	DPWA	K-matrix analysis
100±20	BRICMAN	70B	DPWA	$\overline{K}N \rightarrow \overline{K}N$

Λ(1800) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–40 %
Γ_2	$\Sigma\pi$	seen
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	seen
Γ_5	$N\overline{K}^*(892)$, S=1/2, S-wave	
Γ_6	$N\overline{K}^*(892)$, S=3/2, D-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(1800) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.25 to 0.40 OUR ESTIMATE				
0.36±0.04	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.28±0.05	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.35±0.15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.37±0.05	GOPAL	77	DPWA	See GOPAL 80
1.21 or 0.70	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.80	KIM	71	DPWA	K-matrix analysis
0.18±0.02	BRICMAN	70B	DPWA	$\overline{K}N \rightarrow \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.08±0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.74 or −0.43	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.24	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.056±0.028	[2] CAMERON	78	DPWA	$K^- p \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow N\overline{K}^*(892)$, S=1/2, S-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.17±0.03	[2] CAMERON	78B	DPWA	$K^- p \rightarrow N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Lambda(1800) \rightarrow N\overline{K}^*(892)$, S=3/2, D-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.13±0.04	CAMERON	78B	DPWA	$K^- p \rightarrow N\overline{K}^*$

Λ(1800) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1800) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
BRICMAN	70B	PL 33B 511	+Ferro-Luzzi, Lagnaux	(CERN) IJP

Λ(1810) P_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

Almost all the recent analyses contain a P_{01} state, and sometimes two of them, but the masses, widths, and branching ratios vary greatly. See also the Λ(1600) P_{01}.

Λ(1810) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1750 to 1850 OUR ESTIMATE				
1841±20	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1853±20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1735± 5	CARROLL	76	DPWA	Isospin-0 total σ
1746±10	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$
1780±20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1861 or 1953	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1755	KIM	71	DPWA	K-matrix analysis
1800	ARMENTEROS	70	HBC	$\overline{K}N \rightarrow \overline{K}N$
1750	ARMENTEROS	70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
1690±10	BARBARO-...	70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
1740	BAILEY	69	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1745	ARMENTEROS	68B	HBC	$\overline{K}N \rightarrow \overline{K}N$

Λ(1810) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
50 to 250 OUR ESTIMATE Our best guess is 150 MeV.				
164±20	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
90±20	CAMERON	78B	DPWA	$K^- p \rightarrow N\overline{K}^*$
166±20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
46±20	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$
120±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
535 or 585	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
28	CARROLL	76	DPWA	Isospin-0 total σ
35	KIM	71	DPWA	K-matrix analysis
30	ARMENTEROS	70	HBC	$\overline{K}N \rightarrow \overline{K}N$
70	ARMENTEROS	70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
22	BARBARO-...	70	HBC	$\overline{K}N \rightarrow \Sigma\pi$
300	BAILEY	69	DPWA	$\overline{K}N \rightarrow \overline{K}N$
147	ARMENTEROS	68B	HBC	

Λ(1810) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–50 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	30–60 %
Γ_5	$N\overline{K}^*(892)$, S=1/2, P-wave	
Γ_6	$N\overline{K}^*(892)$, S=3/2, P-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(1810) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.2 to 0.5 OUR ESTIMATE				
0.24±0.04	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.36±0.05	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.21±0.04	GOPAL 77	DPWA	See GOPAL 80
0.52 or 0.49	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
0.30	KIM 71	DPWA	K-matrix analysis
0.15	ARMENTEROS70	DPWA	$\overline{K}N \to \overline{K}N$
0.55	BAILEY 69	DPWA	$\overline{K}N \to \overline{K}N$
0.4	ARMENTEROS68B	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.24±0.04	GOPAL 77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.25 or +0.23	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
< 0.01	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
0.17	KIM 71	DPWA	K-matrix analysis
+0.20	[2] ARMENTEROS70	DPWA	$\overline{K}N \to \Sigma\pi$
−0.13±0.03	BARBARO-... 70	DPWA	$\overline{K}N \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.18±0.10	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to N\overline{K}^*(892)$, S=1/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.14±0.03	[2] CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1810) \to N\overline{K}^*(892)$, S=3/2, P-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.35±0.06	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

Λ(1810) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1810) REFERENCES

GOPAL 80 Toronto Conf. 159 (RHEL) IJP
CAMERON 78B NP B146 327 +Franek, Gopal, Kalmus, McPherson+ (RHEL, LOIC) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
PREVOST 74 NP B69 246 +Barloutaud+ (SACL, CERN, HEID)
LANGBEIN 72 NP B47 477 +Wagner (MPIM) IJP
KIM 71 PRL 27 356 (HARV) IJP
Also 70 Duke Conf. 161 Kim (HARV) IJP
ARMENTEROS 70 Duke Conf. 123 +Baillon+ (CERN, HEID, SACL) IJP
BARBARO-... 70 Duke Conf. 173 Barbaro-Galtieri (LRL) IJP
BAILEY 69 UCRL 50617 Thesis (LLL) IJP
ARMENTEROS 68B NP B8 195 +Baillon+ (CERN, HEID, SACL) IJP

$\Lambda(1820)$ F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗∗

This resonance is the cornerstone for all partial-wave analyses in this region. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

Most of the quoted errors are statistical only; the systematic errors due to the particular parametrizations used in the partial-wave analyses are not included. For this reason we do not calculate weighted averages for the mass and width.

Λ(1820) MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1815 to 1825 OUR ESTIMATE			
1823±3	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1819±2	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1822±2	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1821±2	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1830	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
1817 or 1819	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

Λ(1820) WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
70 to 90 OUR ESTIMATE Our best guess is 80 MeV.			
77±5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
72±5	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
81±5	GOPAL 77	DPWA	$\overline{K}N$ multichannel
87±3	KANE 74	DPWA	$K^- p \to \Sigma\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •			
82	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
76 or 76	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

Λ(1820) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	55–65 %
Γ_2	$\Sigma\pi$	8–14 %
Γ_3	$\Sigma(1385)\pi$	5–10 %
Γ_4	$\Sigma(1385)\pi$, P-wave	
Γ_5	$\Sigma(1385)\pi$, F-wave	
Γ_6	$\Lambda\eta$	
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

Λ(1820) BRANCHING RATIOS

Errors quoted do not include uncertainties in the parametrizations used in the partial-wave analyses and are thus too small. See also "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.55 to 0.65 OUR ESTIMATE			
0.58±0.02	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.60±0.03	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.51	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
0.57±0.02	GOPAL 77	DPWA	See GOPAL 80
0.59 or 0.58	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.28±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.28±0.01	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.25 or −0.25	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Lambda\eta$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*
$-0.096^{+0.040}_{-0.020}$	RADER 73	MPWA

$\Gamma(\Sigma\pi\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
no clear signal	[2] ARMENTEROS68C	HDBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
−0.167±0.054	[3] CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$
+0.27 ±0.03	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
+0.065±0.029	[3] CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$

Λ(1820) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] There is a suggestion of a bump, enough to be consistent with what is expected from $\Sigma(1385) \to \Sigma\pi$ decay.

[3] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1820) REFERENCES

GOPAL 80 Toronto Conf. 159 (RHEL) IJP
ALSTON-... 78 PR D18 182 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
Also 77 PRL 38 1007 Alston-Garnjost, Kenney+ (LBL, MTHO, CERN) IJP
CAMERON 78 NP B143 189 +Franek, Gopal, Bacon, Butterworth+ (RHEL, LOIC) IJP
DECLAIS 77 CERN 77-16 +Duchon, Louvel, Patry, Seguinot+ (CAEN, CERN) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
MARTIN 77 NP B127 349 +Pidcock, Moorhouse (LOUC, GLAS) IJP
Also 77B NP B126 266 Martin, Pidcock (LOUC)
Also 77C NP B126 285 Martin, Pidcock (LOUC) IJP
KANE 74 LBL-2452 (LBL) IJP
PREVOST 74 NP B69 246 +Barloutaud+ (SACL, CERN, HEID)
RADER 73 NC 16A 178 +Barloutaud+ (SACL, HEID, CERN, RHEL, CDEF)
ARMENTEROS 68C NP B8 216 +Baillon+ (CERN, HEID, SACL) I

$\Lambda(1830)$ D_{05}

$I(J^P) = 0(\frac{5}{2}^-)$ Status: ∗∗∗∗

For results published before 1973 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

The best evidence for this resonance is in the $\Sigma\pi$ channel.

$\Lambda(1830)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1810 to 1830 OUR ESTIMATE				
1831 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1825 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$1825\pm\ 1$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1817 or 1818	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1830)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 110 OUR ESTIMATE Our best guess is 95 MeV.				
100 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
94 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$119\pm\ 3$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
56 or 56	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1830)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	3–10 %
Γ_2	$\Sigma\pi$	35–75 %
Γ_3	$\Sigma(1385)\pi$	>15 %
Γ_4	$\Sigma(1385)\pi$, D-wave	
Γ_5	$\Lambda\eta$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1830)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 to 0.10 OUR ESTIMATE				
0.08 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.02 ± 0.02	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.04 or 0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1830) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.17 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.15 ± 0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.17 or -0.17	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1830) \to \Lambda\eta$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN
-0.044 ± 0.020	RADER	73	MPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1830) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.141\pm0.014$	[2] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
$+0.13\ \pm0.03$	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$\Lambda(1830)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The CAMERON 78 upper limit on G-wave decay is 0.03. The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(1830)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)

$\Lambda(1890)$ P_{03}

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

The $J^P = 3/2^+$ assignment is consistent with all available data (including polarization) and recent partial-wave analyses. The dominant inelastic modes remain unknown.

$\Lambda(1890)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1850 to 1910 OUR ESTIMATE				
$1897\pm\ 5$	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1908 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
$1900\pm\ 5$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1894 ± 10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1856 or 1868	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1900	[2] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(1890)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 200 OUR ESTIMATE Our best guess is 100 MeV.				
74 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
119 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
72 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
107 ± 10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
191 or 193	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
100	[2] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(1890)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–35 %
Γ_2	$\Sigma\pi$	3–10 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$\Sigma(1385)\pi$, P-wave	
Γ_5	$\Sigma(1385)\pi$, F-wave	
Γ_6	$N\overline{K}^*(892)$	seen
Γ_7	$N\overline{K}^*(892)$, S=1/2, P-wave	
Γ_8	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1890)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.20 to 0.35 OUR ESTIMATE				
0.20 ± 0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.34 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.24 ± 0.04	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.18 ± 0.02	GOPAL	77	DPWA	See GOPAL 80
0.36 or 0.34	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$+0.15$ or $+0.14$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Lambda\omega$ $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BACCARI	77	IPWA	$K^-p \to \Lambda\omega$
0.032	[2] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.126 ± 0.055	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(1890) $\to N\overline{K}^*(892)$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.07±0.03	[3,4] CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

Λ(1890) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] Found in one of two best solutions.

[3] The published sign has been changed to be in accord with the baryon-first convention.

[4] Upper limits on the P_3 and F_3 waves are each 0.03.

Λ(1890) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP

Λ(2000)

$I(J^P) = 0(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

We list here all the ambiguous resonance possibilities with a mass around 2 GeV. The proposed quantum numbers are D_3 (BARBARO-GALTIERI 70 in $\Sigma\pi$), D_3+F_5, P_3+D_5, or P_1+D_3 (BRANDSTETTER 72 in $\Lambda\omega$), and S_1 (CAMERON 78B in $N\overline{K}^*$). The first two of the above analyses should now be considered obsolete. See also NAKKASYAN 75.

Λ(2000) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2030±30	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$
1935 to 1971	[1] BRANDSTET...72	DPWA	$K^- p \to \Lambda\omega$
1951 to 2034	[1] BRANDSTET...72	DPWA	$K^- p \to \Lambda\omega$
2010±30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Λ(2000) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
125±25	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$
180 to 240	[1] BRANDSTET...72	DPWA	(lower mass)
73 to 154	[1] BRANDSTET...72	DPWA	(higher mass)
130±50	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Λ(2000) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$
Γ_4	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, D-wave

Λ(2000) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(2000) $\to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.20±0.04	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(2000) $\to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.17 to 0.25	[1] BRANDSTET...72	DPWA	(lower mass)
0.04 to 0.15	[1] BRANDSTET...72	DPWA	(higher mass)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(2000) $\to N\overline{K}^*(892)$, S=1/2, S-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.12±0.03	[2] CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(2000) $\to N\overline{K}^*(892)$, S=3/2, D-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.09±0.03	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

Λ(2000) FOOTNOTES

[1] The parameters quoted here are ranges from the three best fits; the lower state probably has $J \leq 3/2$, and the higher one probably has $J \leq 5/2$.

[2] The published sign has been changed to be in accord with the baryon-first convention.

Λ(2000) REFERENCES

CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
BRANDSTET...	72	NP B39 13	Brandstetter, Butterworth+	(RHEL, CDEF, SACL)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

Λ(2020) F_{07}

$I(J^P) = 0(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

In LITCHFIELD 71, need for the state rests solely on a possibly inconsistent polarization measurement at 1.784 GeV/c. HEMINGWAY 75 does not require this state. GOPAL 77 does not need it in either $N\overline{K}$ or $\Sigma\pi$. With new $K^- n$ angular distributions included, DECLAIS 77 sees it. However, this and other new data are included in GOPAL 80 and the state is not required. BACCARI 77 weakly supports it.

Λ(2020) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2140	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$
2117	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
2100±30	LITCHFIELD 71	DPWA	$K^- p \to \overline{K}N$
2020±20	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Λ(2020) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
128	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$
167	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
120±30	LITCHFIELD 71	DPWA	$K^- p \to \overline{K}N$
160±30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Λ(2020) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$

Λ(2020) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
0.05±0.02	LITCHFIELD 71	DPWA	$K^- p \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(2020) $\to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.15±0.02	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to$ Λ(2020) $\to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.05	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$

Λ(2020) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

Λ(2100) G_{07}

$I(J^P) = 0(\frac{7}{2}^-)$ Status: ∗∗∗∗

Discovered by COOL 66 and by WOHL 66. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition (Physics Letters 111B).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and in invariant-mass distributions around 2100 MeV used to be listed in a separate entry immediately following. It may be found in our 1986 edition (Physics Letters 170B).

Λ(2100) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2090 to 2110 OUR ESTIMATE				
2104±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2106±30	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2110±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2105±10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
2115±10	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2094	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
2094	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
2110 or 2089	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

Λ(2100) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
100 to 250 OUR ESTIMATE	Our best guess is 200 MeV.			
157±40	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
250±30	GOPAL	77	DPWA	$\overline{K}N$ multichannel
241±30	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
152±15	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
98	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
250	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
244 or 302	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

Λ(2100) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–35 %
Γ_2	$\Sigma\pi$	∼ 5 %
Γ_3	$\Lambda\eta$	<3 %
Γ_4	ΞK	<3 %
Γ_5	$\Lambda\omega$	<8 %
Γ_6	$N\overline{K}^*(892)$	10–20 %
Γ_7	$N\overline{K}^*(892)$, $S=1/2$, G-wave	
Γ_8	$N\overline{K}^*(892)$, $S=3/2$, D-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(2100) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.25 to 0.35 OUR ESTIMATE				
0.34±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.06	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
0.31±0.03	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.30±0.03	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2100) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.12±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.11±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\eta$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.050±0.020	RADER	73	MPWA	$K^-p \to \Lambda\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2100) \to \Xi K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.035±0.018	LITCHFIELD	71	DPWA	$K^-p \to \Xi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.003	MULLER	69B	DPWA	$K^-p \to \Xi K$
0.05	TRIPP	67	RVUE	$K^-p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\omega$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.070	[2] BACCARI	77	DPWA	GD_{37} wave
+0.011	[2] BACCARI	77	DPWA	GG_{17} wave
+0.008	[2] BACCARI	77	DPWA	GG_{37} wave
0.122 or 0.154	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, S=3/2, D-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.21±0.04	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, S=1/2, G-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.04±0.03	[3] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

Λ(2100) FOOTNOTES

[1] The NAKKASYAN 75 values are from the two best solutions found. Each has the Λ(2100) and one additional resonance (P_3 or F_5).

[2] Note that the three for BACCARI 77 entries are for three different waves.

[3] The published sign has been changed to be in accord with the baryon-first convention. The upper limit on the G_3 wave is 0.03.

Λ(2100) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
LITCHFIELD	71	NP B30 125	+.... Lesquoy+	(RHEL, CDEF, SACL) IJP
MULLER	69B	UCRL 19372 Thesis		(LRL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

Λ(2110) F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B). All the references have been retained.

This resonance is in the Baryon Summary Table, but the evidence for it could be better.

Λ(2110) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2090 to 2140 OUR ESTIMATE				
2092±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2125±25	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
2106±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2140±20	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
2100±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2112± 7	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2137	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
2103	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

Λ(2110) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
150 to 250 OUR ESTIMATE	Our best guess is 200 MeV.			
245±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
160±30	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
251±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
140±20	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
200±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
190±30	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
132	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
391	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

Λ(2110) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–25 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Lambda\omega$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$N\overline{K}^*(892)$	10–60 %
Γ_7	$N\overline{K}^*(892)$, S=1/2, F-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(2110) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.25 OUR ESTIMATE			
0.07±0.03	GOPAL 80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.27±0.06	[2] DEBELLEFON 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.07±0.03	GOPAL 77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Lambda(2110) \rightarrow \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.14±0.01	DEBELLEFON 77	DPWA	$K^-p \rightarrow \Sigma\pi$
+0.20±0.03	KANE 74	DPWA	$K^-p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.10±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Lambda(2110) \rightarrow \Lambda\omega$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.05	BACCARI 77	DPWA	$K^-p \rightarrow \Lambda\omega$
0.112	[1] NAKKASYAN 75	DPWA	$K^-p \rightarrow \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Lambda(2110) \rightarrow \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.071±0.025	[3] CAMERON 78	DPWA	$K^-p \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Lambda(2110) \rightarrow N\overline{K}^*(892)$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.17±0.04	[4] CAMERON 78B	DPWA	$K^-p \rightarrow N\overline{K}^*$

Λ(2110) FOOTNOTES

[1] Found in one of two best solutions.

[2] The published error of 0.6 was a misprint.

[3] The CAMERON 78 upper limit on F-wave decay is 0.03. The sign here has been changed to be in accord with the baryon-first convention.

[4] The published sign has been changed to be in accord with the baryon-first convention. The CAMERON 78B upper limits on the P_3 and F_3 waves are each 0.03.

Λ(2110) REFERENCES

GOPAL 80 Toronto Conf. 159 (RHEL) IJP
CAMERON 78 NP B143 189 +Franek, Gopal, Bacon, Butterworth+ (RHEL, LOIC) IJP
CAMERON 78B NP B146 327 +Franek, Gopal, Kalmus, McPherson+ (RHEL, LOIC) IJP
DEBELLEFON 78 NC 42A 403 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
BACCARI 77 NC 41A 96 +Poulard, Revel, Tallini+ (SACL, CDEF) IJP
DEBELLEFON 77 NC 37A 175 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
GOPAL 77 NP B119 362 +Ross, VanHorn, McPherson+ (LOIC, RHEL) IJP
NAKKASYAN 75 NP B93 85 (CERN) IJP
KANE 74 LBL-2452 (LBL) IJP

$\Lambda(2325)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

BACCARI 77 finds this state with either $J^P = 3/2^-$ or $3/2^+$ in a energy-dependent partial-wave analyses of $K^-p \rightarrow \Lambda\omega$ from 2070 to 2436 MeV. A subsequent semi-energy-independent analysis from threshold to 2436 MeV selects $3/2^-$. DEBELLEFON 78 (same group) also sees this state in an energy-dependent partial-wave analysis of $K^-p \rightarrow \overline{K}N$ data, and finds $J^P = 3/2^-$ or $3/2^+$. They again prefer $J^P = 3/2^-$, but only on the basis of model-dependent considerations.

Λ(2325) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2342±30	DEBELLEFON 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
2327±20	BACCARI 77	DPWA	$K^-p \rightarrow \Lambda\omega$

Λ(2325) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
177±40	DEBELLEFON 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
160±40	BACCARI 77	IPWA	$K^-p \rightarrow \Lambda\omega$

Λ(2325) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\omega$

Λ(2325) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.19±0.06	DEBELLEFON 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \rightarrow \Lambda(2325) \rightarrow \Lambda\omega$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.06±0.02	[1] BACCARI 77	IPWA	DS_{33} wave
0.05±0.02	[1] BACCARI 77	DPWA	DD_{13} wave
0.08±0.03	[1] BACCARI 77	DPWA	DD_{33} wave

Λ(2325) FOOTNOTES

[1] Note that the three BACCARI 77 entries are for three different waves.

Λ(2325) REFERENCES

DEBELLEFON 78 NC 42A 403 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
BACCARI 77 NC 41A 96 +Poulard, Revel, Tallini+ (SACL, CDEF) IJP

$\Lambda(2350)\ H_{09}$

$I(J^P) = 0(\frac{9}{2}^+)$ Status: * * *

DAUM 68 favors $J^P = 7/2^-$ or $9/2^+$. BRICMAN 70 favors $9/2^+$. LASINSKI 71 suggests three states in this region using a Pomeron + resonances model. There are now also three formation experiments from the College de France-Saclay group, DEBELLEFON 77, BACCARI 77, and DEBELLEFON 78, which find $9/2^+$ in energy-dependent partial-wave analyses of $\overline{K}N \rightarrow \Sigma\pi$, $\Lambda\omega$, and $N\overline{K}$.

Λ(2350) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2340 to 2370 OUR ESTIMATE			
2370±50	DEBELLEFON 78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
2365±20	DEBELLEFON 77	DPWA	$K^-p \rightarrow \Sigma\pi$
2358± 6	BRICMAN 70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2372	BACCARI 77	DPWA	$K^-p \rightarrow \Lambda\omega$
2344±15	COOL 70	CNTR	K^-p, K^-d total
2360±20	LU 70	CNTR	$\gamma p \rightarrow K^+Y^*$
2340± 7	BUGG 68	CNTR	K^-p, K^-d total

$\Lambda(2350)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
100 to 250 OUR ESTIMATE Our best guess is 150 MeV.			
204 ± 50	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$
110 ± 20	DEBELLEFON 77	DPWA	$K^- p \to \Sigma\pi$
324 ± 30	BRICMAN 70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •			
257	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$
190	COOL 70	CNTR	$K^- p$, $K^- d$ total
55	LU 70	CNTR	$\gamma p \to K^+ Y^*$
140 ± 20	BUGG 68	CNTR	$K^- p$, $K^- d$ total

$\Lambda(2350)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	$\sim 12\,\%$
Γ_2	$\Sigma\pi$	$\sim 10\,\%$
Γ_3	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(2350)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
~ 0.12 OUR ESTIMATE			
0.12 ± 0.04	DEBELLEFON 78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2350) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.11 ± 0.02	DEBELLEFON 77	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Lambda(2350) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.05	BACCARI 77	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(2350)$ REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
LASINSKI	71	NP B29 125		(EFI) IJP
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
COOL	70	PR D1 1887	+Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
DAUM	68	NP B7 19	+Erne, Lagnaux, Sens, Steuer, Udo	(CERN) JP

$\Lambda(2585)$ Bumps

$I(J^P) = 0(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Lambda(2585)$ MASS (BUMPS)

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2585 ± 45	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
2530 ± 25	LU 70	CNTR	$\gamma p \to K^+ Y^*$

$\Lambda(2585)$ WIDTH (BUMPS)

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
300	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
150	LU 70	CNTR	$\gamma p \to K^+ Y^*$

$\Lambda(2585)$ DECAY MODES (BUMPS)

	Mode
Γ_1	$N\overline{K}$

$\Lambda(2585)$ BRANCHING RATIOS (BUMPS)

$(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

J is not known, so only $(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{\text{total}}$ can be given.

VALUE	DOCUMENT ID	TECN	COMMENT
1	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
0.12 ± 0.12	[1] BRICMAN 70	CNTR	Total, charge exchange

$\Lambda(2585)$ FOOTNOTES (BUMPS)

[1] The resonance is at the end of the region analyzed — no clear signal.

$\Lambda(2585)$ REFERENCES (BUMPS)

ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)

Σ BARYONS

$(S = -1,\ I = 1)$

$\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

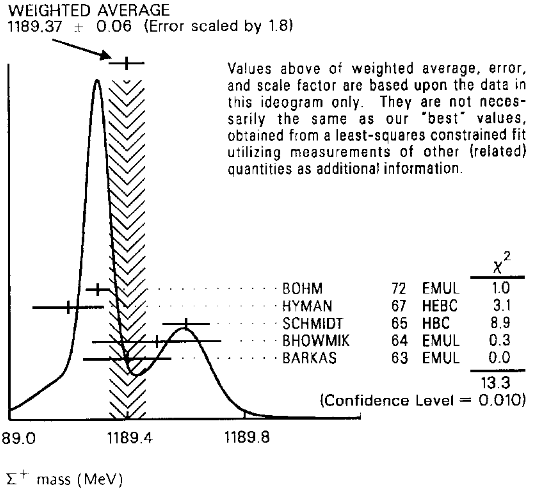
Σ^+ MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1189.37 ± 0.07 OUR FIT Error includes scale factor of 2.1.				
1189.37 ± 0.06 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.				
1189.33 ± 0.04	607	[1] BOHM 72	EMUL	
1189.16 ± 0.12		HYMAN 67	HEBC	
1189.61 ± 0.08	4205	SCHMIDT 65	HBC	See note with Λ mass
1189.48 ± 0.22	58	[2] BHOWMIK 64	EMUL	
1189.38 ± 0.15	144	[2] BARKAS 63	EMUL	

[1] BOHM 72 is updated with our 1973 K^-, π^-, and π^0 masses (RMP **45**, No. 2, Pt. II).

[2] These masses have been raised 30 keV to take into account a 46 keV increase in the proton mass and a 21 keV decrease in the π^0 mass (note added 1967 edition, RMP **39**, 1).



Σ^+ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted.

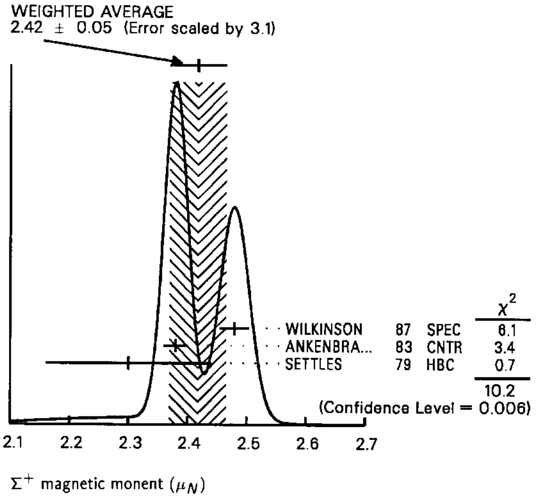
VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.799 ± 0.004 OUR AVERAGE					
0.798 ± 0.005	30k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.807 ± 0.013	5719	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
$0.83\ \pm0.04$	526	BAKKER	71	DBC	$K^- n \rightarrow \Sigma^+ \pi^- \pi^-$
0.795 ± 0.010	20k	EISELE	70	HBC	$K^- p$ at rest
0.803 ± 0.008	10664	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
$0.83\ \pm0.032$	1300	[3] CHANG	66	HBC	
$0.80\ \pm0.07$	381	COOK	66	OSPK	
$0.84\ \pm0.09$	181	BALTAY	65	HBC	
$0.76\ \pm0.03$	900	CARAYAN...	65	HBC	
$0.749^{+0.056}_{-0.052}$	192	GRARD	62	HBC	
0.765 ± 0.04	456	HUMPHREY	62	HBC	

[3] We have increased the CHANG 66 error of 0.018; see our 1970 edition, RMP **42**, 123.

Σ^+ MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings. Measurements with an error $\geq 0.3\ \mu_N$ have been omitted.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$2.42\ \pm0.05$ OUR AVERAGE	Error includes scale factor of 3.1. See the ideogram below.				
$2.479\pm0.012\pm0.022$	137k	WILKINSON	87	SPEC	400 GeV pBe
$2.38\ \pm0.02$	44k	ANKENBRA...	83	CNTR	210 GeV hyperon beam
$2.30\ \pm0.14$	14k	SETTLES	79	HBC	$K^- p$ 0.42–0.50 GeV/c



Σ^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p\pi^0$		(51.57 ± 0.30) %	
Γ_2	$n\pi^+$		(48.30 ± 0.30) %	
Γ_3	$p\gamma$		$(1.25\pm0.07) \times 10^{-3}$	
Γ_4	$n\pi^+\gamma$	[a]	$(4.5\ \pm0.5\ ) \times 10^{-4}$	
Γ_5	$\Lambda e^+ \nu_e$		$(2.0\ \pm0.5\ ) \times 10^{-5}$	

$\Delta S = \Delta Q$ (SQ) or Flavor-Changing neutral current (FC) violating modes

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_6	$ne^+\nu_e$	SQ	$< 5 \times 10^{-6}$	90%
Γ_7	$n\mu^+\nu_\mu$	SQ	$< 3.0 \times 10^{-5}$	90%
Γ_8	pe^+e^-	FC	$< 7 \times 10^{-6}$	

[a] See the Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 13 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 7.5 for 11 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{ccc} x_2 & -100 & \\ x_3 & 9 & -11 \\ & x_1 & x_2 \end{array}$$

Σ^+ BRANCHING RATIOS

$\Gamma(n\pi^+)/\Gamma(N\pi)$ $\qquad \Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.4836 ± 0.0030 OUR FIT					
0.4836 ± 0.0030 OUR AVERAGE					
0.4828 ± 0.0036	10k	[4] MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
$0.488\ \pm0.008$	1861	NOWAK	78	HBC	
$0.484\ \pm0.015$	537	TOVEE	71	EMUL	
$0.488\ \pm0.010$	1331	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
$0.46\ \ \pm0.02$	534	CHANG	66	HBC	
$0.490\ \pm0.024$	308	HUMPHREY	62	HBC	

[4] MARRAFFINO 80 actually gives $\Gamma(p\pi^0)/\Gamma(\text{total}) = 0.5172 \pm 0.0036$.

$\Gamma(p\gamma)/\Gamma(p\pi^0)$ $\qquad \Gamma_3/\Gamma_1$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.43 ± 0.14 OUR FIT					
2.43 ± 0.14 OUR AVERAGE					
$2.81\pm0.39^{+0.21}_{-0.43}$	408	HESSEY	89	CNTR	$K^- p \rightarrow \Sigma^+ \pi^-$ at rest
2.52 ± 0.28	190	[5] KOBAYASHI	87	CNTR	$\pi^+ p \rightarrow \Sigma^+ K^+$
$2.46^{+0.30}_{-0.35}$	155	BIAGI	85	CNTR	CERN hyperon beam
2.11 ± 0.38	46	MANZ	80	HBC	$K^- p \rightarrow \Sigma^+ \pi^-$
$2.1\ \pm0.3$	45	ANG	69B	HBC	$K^- p$ at rest
2.76 ± 0.51	31	GERSHWIN	69B	HBC	$K - p \rightarrow \Sigma^+ \pi^-$
$3.7\ \pm0.8$	24	BAZIN	65	HBC	$K^- p$ at rest

[5] KOBAYASHI 87 actually gives $\Gamma(p\gamma)/\Gamma(\text{total}) = (1.30 \pm 0.15) \times 10^{-3}$.

$\Gamma(n\pi^+\gamma)/\Gamma(n\pi^+)$ $\qquad \Gamma_4/\Gamma_2$

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value in the Summary Table.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.93 ± 0.10	180	EBENHOH	73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.27 ± 0.05	29	ANG	69B	HBC	$\pi^+ < 110$ MeV/c
~ 1.8		BAZIN	65B	HBC	$\pi^+ < 116$ MeV/c

$\Gamma(\Lambda e^+\nu_e)/\Gamma_{\text{total}}$ $\qquad \Gamma_5/\Gamma$

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.0 ± 0.5 OUR AVERAGE					
1.6 ± 0.7	5	BALTAY	69	HBC	$K^- p$ at rest
2.9 ± 1.0	10	EISELE	69	HBC	$K^- p$ at rest
2.0 ± 0.8	6	BARASH	67	HBC	$K^- p$ at rest

$\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ $\qquad \Gamma_6/\Gamma_2$

Test of $\Delta S = \Delta Q$ rule. Experiments with an effective denominator less than 100,000 have been omitted.

EFFECTIVE DENOM.	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$< 1.1 \times 10^{-5}$ OUR LIMIT	Our 90% CL limit = (2.3 events)/(effective denominator sum). [Number of events increased to 2.3 for a 90% confidence level.]				
111000	0	[6] EBENHOH	74	HBC	$K^- p$ at rest
105000	0	[6] SECHI-ZORN	73	HBC	$K^- p$ at rest

[6] Effective denominator calculated by us.

$\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ $\qquad \Gamma_7/\Gamma_2$

Test of $\Delta S = \Delta Q$ rule.

EFFECTIVE DENOM.	*EVTS*	*DOCUMENT ID*		*TECN*
$< 6.2 \times 10^{-5}$ OUR LIMIT	Our 90% CL limit = (6.7 events)/(effective denominator sum). [Number of events increased to 6.7 for a 90% confidence level.]			
33800	0	BAGGETT	69B	HBC
62000	2	[7] EISELE	69B	HBC
10150	0	[8] COURANT	64	HBC
1710	0	[8] NAUENBERG	64	HBC
120	1	GALTIERI	62	EMUL

[7] Effective denominator calculated by us.

[8] Effective denominator taken from EISELE 67.

$\Gamma(pe^+e^-)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE (units 10^{-6})	DOCUMENT ID		TECN	COMMENT
<7	[9] ANG	69B	HBC	$K^- p$ at rest

[9] ANG 69B found three pe^+e^- events in agreement with $\gamma \to e^+e^-$ conversion from $\Sigma^+ \to p\gamma$. The limit given here is for neutral currents.

$\Gamma(\Sigma^+ \to ne^+\nu_e)/\Gamma(\Sigma^- \to ne^-\overline{\nu}_e)$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.009 OUR LIMIT	Our 90% CL limit, using $\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ above.					
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.019	90	0	EBENHOH	74	HBC	$K^- p$ at rest
<0.018	90	0	SECHI-ZORN	73	HBC	$K^- p$ at rest
<0.12	95	0	COLE	71	HBC	$K^- p$ at rest
<0.03	90	0	EISELE	69B	HBC	See EBENHOH 74

$\Gamma(\Sigma^+ \to n\mu^+\nu_\mu)/\Gamma(\Sigma^- \to n\mu^-\overline{\nu}_\mu)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.12 OUR LIMIT	Our 90% CL limit, using $\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ above.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.06^{+0.045}_{-0.03}$	2	EISELE	69B	HBC	$K^- p$ at rest

$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu})$

Test of $\Delta S = \Delta Q$ rule.

VALUE	EVTS	DOCUMENT ID		TECN
<0.043 OUR LIMIT	Our 90% CL limit, using $\left[\Gamma(ne^+\nu_e) + \Gamma(n\mu^+\nu_\mu)\right]/\Gamma(n\pi^+)$.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	1	NORTON	69	HBC
<0.034	0	BAGGETT	67	HBC

Σ^+ DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings. A few early results have been omitted.

α_0 FOR $\Sigma^+ \to p\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{-0.980^{+0.017}_{-0.015}}$ **OUR FIT**					
$\mathbf{-0.980^{+0.017}_{-0.013}}$ **OUR AVERAGE**					
$-0.945^{+0.055}_{-0.042}$	1259	[10] LIPMAN	73	OSPK	$\pi^+ p \to \Sigma^+$
-0.940 ± 0.045	16k	BELLAMY	72	ASPK	$\pi^+ p \to \Sigma^+ K^+$
$-0.98\ ^{+0.05}_{-0.02}$	1335	[11] HARRIS	70	OSPK	$\pi^+ p \to \Sigma^+ K^+$
-0.999 ± 0.022	32k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

[10] Decay protons scattered off aluminum.

[11] Decay protons scattered off carbon.

ϕ_0 ANGLE FOR $\Sigma^+ \to p\pi^0$ $(\tan\phi_0 = \beta\ /\ \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
36 ±34 OUR AVERAGE					
$38.1^{+35.7}_{-37.1}$	1259	[12] LIPMAN	73	OSPK	$\pi^+ p \to \Sigma^+ K^+$
22 ±90		[13] HARRIS	70	OSPK	$\pi^+ p \to \Sigma^+ K^+$

[12] Decay proton scattered off aluminum.

[13] Decay protons scattered off carbon.

$\alpha_+\ /\ \alpha_0$

Older results have been omitted.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.069±0.013 OUR FIT					
−0.073±0.021	23k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c

α_+ FOR $\Sigma^+ \to n\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.068±0.013 OUR FIT					
0.066±0.016 OUR AVERAGE					
0.037±0.049	4101	BERLEY	70B	HBC	
0.069±0.017	35k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

ϕ_+ ANGLE FOR $\Sigma^+ \to n\pi^+$ $(\tan\phi_+ = \beta\ /\ \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
167±20 OUR AVERAGE	Error includes scale factor of 1.1.				
184±24	1054	[14] BERLEY	70B	HBC	
143±29	560	BANGERTER	69B	HBC	$K^- p$ 0.4 GeV/c

[14] Changed from 176 to 184° to agree with our sign convention.

α_γ FOR $\Sigma^+ \to p\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.83±0.12 OUR AVERAGE					
$-0.86 \pm 0.13 \pm 0.04$	190	KOBAYASHI	87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$-0.53^{+0.38}_{-0.36}$	46	MANZ	80	HBC	$K^- p \to \Sigma^- \pi^-$
$-1.03^{+0.52}_{-0.42}$	61	GERSHWIN	69B	HBC	$K^- p \to \Sigma^- \pi^-$

REFERENCES FOR Σ^+

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

HESSEY	89	ZPHY C42 175	+Booth, Fickinger, Gall+	(BNL-811 Collab.)
KOBAYASHI	87	PRL 59 868	+Haba, Homma, Kawai, Miyake+	(KYOT)
WILKINSON	87	PRL 58 855	+Handler+	(WISC, MICH, RUTG, MINN)
BIAGI	85	ZPHY C28 495	+Bourquin+	(BRIS, CERN, GEVA, HEID+)
ANKENBRA...	83	PRL 51 863	Ankenbrandt, Berge+	(FNAL, IOWA, ISU, YALE)
MANZ	80	PL 96B 217	+Reucroft, Settles, Wolf+	(MPIM, VAND)
MARRAFFINO	80	PR D21 2501	+Reucroft, Roos, Waters+	(VAND, MPIM)
SETTLES	79	PR D20 2154	+Manz, Matt, Hansl, Herynek+	(MPIM, VAND)
NOWAK	78	NP B139 61	+Armstrong, Davis+	(LOUC, BELG, DURH, WARS)
CONFORTO	76	NP B105 189	+Gopal, Kalmus, Litchfield, Ross+	(RHEL, LOIC)
EBENHOH	74	ZPHY 266 367	+Eisele, Engelmann, Filthuth, Hepp+	(HEID)
EBENHOH	73	ZPHY 264 413	+Eisele, Filthuth, Hepp, Leitner, Thouw+	(HEID)
LIPMAN	73	PL 43B 89	+Uto, Walker, Montgomery+	(RHEL, SUSS, LOWC)
SECHI-ZORN	73	PR D8 12	+Snow	(UMD)
BELLAMY	72	PL 39B 299	+Anderson, Crawford+	(LOWC, RHEL, SUSS)
BOHM	72	NP B48 1	+	(BERL, UBEL, BRUX, IASD, DUUC, LOUC+)
Also	73	IIHE-73.2 Nov	Bohm	(BERL, UBEL, BRUX, IASD, DUUC, LOUC+)
BAKKER	71	LNC 1 37	+Hoogland, Kluyver, Massard+	(SABRE Collab.)
COLE	71	PR D4 631	+Lee-Franzini, Loveless, Baltay+	(STON, COLU)
TOVEE	71	NP B33 493	+	(LOUC, UBEL, BERL, BRUX, DUUC, WARS)
BERLEY	70B	PR D1 2015	+Yamin, Hertzbach, Kofler+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
HARRIS	70	PRL 24 165	+Overseth, Pondrom, Dettmann	(MICH, WISC)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69B	MDDP-TR-973 Thesis		(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	UCRL 19244 Thesis		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
Also	64	PRL 13 291	Willis, Courant+	(BNL, CERN, HEID, UMD)
EISELE	69B	ZPHY 221 401	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
GERSHWIN	69B	PR 188 2077	+Alston-Garnjost, Bangerter+	(LRL)
Also	69	UCRL 19246 Thesis	Gershwin	(LRL)
NORTON	69	Nevis 175 Thesis		(COLU)
BAGGETT	67	PRL 19 1458	+Day, Glasser, Kehoe, Knop+	(UMD)
Also	68	Vienna Abs. 374	Baggett, Kehoe	(UMD)
Also	68B	Private Comm.	Baggett	(UMD)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
EISELE	67	ZPHY 205 409	+Engelmann, Filthuth, Folish, Hepp+	(HEID)
HYMAN	67	PL 25B 376	+Loken, Pewitt, McKenzie+	(ANL, CMU, NWES)
CHANG	66	PR 151 1081		(COLU)
Also	65	Nevis 145 Thesis	Chang	(COLU)
COOK	66	PRL 17 223	+Ewart, Masek, Orr, Platner	(WASH)
BALTAY	65	PR 140B 1027	+Sandweiss, Culwick, Kopp+	(YALE, BNL)
BAZIN	65	PRL 14 154	+Blumenfeld, Nauenberg+	(PRIN, COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
CARAYAN...	65	PR 138B 433	Carayannopoulos, Tautfest, Willmann	(PURD)
SCHMIDT	65	PR 140B 1328		(COLU)
BHOWMIK	64	NP 53 22	+Jain, Mathur, Lakshmi	(DELH)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
NAUENBERG	64	PRL 12 679	+Marateck+	(COLU, RUTG, PRIN)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
Also	61	UCRL 9450 Thesis	Dyer	(LRL)
GALTIERI	62	PRL 9 26	+Barkas, Heckman, Patrick, Smith	(LRL)
GRARD	62	PR 127 607	+Smith	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

$\boxed{\Sigma^0}$

$$I(J^P) = 1(\tfrac{1}{2}^+)$$

The spin and parity have not been measured directly. They are of course assumed to be the same as for the Σ^+ and Σ^-.

Σ^0 MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	DOCUMENT ID
1192.55±0.10 OUR FIT	Error includes scale factor of 1.4.

$\Sigma^- - \Sigma^0$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4.89±0.08 OUR FIT	Error includes scale factor of 1.2.				
4.86±0.08 OUR AVERAGE	Error includes scale factor of 1.2.				
4.87±0.12	37	DOSCH	65	HBC	
5.01±0.12	12	SCHMIDT	65	HBC	See note with Λ mass
4.75±0.1	18	BURNSTEIN	64	HBC	

$\Sigma^0 - \Lambda$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
76.92±0.10 OUR FIT	Error includes scale factor of 1.4.				
76.55±0.25 OUR AVERAGE					
76.23±0.55	109	COLAS	75	HLBC	$\Sigma^0 \to \Lambda\gamma$
76.63±0.28	208	SCHMIDT	65	HBC	See note with Λ mass

Σ^0 MEAN LIFE

These lifetimes are deduced from measurements of the cross sections for the Primakoff process $\Lambda \rightarrow \Sigma^0$ in nuclear Coulomb fields. An alternative expression of the same information is the Σ^0-Λ transition magnetic moment given in the following section. The relation is $(\mu_{\Sigma\Lambda}/\mu_N)^2\ \tau = 1.92951 \times 10^{-19}$ s (see DEVLIN 86).

VALUE (10^{-20} s)	*DOCUMENT ID*	*TECN*	*COMMENT*
7.4±0.7 OUR EVALUATION	Using $\mu_{\Sigma\Lambda}$ (see the above note).		
$6.5^{+1.7}_{-1.1}$	[1] DEVLIN 86	SPEC	Primakoff effect
7.6±0.5±0.7	[2] PETERSEN 86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.8±1.3	[1] DYDAK 77	SPEC	See DEVLIN 86

[1] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.

[2] An additional uncertainty of the Primakoff formalism is estimated to be < 5%.

$|\mu(\Sigma^0 \rightarrow \Lambda)|$ TRANSITION MAGNETIC MOMENT

See the note in the Σ^0 mean-life section above. Also, see the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	*DOCUMENT ID*	*TECN*	*COMMENT*
1.61±0.08 OUR AVERAGE			
$1.72^{+0.17}_{-0.19}$	[3] DEVLIN 86	SPEC	Primakoff effect
1.59±0.05±0.07	[4] PETERSEN 86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$1.82^{+0.25}_{-0.18}$	[3] DYDAK 77	SPEC	See DEVLIN 86

[3] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.

[4] An additional uncertainty of the Primakoff formalism is estimated to be < 2.5%.

Σ^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\gamma$	100 %	
Γ_2	$\Lambda\gamma\gamma$	< 3 %	90%
Γ_3	$\Lambda e^+ e^-$	[a] 5×10^{-3}	

[a] A theoretical value using QED; see the Full Listings.

Σ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*CL%*	*DOCUMENT ID*	*TECN*
<0.03	90	COLAS 75	HLBC

$\Gamma(\Lambda e^+ e^-)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*	*COMMENT*
0.00545	FEINBERG 58	Theoretical QED calculation

REFERENCES FOR Σ^0

DEVLIN	86	PR D34 1626	+Petersen, Beretvas	(RUTG)
PETERSEN	86	PRL 57 949	+Beretvas, Devlin, Luk+	(RUTG, WISC, MICH, MINN)
DYDAK	77	NP B118 1	+Navarria, Overseth, Steffen+	(CERN, DORT, HEID)
COLAS	75	NP B91 253	+Farwell, Ferrer, Six	(ORSA)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
FEINBERG	58	PR 109 1019		(BNL)

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

Σ^- MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1197.43 ±0.06 OUR FIT	Error includes scale factor of 1.6.			
1197.50 ±0.05 OUR AVERAGE				
1197.532±0.057		GALL 88	CNTR	Σ^- Pb, Σ^- W atoms
1197.43 ±0.08	3000	SCHMIDT 65	HBC	See note with Λ mass
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1197.24 ±0.15		[1] DUGAN 75	CNTR	Exotic atoms

[1] GALL 88 concludes that the DUGAN 75 mass needs to be reevaluated.

Σ^- − Σ^+ MASS DIFFERENCE

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*
8.07±0.09 OUR FIT	Error includes scale factor of 1.9.		
8.09±0.16 OUR AVERAGE			
7.91±0.23	86	BOHM 72	EMUL
8.25±0.25	2500	DOSCH 65	HBC
8.25±0.40	87	BARKAS 63	EMUL

Σ^- − Λ MASS DIFFERENCE

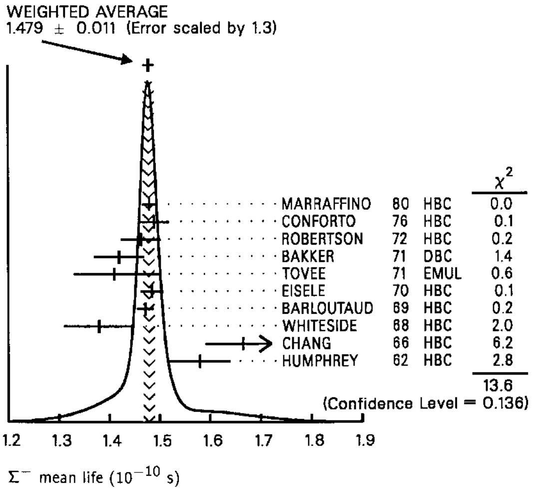
VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
81.81±0.07 OUR FIT	Error includes scale factor of 1.5.			
81.69±0.07 OUR AVERAGE				
81.64±0.09	2279	HEPP 68	HBC	
81.80±0.13	85	SCHMIDT 65	HBC	See note with Λ mass
81.70±0.19		BURNSTEIN 64	HBC	

Σ^- MEAN LIFE

Measurements with an error $\geq 0.2 \times 10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.479±0.011 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			
1.480±0.014	16k	MARRAFFINO 80	HBC	$K^- p$ 0.42–0.5 GeV/c
1.49 ±0.03	8437	CONFORTO 76	HBC	$K^- p$ 1–1.4 GeV/c
1.463±0.039	2400	ROBERTSON 72	HBC	$K^- p$ 0.25 GeV/c
1.42 ±0.05	1383	BAKKER 71	DBC	$K^- N \rightarrow \Sigma^- \pi\pi$
$1.41\ ^{+0.09}_{-0.08}$		TOVEE 71	EMUL	
1.485±0.022	100k	EISELE 70	HBC	$K^- p$ at rest
1.472±0.016	10k	BARLOUTAUD 69	HBC	$K^- p$ 0.4–1.2 GeV/c
1.38 ±0.07	506	WHITESIDE 68	HBC	$K^- p$ at rest
1.666±0.075	3267	[2] CHANG 66	HBC	$K^- p$ at rest
1.58 ±0.06	1208	HUMPHREY 62	HBC	$K^- p$ at rest

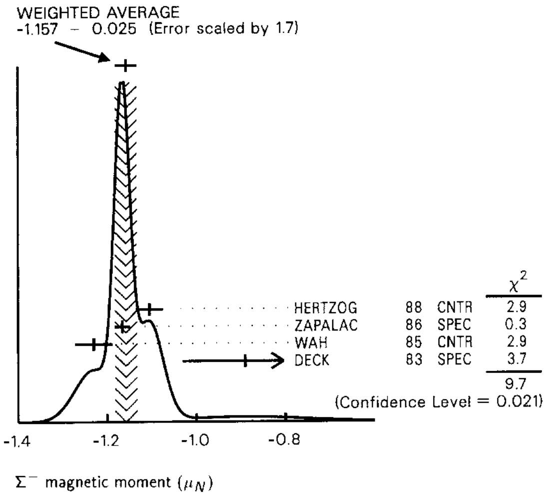
[2] We have increased the CHANG 66 error of 0.018; see our 1970 edition, RMP **42**, 123.



Σ^- MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings. Measurements with an error $\geq 0.3\ \mu_N$ have been omitted.

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
-1.157 ± 0.025 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.			
$-1.105\pm0.029\pm0.010$		HERTZOG 88	CNTR	Σ^- Pb, Σ^- W atoms
$-1.166\pm0.014\pm0.010$	671k	ZAPALAC 86	SPEC	$ne^-\nu$, $n\pi^-$ decays
$-1.23\ \pm0.03\ \pm0.03$		WAH 85	CNTR	pCu $\rightarrow$ Σ^- X
$-0.89\ \pm0.14$	516k	DECK 83	SPEC	pBe $\rightarrow$ Σ^- X



Σ^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$n\pi^-$	(99.848 ± 0.005) %
Γ_2	$n\pi^-\gamma$	[a] $(\ 4.6\ \ \pm0.6\ \ )\times10^{-4}$
Γ_3	$ne^-\overline{\nu}_e$	$(\ 1.017\pm0.034)\times10^{-3}$
Γ_4	$n\mu^-\overline{\nu}_\mu$	$(\ 4.5\ \ \pm0.4\ \ )\times10^{-4}$
Γ_5	$\Lambda e^-\overline{\nu}_e$	$(\ 5.73\ \pm0.27\ )\times10^{-5}$

[a] See the Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 16 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 8.7 for 13 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i\delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

$$\begin{array}{cccc}
x_3 & -64 & & \\
x_4 & -77 & 0 & \\
x_5 & -5 & 0 & 0 \\
 & x_1 & x_3 & x_4
\end{array}$$

Σ^- BRANCHING RATIOS

$\Gamma(n\pi^-\gamma)/\Gamma(n\pi^-)$ Γ_2/Γ_1

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value in the Summary Table.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.46 ± 0.06	292	EBENHOH 73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ± 0.02	23	ANG 69B	HBC	$\pi^- < 110$ MeV/c
~1.1		BAZIN 65B	HBC	$\pi^- < 166$ MeV/c

$\Gamma(ne^-\overline{\nu}_e)/\Gamma(n\pi^-)$ Γ_3/Γ_1

Measurements with an error $\geq 0.2\times10^{-3}$ have been omitted.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1.019 ± 0.034 OUR FIT				
$1.019^{+0.031}_{-0.036}$ OUR AVERAGE				
$0.96\ \pm0.05$	2847	BOURQUIN 83C	SPEC	SPS hyperon beam
$1.09\ {}^{+0.06}_{-0.08}$	601	[3] EBENHOH 74	HBC	K^-p at rest
$1.05\ {}^{+0.07}_{-0.13}$	455	[3] SECHI-ZORN 73	HBC	K^-p at rest
$0.97\ \pm0.15$	57	COLE 71	HBC	K^-p at rest
$1.11\ \pm0.09$	180	BIERMAN 68	HBC	

[3] An additional negative systematic error is included for internal radiative corrections and latest form factors; see BOURQUIN 83C.

$\Gamma(n\mu^-\overline{\nu}_\mu)/\Gamma(n\pi^-)$ Γ_4/Γ_1

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.45 ± 0.04 OUR FIT				
0.45 ± 0.04 OUR AVERAGE				
0.38 ± 0.11	13	COLE 71	HBC	K^-p at rest
0.43 ± 0.06	72	ANG 69	HBC	K^-p at rest
0.43 ± 0.09	56	BAGGETT 69	HBC	K^-p at rest
0.56 ± 0.20	11	BAZIN 65B	HBC	K^-p at rest
0.66 ± 0.15	22	COURANT 64	HBC	

$\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(n\pi^-)$ Γ_5/Γ_1

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.574 ± 0.027 OUR FIT				
0.574 ± 0.027 OUR AVERAGE				
0.561 ± 0.031	1620	[4] BOURQUIN 82	SPEC	SPS hyperon beam
$0.63\ \pm0.11$	114	THOMPSON 80	ASPK	Hyperon beam
$0.52\ \pm0.09$	31	BALTAY 69	HBC	K^-p at rest
$0.69\ \pm0.12$	31	EISELE 69	HBC	K^-p at rest
$0.64\ \pm0.12$	35	BARASH 67	HBC	K^-p at rest
$0.75\ \pm0.28$	11	COURANT 64	HBC	K^-p at rest

[4] The value is from BOURQUIN 83B, and includes radiation corrections and new acceptance.

Σ^- DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings. Older, outdated results have been omitted.

α_- FOR $\Sigma^- \rightarrow n\pi^-$

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
-0.068 ± 0.008 OUR AVERAGE				
-0.062 ± 0.024	28k	HANSL 78	HBC	$K^-p\rightarrow\Sigma^-\pi^+$
-0.067 ± 0.011	60k	BOGERT 70	HBC	K^-p 0.4 GeV/c
-0.071 ± 0.012	51k	BANGERTER 69	HBC	K^-p 0.4 GeV/c

ϕ ANGLE FOR $\Sigma^- \rightarrow n\pi^-$ $(\tan\phi = \beta\ /\ \gamma)$

VALUE (°)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
10 ± 15 OUR AVERAGE				
$+\ 5\pm23$	1092	[5] BERLEY 70B	HBC	n rescattering
14 ± 19	1385	BANGERTER 69B	HBC	K^-p 0.4 GeV/c

[5] BERLEY 70B changed from -5 to $+5°$ to agree with our sign convention.

g_A/g_V FOR $\Sigma^- \rightarrow ne^-\overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the Note on Baryon Decay Parameters in the neutron Listings. What is actually listed is $|g_1/f_1 - 0.237g_2/f_1|$. This reduces to $g_A/g_V \equiv g_1(0)/f_1(0)$ on making the usual assumption that $g_2 = 0$. See also the note on HSUEH 88.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.340 ± 0.017 OUR AVERAGE				
$+0.327\pm0.007\pm0.019$	50k	[6] HSUEH 88	SPEC	Σ^- 250 GeV
$+0.34\ \pm0.05$	4456	[7] BOURQUIN 83C	SPEC	SPS hyperon beam
0.385 ± 0.037	3507	[8] TANENBAUM 74	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.29\ \pm0.07$	25k	HSUEH 85	SPEC	See HSUEH 88
$0.17\ {}^{+0.07}_{-0.09}$	519	DECAMP 77	ELEC	Hyperon beam

[6] The sign is, *with our conventions*, unambiguously positive. The value assumes, as usual, that $g_2 = 0$. If g_2 is included in the fit, than (with our sign convention) $g_2 = -0.56 \pm 0.37$, with a corresponding reduction of g_A/g_V to $+0.20 \pm 0.08$.

[7] BOURQUIN 83C favors the positive sign by at least 2.6 standard deviations.

[8] TANENBAUM 74 gives 0.435 ± 0.035, assuming no q^2 dependence in g_A and g_V. The listed result allows q^2 dependence, and is taken from HSUEH 88.

$f_2(0)/f_1(0)$ FOR $\Sigma^- \rightarrow ne^-\overline{\nu}_e$

The signs have been changed to be in accord with our conventions, given in the Note on Baryon Decay Parameters in the neutron Listings.

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.97 ± 0.14 OUR AVERAGE				
$0.96\pm0.07\pm0.13$	50k	HSUEH 88	SPEC	Σ^- 250 GeV
1.02 ± 0.34	4456	BOURQUIN 83C	SPEC	SPS hyperon beam

TRIPLE CORRELATION COEFFICIENT D for $\Sigma^- \rightarrow ne^-\overline{\nu}_e$

The coefficient D of the term $DP\cdot(\hat{p}_e \times \hat{p}_\nu)$ in the $\Sigma^- \rightarrow ne^-\overline{\nu}$ decay angular distribution. A nonzero value would indicate a violation of time-reversal invariance.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.11±0.10	50k	HSUEH 88	SPEC	Σ^- 250 GeV

NOTE ON $\Sigma^- \rightarrow \Lambda e^-\overline{\nu}_e$ DECAY

The vector part of the hadronic amplitude for the decay $\Sigma^- \rightarrow \Lambda e^-\overline{\nu}_e$ is of special interest because the vector weak current is proportional to an isospin rotation of the isovector part of the electromagnetic current. This strong form of CVC predicts that

$$f_1(q^2) = 0 \quad \text{for} \quad 0 < q^2 \leq (m_{\Sigma^-} - m_\Lambda)^2 \ ,$$

and also relates $f_2(0)$ to the $\Sigma^0\Lambda$ transition magnetic moment or to the amplitude for the decay $\Sigma^0 \rightarrow \Lambda\gamma$ by

$$\begin{aligned} f_2(0) &= -\sqrt{2}\ \mu_{\Sigma^0\Lambda}/e\hbar \\ &= -\sqrt{3/2}\ \mu_n/e\hbar \qquad \text{[by SU(3)]} \\ &= 1.17\ m_p^{-1}\ . \end{aligned}$$

No SU(3) symmetry is assumed here except in the relation of $\mu_{\Sigma^0\Lambda}$ to the magnetic moment of the neutron, μ_n.

The experimental data were analyzed on the assumption that $f_1(q^2) = 0$ and $f_2(q^2) = f_2(0)$ over the entire kinematical range of q^2 for $\Sigma^- \rightarrow \Lambda e^-\overline{\nu}_e$. The results are listed in the ratio of $g_{MW} = -m_{\Sigma^-}\ f_2(0)$ to $g_A = g_1(0)$.

See also the Note on Baryon Decay Parameters in the neutron section of the Full Listings.

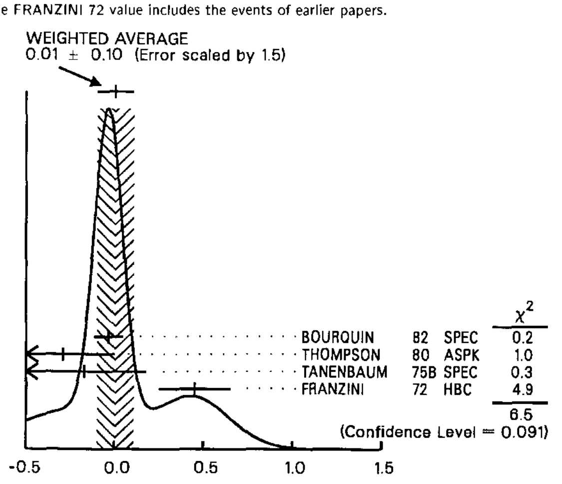
g_V/g_A FOR $\Sigma^- \rightarrow \Lambda e^-\nu$

For the sign convention, see the Note on Baryon Decay Parameters in the neutron Listings. The value is predicted to be zero by conserved vector current theory. The values averaged assume CVC-SU(3) weak magnetism term.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.01 ±0.10 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.		
−0.034±0.080	1620	[9] BOURQUIN 82	SPEC	SPS hyperon beam
−0.29 ±0.29	114	THOMPSON 80	ASPK	BNL hyperon beam
−0.17 ±0.35	55	TANENBAUM 75B	SPEC	BNL hyperon beam
+0.45 ±0.20	186	[9,10] FRANZINI 72	HBC	

[9] The sign has been changed to agree with our convention.

[10] The FRANZINI 72 value includes the events of earlier papers.



g_V/g_A for $\Sigma^- \rightarrow \Lambda e^-\nu$

g_{WM}/g_A FOR $\Sigma^- \rightarrow \Lambda e^-\nu$

The values quoted assume the CVC prediction $g_V = 0$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
2.4 ±1.7 OUR AVERAGE				
1.75±3.5	114	THOMPSON 80	ASPK	BNL hyperon beam
3.5 ±4.5	55	TANENBAUM 75B	SPEC	BNL hyperon beam
2.4 ±2.1	186	FRANZINI 72	HBC	

REFERENCES FOR Σ^-

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

GALL	88	PRL 60 186	+Austin+	(BOST, MIT, WILL, CIT, CMU, WYOM)
HERTZOG	88	PR D37 1142	+Eckhause+	(WILL, BOST, MIT, CIT, CMU, WYOM)
HSUEH	88	PR D38 2056	+	(CHIC, ELMT, FNAL, IOWA, ISU, LENI, YALE)
ZAPALAC	86	PRL 57 1526	+	(EFI, ELMT, FNAL, IOWA, ISU, LENI, YALE)
HSUEH	85	PRL 54 2399	+Muller+	(CHIC, ELMT, FNAL, ISU, LENI, YALE)
WAH	85	PRL 55 2551	+Cardello, Cooper, Teig+	(FNAL, IOWA, ISU)
BOURQUIN	83B	ZPHY C21 27	+	(BRIS, GEVA, HEID, LALO, RL, STRB)
BOURQUIN	83C	ZPHY C21 17	+	(BRIS, GEVA, HEID, LALO, RL, STRB)
DECK	83	PR D28 1	+Beretvas, Devlin, Luk+	(RUTG, WISC, MICH, MINN)
BOURQUIN	82	ZPHY C12 307	+Brown+	(BRIS, GEVA, HEID, LALO, RL, STRB)
MARRAFFINO	80	PR D21 2501	+Reucroft, Roos, Waters+	(VAND, MPIM)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
HANSL	78	NP B132 45	+Manz, Matt, Reucroft, Settles+	(MPIM, VAND)
DECAMP	77	PL 66B 295	+Badier, Bland, Chollet, Gaillard+	(LALO, EPOL)
CONFORTO	76	NP B105 189	+Gopal, Kalmus, Litchfield, Ross+	(RHEL, LOIC)
DUGAN	75	NP A254 396	+Asano, Chen, Cheng, Hu, Lidofsky+	(COLU, YALE)
TANENBAUM	75B	PR D12 1871	+Hungerbuhler+	(YALE, FNAL, BNL)
EBENHOH	74	ZPHY 266 367	+Eisele, Engelmann, Filthuth, Hepp+	(HEID)
TANENBAUM	74	PRL 33 175	+Hungerbuhler+	(YALE, FNAL, BNL)
EBENHOH	73	ZPHY 264 413	+Eisele, Filthuth, Hepp, Leitner, Thouw+	(HEID)
SECHI-ZORN	73	PR D8 12	+Snow	(UMD)
BOHM	72	NP B48 1	+	(BERL, UBEL, BRUX, IASD, DUUC, LOUC+)
FRANZINI	72	PR D6 2417	+	(COLU, HEID, UMD, STON)
ROBERTSON	72	Thesis		(IIT)
BAKKER	71	LNC 1 37	+Hoogland, Kluyver, Massard+	(SABRE Collab.)
COLE	71	PR D4 631	+Lee-Franzini, Loveless, Baltay+	(STON, COLU)
Also	69	Nevis 175 Thesis	Norton	(COLU)
TOVEE	71	NP B33 493	+	(LOUC, UBEL, BERL, BRUX, DUUC, WARS)
BERLEY	70B	PR D1 2015	+Yamin, Hertzbach, Kofler+	(BNL, MASA, YALE)
BOGERT	70	PR D2 6	+Lucas, Taft, Willis, Berley+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
ANG	69	ZPHY 223 103	+Eisele, Engelmann, Filthuth+	(HEID)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69	PRL 23 249	+Kehoe, Snow	(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	UCRL 19244 Thesis		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
BIERMAN	68	PRL 20 1459	+Kounosu, Nauenberg+	(PRIN)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
WHITESIDE	68	NC 54A 537	+Gollub	(OBER)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
CHANG	66	PR 151 1081		(COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
Also	66	PR 151 1081	Chang	(COLU)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

$\Sigma(1385)\ P_{13}$

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗∗∗

Discovered by ALSTON 60. Early measurements of the mass and width for combined charge states have been omitted. They may be found in our 1984 edition (Rev. Mod. Phys. 56, No. 2, Part II, April 1984).

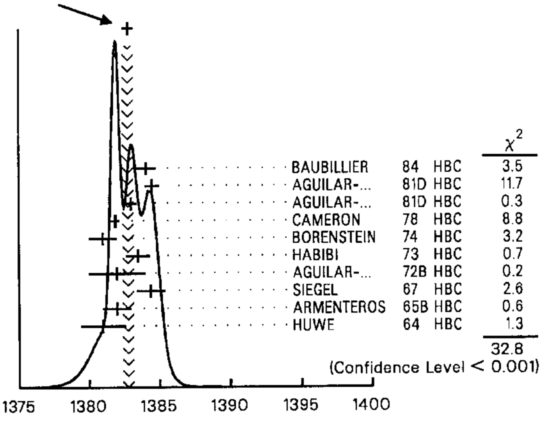
We average only the most significant determinations. We do not average results from inclusive experiments with large backgrounds or results which are not accompanied by some discussion of experimental resolution. Nevertheless systematic differences between experiments remain. (See the ideograms in the Listings below.) These differences could arise from interference effects that change with production mechanism and/or beam momentum. They can also be accounted for in part by differences in the parametrizations employed. (See BORENSTEIN 74 for a discussion on this point.) Thus BORENSTEIN 74 uses a Breit-Wigner with energy-independent width, since a P-wave was found to give unsatisfactory fits. CAMERON 78 uses the same form. On the other hand HOLMGREN 77 obtains a good fit to their $\Lambda\pi$ spectrum with a P-wave Breit-Wigner, but includes the partial width for the $\Sigma\pi$ decay mode in the parametrization. AGUILAR-BENITEZ 81D gives masses and widths for five different Breit-Wigner shapes. The results vary considerably. Only the best-fit S-wave results are given here.

Σ(1385) MASSES

Σ(1385)$^+$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1382.8±0.4	**OUR AVERAGE**	Error includes scale factor of 2.0. See the ideogram below.			
1384.1±0.7	1897	BAUBILLIER	84	HBC	$K^- p$ 8.25 GeV/c
1384.5±0.5	5256	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1383.0±0.4	9361	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1381.9±0.3	6900	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
1381 ±1	6846	BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
1383.5±0.85	2300	HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
1382 ±2	400	AGUILAR-...	72B	HBC	$K^- p \to \Lambda\pi$'s
1384.4±1.0	1260	SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
1382 ±1	750	ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1381.0±1.6	859	HUWE	64	HBC	$K^- p$ 1.22 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1385.1±1.2	600	BAKER	80	HYBR	$\pi^+ p$ 7 GeV/c
1383.2±1.0	750	BAKER	80	HYBR	$K^- p$ 7 GeV/c
1381 ±2	7k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
1391 ±2	2k	CAUTIS	79	HYBR	$\pi^+ p/K^- p$ 11.5 GeV
1390 ±2	100	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
1385 ±3	22k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
1385 ±1	2594	HOLMGREN	77	HBC	See AGUILAR 81D
1380 ±2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
1382 ±1	3740	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
1390 ±6	46	AGUILAR-...	70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
1383 ±8	62	[4] BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
1378 ±5	135	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
1384.3±1.9	250	[4] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
1382.6±2.1	250	[4] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
1375.0±3.9	170	COOPER	64	HBC	$K^- p$ 1.45 GeV/c
1376.0±3.9	154	[4] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

WEIGHTED AVERAGE
1382.8 ± 0.4 (Error scaled by 2.0)

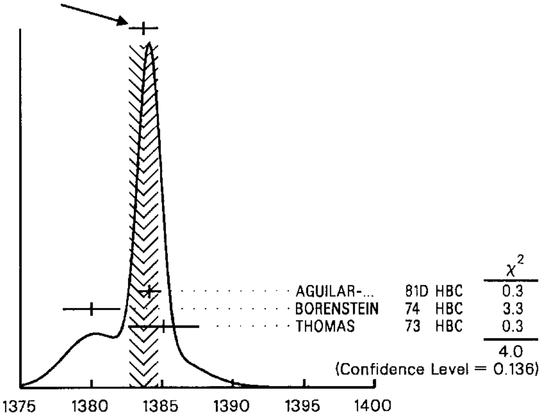


Σ(1385)$^+$ mass (MeV)

Σ(1385)^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1383.7±1.0	**OUR AVERAGE**	Error includes scale factor of 1.4. See the ideogram below.			
1384.1±0.8	5722	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1380 ±2	3100	[5] BORENSTEIN	74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
1385.1±2.5	240	[4] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1389 ±3	500	[6] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c

WEIGHTED AVERAGE
1383.7 ± 1.0 (Error scaled by 1.4)

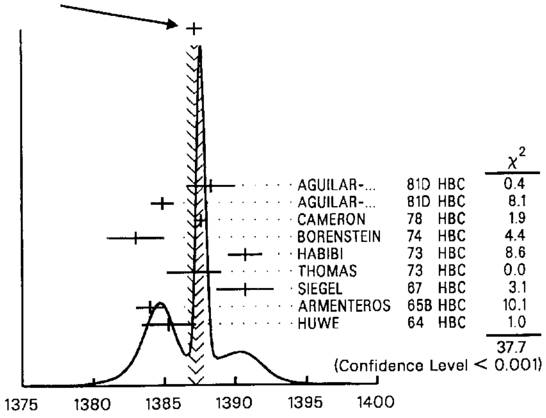


Σ(1385)^0 mass (MeV)

Σ(1385)$^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1387.2±0.5	**OUR AVERAGE**	Error includes scale factor of 2.2. See the ideogram below.			
1388.3±1.7	620	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1384.9±0.8	3346	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1387.6±0.3	9720	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
1383 ±2	2303	BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
1390.7±1.2	1900	HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
1387.1±1.9	630	[4] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^+$
1390.7±2.0	370	SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
1384 ±1	1380	ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1385.3±1.9	1086	[4] HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1383 ±1	4.5k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
1380 ±6	150	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
1387 ±3	12k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
1391 ±3	193	HOLMGREN	77	HBC	See AGUILAR 81D
1383 ±2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
1389 ±1	3060	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
1389 ±9	15	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
1391.5±2.6	120	[4] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
1399.8±2.2	58	[4] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
1392.0±6.2	200	COOPER	64	HBC	$K^- p$ 1.45 GeV/c
1382 ±3	93	DAHL	61	DBC	$K^- d$ 0.45 GeV/c
1376.0±4.4	224	[4] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

WEIGHTED AVERAGE
1387.2 ± 0.5 (Error scaled by 2.2)



Σ(1385)$^-$ mass (MeV)

Σ(1385)$^-$ – Σ(1385)$^+$ MASS DIFFERENCE

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
– 2 to +6	95	[7] BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
7.2±1.4		[7] HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
6.3±2.0		[7] SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
11 ±9		[7] LONDON 66	HBC	$K^- p$ 2.24 GeV/c
9 ±6		LONDON 66	HBC	$\Lambda 3\pi$ events
2.0±1.5		[7] ARMENTEROS 65B	HBC	$K^- p$ 0.9–1.2 GeV/c
7.2±2.1		[7] SMITH 65	HBC	$K^- p$ 1.8 GeV/c
17.2±2.0		[7] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
17 ±7		[7] COOPER 64	HBC	$K^- p$ 1.45 GeV/c
4.3±2.2		[7] HUWE 64	HBC	$K^- p$ 1.22 GeV/c
0.0±4.2		[7] ELY 61	HLBC	$K^- p$ 1.11 GeV/c

Σ(1385)^0 – Σ(1385)$^+$ MASS DIFFERENCE

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
–4 to +4	95	[7] BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c

Σ(1385)$^-$ – Σ(1385)^0 MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.0±2.4	[7] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^- K^+$

Σ(1385) WIDTHS

Σ(1385)$^+$ WIDTH

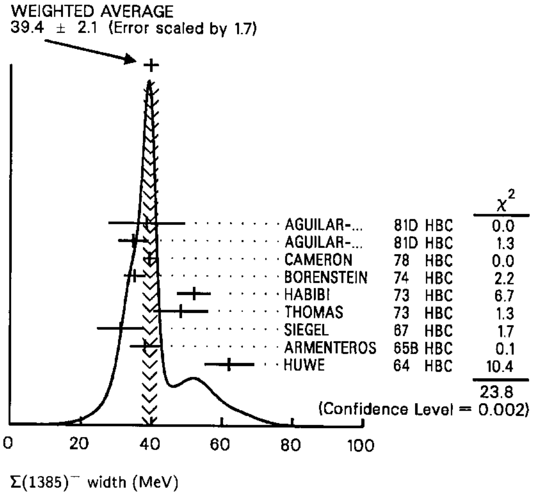
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
35.8± 0.8 OUR AVERAGE				
37.2± 2.0	1897	BAUBILLIER 84	HBC	$K^- p$ 8.25 GeV/c
35.1± 1.7	5256	AGUILAR-... 81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
37.5± 2.0	9361	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
35.5± 1.9	6900	CAMERON 78	HBC	$K^- p$ 0.96–1.36 GeV/c
34.0± 1.6	6846	[8] BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
38.3± 3.2	2300	[9] HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
32.5± 6.0	400	AGUILAR-... 72B	HBC	$K^- p \to \Lambda\pi$'s
36 ± 4	1260	[9] SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
32.0± 4.7	750	[9] ARMENTEROS 65B	HBC	$K^- p$ 0.95–1.20 GeV/c
46.5± 6.4	859	[9] HUWE 64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
40 ± 3	600	BAKER 80	HYBR	$\pi^+ p$ 7 GeV/c
37 ± 2	750	BAKER 80	HYBR	$K^- p$ 7 GeV/c
37 ± 2	7k	[1] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c
30 ± 4	2k	CAUTIS 79	HYBR	$\pi^+ p / K^- p$ 11.5 GeV
30 ± 6	100	[1] SUGAHARA 79B	HBC	$\pi^- p$ 6 GeV/c
43 ± 5	22k	[1,2] BARREIRO 77B	HBC	$K^- p$ 4.2 GeV/c
34 ± 2	2594	HOLMGREN 77	HBC	See AGUILAR 81D
40.0± 3.2		[1] BARDADIN-... 75	HBC	$K^- p$ 14.3 GeV/c
48 ± 3	3740	[3] BERTHON 74	HBC	$K^- p$ 1263–1843 MeV/c
33 ±20	46	[9] AGUILAR-... 70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
25 ±32	62	[9] BIRMINGHAM 66	HBC	$K^- p$ 3.5 GeV/c
30.3± 7.5	250	[9] SMITH 65	HBC	$K^- p$ 1.8 GeV/c
33.1± 8.3	250	[9] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
51 ±16	170	[9] COOPER 64	HBC	$K^- p$ 1.45 GeV/c
48 ±16	154	[9] ELY 61	HLBC	$K^- p$ 1.11 GeV/c

Σ(1385)^0 WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
36 ± 5 OUR AVERAGE				
34.8± 5.6	5722	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.3±10.2	240	[9] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
53 ± 8	3100	[10] BORENSTEIN 74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
30 ± 9	106	CURTIS 63	OSPK	$\pi^- p$ 1.5 GeV/c

Σ(1385)$^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
39.4± 2.1 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.				
38.4±10.7	620	AGUILAR-... 81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
34.6± 4.2	3346	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.2± 1.7	9720	CAMERON 78	HBC	$K^- p$ 0.96–1.36 GeV/c
35 ± 3	2303	[8] BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
51.9± 4.8	1900	[9] HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
48.2± 7.7	630	[9] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^- K^0$
31.0± 6.5	370	[9] SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
38.0± 4.1	1382	[9] ARMENTEROS 65B	HBC	$K^- p$ 0.95–1.20 GeV/c
62 ± 7	1086	HUWE 64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
44 ± 4	4.5k	[1] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c
58 ± 4	150	[1] SUGAHARA 79B	HBC	$\pi^- p$ 6 GeV/c
45 ± 5	12k	[1,2] BARREIRO 77B	HBC	$K^- p$ 4.2 GeV/c
35 ±10	193	HOLMGREN 77	HBC	See AGUILAR 81D
47 ± 6		[1] BARDADIN-... 75	HBC	$K^- p$ 14.3 GeV/c
40 ± 3	3060	[3] BERTHON 74	HBC	$K^- p$ 1263–1843 MeV/c
29.2±10.6	120	[9] SMITH 65	HBC	$K^- p$ 1.80 GeV/c
17.1± 8.9	58	[9] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
88 ±24	200	[9] COOPER 64	HBC	$K^- p$ 1.45 GeV/c
40		DAHL 61	DBC	$K^- d$ 0.45 GeV/c
66 ±18	224	[9] ELY 61	HLBC	$K^- p$ 1.11 GeV/c



Σ(1385) POLE POSITIONS

Σ(1385)$^+$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1379±1	LICHTENBERG 74	Extrapolates HABIBI 73

Σ(1385)$^+$ –IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
17.5±1.5	LICHTENBERG 74	Extrapolates HABIBI 73

Σ(1385)$^-$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1383±1	LICHTENBERG 74	Extrapolates HABIBI 73

Σ(1385)$^-$ –IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
22.5±1.5	LICHTENBERG 74	Extrapolates HABIBI 73

Σ(1385) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	88±2 %
Γ_2	$\Sigma\pi$	12±2 %
Γ_3	$\Lambda\gamma$	
Γ_4	$\Sigma\gamma$	
Γ_5	$N\overline{K}$	

The above branching fractions are our estimates, not fits or averages.

Σ(1385) BRANCHING RATIOS

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.135±0.011 OUR AVERAGE				
0.20 ±0.06	DIONISI 78B	HBC	±	$K^- p \to Y^* K \overline{K}$
0.16 ±0.03	BERTHON 74	HBC	+	$K^- p$ 1.26–1.84 GeV/c
0.11 ±0.02	BERTHON 74	HBC	–	$K^- p$ 1.26–1.84 GeV/c
0.21 ±0.05	BORENSTEIN 74	HBC	+	$K^- p \to \Lambda\pi^+\pi^-, \Sigma^0\pi^+\pi^-$
0.18 ±0.04	MAST 73	MPWA	±	$K^- p \to \Lambda\pi^+\pi^-, \Sigma^0\pi^+\pi^-$
0.10 ±0.05	THOMAS 73	HBC	–	$\pi^- p \to \Lambda K\pi, \Sigma K\pi$

0.16 ±0.07	AGUILAR-... 72B	HBC	+	$K^- p$ 3.9, 4.6 GeV/c
0.13 ±0.04	COLLEY 71B	DBC	−0	$K^- N$ 1.5 GeV/c
0.13 ±0.04	PAN 69	HBC	+	$\pi^+ p \rightarrow \Lambda K \pi$, $\Sigma K \pi$
0.08 ±0.06	LONDON 66	HBC	+	$K^- p$ 2.24 GeV/c
0.163±0.041	ARMENTEROS65B	HBC	±	$K^- p$ 0.95–1.20 GeV/c
0.09 ±0.04	HUWE 64	HBC	±	$K^- p$ 1.2–1.7 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<0.04	ALSTON 62	HBC	±0	$K^- p$ 1.15 GeV/c
0.04 ±0.04	BASTIEN 61	HBC	±	

$\Gamma(\Lambda\gamma)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.17±0.17	1	MEISNER 72	HBC	1 event only

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

<0.06	90	COLAS 75	HLBC	$K^- p$ 575–970 MeV

$\Gamma(\Sigma\gamma)/\Gamma(\Lambda\pi)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT

• • • We do not use the following data for averages, fits, limits, etc. • • •

<0.05	90	COLAS 75	HLBC	$K^- p$ 575–970 MeV

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(1385) \rightarrow \Lambda\pi$ — $(\Gamma_5\Gamma_1)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	CHG	COMMENT
+0.586±0.319	[11] DEVENISH 74B	0	Fixed-t dispersion rel.

Σ(1385) FOOTNOTES

[1] From fit to inclusive $\Lambda\pi$ spectrum.
[2] Includes data of HOLMGREN 77.
[3] The errors are statistical only. The resolution is not unfolded.
[4] The error is enlarged to $\Gamma/N^{1/2}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[5] From a fit to $\Lambda\pi^0$ with the width fixed at 34 MeV.
[6] From fit to inclusive $\Lambda\pi^0$ spectrum with the width fixed at 40 MeV.
[7] Redundant with data in the mass Listings.
[8] Results from $\Lambda\pi^+\pi^-$ and $\Lambda\pi^+\pi^-\pi^0$ combined by us.
[9] The error is enlarged to $4\Gamma/N^{1/2}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[10] Consistent with +, 0, and − widths equal.
[11] An extrapolation of the parametrized amplitude below threshold.

Σ(1385) REFERENCES

BAUBILLIER 84 ZPHY C23 213 + (BIRM, CERN, GLAS, MSU, LPNP)
AGUILAR-... 81D AFIS A77 144 Aguilar-Benitez, Salicio (MADR)
BAKER 80 NP B166 207 +Chima, Dornan, Gibbs, Hall, Miller+ (LOIC)
BAUBILLIER 79B NP B148 18 + (BIRM, CERN, GLAS, MSU, LPNP)
CAUTIS 79 NP B156 507 +Ballam, Bouchez, Carroll, Chadwick+ (SLAC)
SUGAHARA 79B NP B156 237 +Ochiai, Fukui, Cooper+ (KEK, OSKC, KINK)
CAMERON 78 NP B143 189 +Franek, Gopal, Bacon, Butterworth+ (RHEL, LOIC)
DIONISI 78B PL 78B 154 +Armenteros, Diaz (CERN, AMST, NIJM, OXF)
BARREIRO 77B NP B126 319 +Berge, Ganguli, Blokzijl+ (CERN, AMST, NIJM)
HOLMGREN 77 NP B119 261 +Aguilar-Benitez, Kluyver+ (CERN, AMST, NIJM)
BARDADIN-... 75 NP B98 418 Bardadin-Otwinowska+ (SACL, EPOL, RHEL)
COLAS 75 NP B91 253 +Farwell, Ferrer, Six (ORSA)
BERTHON 74 NC 21A 146 +Tristram+ (CDEF, RHEL, SACL, STRB)
BORENSTEIN 74 PR D9 3006 +Kalbfleisch, Strand+ (BNL, MICH)
DEVENISH 74B NP B81 330 +Froggatt, Martin (DESY, NORD, LOUC)
LICHTENBERG 74 PR D10 3865 (IND)
    Also 74B Private Comm. Lichtenberg (IND)
HABIBI 73 Nevis 199 Thesis (COLU)
    Also 73 Purdue Conf. 387 Baltay, Bridgewater, Cooper+ (COLU, BING)
MAST 73 PR D7 3212 +Bangerter, Alston-Garnjost+ (LBL) IJP
    Also 73B PR D7 5 Mast, Bangerter, Alston-Garnjost+ (LBL) IJP
THOMAS 73 NP B56 15 +Engler, Fisk, Kraemer (CMU) JP
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
MEISNER 72 NC 12A 62 (UNC, LBL)
COLLEY 71B NP B31 61 +Cox, Eastwood, Fry+ (BIRM, EDIN, GLAS, LOIC)
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
PAN 69 PRL 23 808 +Forman (PENN) I
SIEGEL 67 UCRL 18041 Thesis (LRL)
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) J
ARMENTEROS 65B PL 19 75 + (CERN, HEID, SACL)
SMITH 65 UCLA Thesis (UCLA)
COOPER 64 PL 8 365 +Filthuth, Fridman, Malamud+ (CERN, AMST)
HUWE 64 UCRL 11291 Thesis (LRL) JP
    Also 69 PR 180 1824 Huwe (LRL)
CURTIS 63 PR 132 1771 +Coffin, Meyer, Terwilliger (MICH) J
ALSTON 62 CERN Conf. 311 +Alvarez, Ferro-Luzzi+ (LRL)
BASTIEN 61 PRL 6 702 +Ferro-Luzzi, Rosenfeld (LRL)
DAHL 61 PRL 6 142 +Horwitz, Miller, Murray, White (LRL)
ELY 61 PRL 7 461 +Fung, Gidal, Pan, Powell, White (LRL) J
ALSTON 60 PRL 5 520 +Alvarez, Eberhard, Good, Graziano+ (LRL) I

Σ(1480) Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

These are peaks seen in $\Lambda\pi$ and $\Sigma\pi$ spectra in the reaction $\pi^+ p \rightarrow (Y\pi)K^+$ at 1.7 GeV/c. Also, the Y polarization oscillates in the same region.

MILLER 70 suggests a possible alternate explanation in terms of a reflection of $N(1675) \rightarrow \Lambda K$ decay. However, such an explanation for the $(\Sigma^+\pi^0)K^+$ channel in terms of $\Delta(1650) \rightarrow \Sigma K$ decay seems unlikely (see PAN 70). In addition such reflections would also have to account for the oscillation of the Y polarization in the 1480 MeV region.

HANSON 71, with less data than PAN 70, can neither confirm nor deny the existence of this state. MAST 75 sees no structure in this region in $K^- p \rightarrow \Lambda\pi^0$.

ENGELEN 80 performs a multichannel analysis of $K^- p \rightarrow p\overline{K}^0\pi^-$ at 4.2 GeV/c. They observe a 3.5 standard-deviation signal at 1480 MeV in $p\overline{K}^0$ which cannot be explained as a reflection of any competing channel.

Σ(1480) MASS
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1480	120	ENGELEN 80	HBC	+	$K^- p \rightarrow (p\overline{K}^0)\pi^-$
1485±10		CLINE 73	MPWA	−	$K^- d \rightarrow (\Lambda\pi^-)p$
1479±10		PAN 70	HBC	+	$\pi^+ p \rightarrow (\Lambda\pi^+)K^+$
1465±15		PAN 70	HBC	+	$\pi^+ p \rightarrow (\Sigma\pi)K^+$

Σ(1480) WIDTH
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
80±20	120	ENGELEN 80	HBC	+	$K^- p \rightarrow (p\overline{K}^0)\pi^-$
40±20		CLINE 73	MPWA	−	$K^- d \rightarrow (\Lambda\pi^-)p$
31±15		PAN 70	HBC	+	$\pi^+ p \rightarrow (\Lambda\pi^+)K^+$
30±20		PAN 70	HBC	+	$\pi^+ p \rightarrow (\Sigma\pi)K^+$

Σ(1480) DECAY MODES
(PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(1480) BRANCHING RATIOS
(PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	CHG
0.82±0.51	PAN 70	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	CHG
0.72±0.50	PAN 70	HBC	+

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
small	CLINE 73	MPWA	$K^- d \rightarrow (\Lambda\pi^-)p$

Σ(1480) REFERENCES
(PRODUCTION EXPERIMENTS)

ENGELEN 80 NP B167 61 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)
MAST 75 PR D11 3078 +Alston-Garnjost, Bangerter+ (LBL)
CLINE 73 LNC 6 205 +Laumann, Mapp (WISC) IJP
HANSON 71 PR D4 1296 +Kalmus, Louie (LBL) I
MILLER 70 Duke Conf. 229 (PURD)
PAN 70 PR D2 49 +Forman, Ko, Hagopian, Selove (PENN)
    Also 69 PRL 23 808 Pan, Forman (PENN) I
    Also 69B PRL 23 806 Pan, Forman (PENN) I

Σ(1560) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

This entry lists peaks reported in mass spectra around 1560 MeV without implying that they are necessarily related.

DIONISI 78B observes a 6 standard-deviation enhancement at 1553 MeV in the charged $\Lambda/\Sigma\pi$ mass spectra from $K^- p \to (\Lambda/\Sigma)\pi K\overline{K}$ at 4.2 GeV/c. In a CERN ISR experiment, LOCKMAN 78 reports a narrow 6 standard-deviation enhancement at 1572 MeV in $\Lambda\pi^\pm$ from the reaction $pp \to \Lambda\pi^+\pi^- X$. These enhancements are unlikely to be associated with the Σ(1580) (which has not been confirmed by several recent experiments – see the next entry in the Listings).

CARROLL 76 observes a bump at 1550 MeV (as well as one at 1580 MeV) in the isospin-1 $\overline{K}N$ total cross section, but uncertainties in cross section measurements outside the mass range of the experiment preclude estimating its significance.

See also MEADOWS 80 for a review of this state.

Σ(1560) MASS
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1553±7	121	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
1572±4	40	LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

Σ(1560) WIDTH
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
79±30	121	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
15± 6	40	[1] LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

Σ(1560) DECAY MODES
(PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$\Lambda\pi$
Γ_2	$\Sigma\pi$

Σ(1560) BRANCHING RATIOS
(PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/[\Gamma(\Lambda\pi) + \Gamma(\Sigma\pi)]$ $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.35±0.12	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$

$\Gamma(\Lambda\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
seen	LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

Σ(1560) FOOTNOTES
(PRODUCTION EXPERIMENTS)

[1] The width observed by LOCKMAN 78 is consistent with experimental resolution.

Σ(1560) REFERENCES
(PRODUCTION EXPERIMENTS)

MEADOWS	80	Toronto Conf. 283		(CINC)
DIONISI	78B	PL 78B 154	+Armenteros, Diaz	(CERN, AMST, NIJM, OXF) I
LOCKMAN	78	CEN DPHPE 78-01	+Meyer, Rander, Poster, Schlein+	(UCLA, SACL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I

Σ(1580) D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Seen in the isospin-1 $\overline{K}N$ cross section at BNL (LI 73, CARROLL 76) and in a partial-wave analysis of $K^- p \to \Lambda\pi^0$ for c.m. energies 1560–1600 MeV by LITCHFIELD 74. LITCHFIELD 74 finds $J^P = 3/2^-$. Not seen by ENGLER 78 or by CAMERON 78C (with larger statistics in $K^0_L p \to \Lambda\pi^+$ and $\Sigma^0\pi^+$).

Σ(1580) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1583±4	[1] CARROLL	76	DPWA	Isospin-1 total σ
1582±4	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

Σ(1580) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
15	[1] CARROLL	76	DPWA	Isospin-1 total σ
11±4	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

Σ(1580) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(1580) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.03±0.01	[2] LITCHFIELD	74	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1580) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
not seen	CAMERON	78C	HBC	$K^0_L p \to \Lambda\pi^+$
not seen	ENGLER	78	HBC	$K^0_L p \to \Lambda\pi^+$
+0.10±0.02	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1580) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
not seen	CAMERON	78C	HBC	$K^0_L p \to \Sigma^0\pi^+$
not seen	ENGLER	78	HBC	$K^0_L p \to \Sigma^0\pi^+$
+0.03±0.04	[2] LITCHFIELD	74	DPWA	$\overline{K}N$ multichannel

Σ(1580) FOOTNOTES

[1] CARROLL 76 sees a total-cross-section bump with $(J+1/2)\ \Gamma_{\text{el}}\ /\ \Gamma_{\text{total}} = 0.06$.

[2] The main effect observed by LITCHFIELD 74 is in the $\Lambda\pi$ final state; the $\overline{K}N$ and $\Sigma\pi$ couplings are estimated from a multichannel fit including total-cross-section data of LI 73.

Σ(1580) REFERENCES

CAMERON	78C	NP B132 189	+Capiluppi+	(BGNA, EDIN, GLAS, PISA, RHEL) I
ENGLER	78	PR D18 3061	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
LITCHFIELD	74	PL 51B 509		(CERN) IJP
LI	73	Purdue Conf. 283		(BNL) I

OTHER RELATED PAPERS

ENGLER	76	PL 63B 231	+Keyes, Kraemer, Schlereth, Tanaka+	(CMU, ANL) I

Σ(1620) S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The S_{11} state at 1697 MeV reported by VANHORN 75 is tentatively listed under the Σ(1750). CARROLL 76 sees two bumps in the isospin-1 total cross section near this mass.

Production experiments are listed separately in the next entry.

Σ(1620) MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
1600 ± 6	[1] MORRIS 78	DPWA	$K^- n \to \Lambda\pi^-$
1608 ± 5	[2] CARROLL 76	DPWA	Isospin-1 total σ
1633 ± 10	[3] CARROLL 76	DPWA	Isospin-1 total σ
1630 ± 10	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
1620	KIM 71	DPWA	K-matrix analysis

Σ(1620) WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
87 ± 19	[1] MORRIS 78	DPWA	$K^- n \to \Lambda\pi^-$
15	[2] CARROLL 76	DPWA	Isospin-1 total σ
10	[3] CARROLL 76	DPWA	Isospin-1 total σ
65 ± 20	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
40	KIM 71	DPWA	K-matrix analysis

Σ(1620) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(1620) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.22 ± 0.02	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
0.05	KIM 71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1620) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.12 ± 0.02	[1] MORRIS 78	DPWA	$K^- n \to \Lambda\pi^-$
not seen	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
0.15	KIM 71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1620) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
not seen	HEPP 76B	DPWA	$K^- N \to \Sigma\pi$
0.40 ± 0.06	LANGBEIN 72	IPWA	$\overline{K}N$ multichannel
0.08	KIM 71	DPWA	K-matrix analysis

Σ(1620) FOOTNOTES

[1] MORRIS 78 obtains an equally good fit without including this resonance.

[2] Total cross-section bump with $(J+1/2)\ \Gamma_{\text{el}}\ /\ \Gamma_{\text{total}}$ is 0.06 seen by CARROLL 76.

[3] Total cross-section bump with $(J+1/2)\ \Gamma_{\text{el}}\ /\ \Gamma_{\text{total}}$ is 0.04 seen by CARROLL 76.

Σ(1620) REFERENCES

MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP

Σ(1620) Production Experiments

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the previous entry.

The results of CRENNELL 69B at 3.9 GeV/c are not confirmed by SABRE 70 at 3.0 GeV/c. However, at 4.5 GeV/c, AMMANN 70 sees a peak at 1642 MeV which on the basis of branching ratios they do not associate with the Σ(1670). See MILLER 70 for a review of these conflicts.

Σ(1620) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
1642 ± 12		AMMANN 70	DBC		$K^- N$ 4.5 GeV/c
1618 ± 3	20	BLUMENFELD 69	HBC	+	$K^0_L p$
1619 ± 8		CRENNELL 69B	DBC	±	$K^- N \to \Lambda\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1616 ± 8		CRENNELL 68	DBC	±	See CRENNELL 69B

Σ(1620) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
55 ± 24		AMMANN 70	DBC		$K^- N$ 4.5 GeV/c
30 ± 10	20	BLUMENFELD 69	HBC	+	
72^{+22}_{-15}		CRENNELL 69B	DBC	±	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
66 ± 16		CRENNELL 68	DBC	±	See CRENNELL 69B

Σ(1620) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma(1385)\pi$
Γ_6	$\Lambda(1405)\pi$

Σ(1620) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda\pi\pi)/\Gamma(\Lambda\pi)$ Γ_4/Γ_2

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
~ 2.5	14	BLUMENFELD 69	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.4 ± 0.4	AMMANN 70	DBC		$K^- p$ 4.5 GeV/c
0.0 ± 0.1	CRENNELL 68	DBC	−	See CRENNELL 69B

$\Gamma(\Lambda\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*	*TECN*	*CHG*
large	CRENNELL 68	DBC	±

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ Γ_5/Γ_2

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
<0.3	95	AMMANN 70	DBC		$K^- p$ 4.5 GeV/c
0.2 ± 0.1		CRENNELL 68	DBC	±	

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.1	95	AMMANN 70	DBC	$K^- N$ 4.5 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Lambda\pi)$ Γ_6/Γ_2

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.7 ± 0.4	AMMANN 70	DBC	$K^- p$ 4.5 GeV/c

Σ(1620) REFERENCES (PRODUCTION EXPERIMENTS)

AMMANN	70	PRL 24 327	+Garfinkel, Carmony, Gutay+	(PURD, IND)
Also	73	PR D7 1345	Ammann, Carmony, Garfinkel+	(PURD, IUPU)
MILLER	70	Duke Conf. 229		(PURD)
SABRE	70	NP B16 201	Barloutaud, Merril, Schever+	(SABRE Collab.)
BLUMENFELD	69	PL 29B 58	+Kalbfleisch	(BNL) I
CRENNELL	69B	Lund Paper 183	+Karshon, Lai, O'Neil, Scarr+	(BNL, CUNY) I
Results are quoted in LEVI-SETTI 69C.				
Also	69C	Lund Conf.	Levi-Setti	(EFI)
CRENNELL	68	PRL 21 648	+Delaney, Flaminio, Karshon+	(BNL, CUNY) I

$\Sigma(1660)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

Σ(1660) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1630 to 1690 OUR ESTIMATE				
1665.1±11.2	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1670 ±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1676 ±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1668 ±25	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1670 ±20	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1565 or 1597	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1660 ±30	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1671 ± 2	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

Σ(1660) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 to 200 OUR ESTIMATE	Our best guess is 100 MeV.			
81.5± 22.2	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
152 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
38 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
120 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
230^{+165}_{-60}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
250 ±110	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
202 or 217	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80 ± 40	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
81 ± 10	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

Σ(1660) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–30 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen

Σ(1660) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ $\qquad \Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.3 OUR ESTIMATE				
0.12±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.10±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.04	GOPAL	77	DPWA	See GOPAL 80
0.27 or 0.29	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1660) \to \Lambda\pi$ $\qquad (\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$0.12^{+0.12}_{-0.04}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.10 or −0.11	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.04±0.02	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.16±0.01	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1660) \to \Sigma\pi$ $\qquad (\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.13±0.04	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
−0.16±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.11±0.01	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.34 or −0.37	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$

Σ(1660) FOOTNOTES

[1] The evidence of KOISO 85 is weak.
[2] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[3] From solution 1 of BAILLON 75; not present in solution 2.
[4] From solution 2 of PONTE 75; not present in solution 1.

Σ(1660) REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
KANE	74	LBL-2452		(LBL) IJP

NOTE ON THE Σ(1670) REGION

Production experiments: The measured $\Sigma\pi/\Sigma\pi\pi$ branching ratio for produced $\Sigma(1670)$'s is strongly dependent on momentum transfer. This was first discovered by EBERHARD 69, who suggested that there exist two Σ resonances with the same mass and quantum numbers: one with a large $\Sigma\pi\pi$ [mainly $\Lambda(1405)\pi$] decay mode produced peripherally, and the other with a large $\Sigma\pi$ decay mode produced at larger angles. These results were confirmed by AGUILAR-BENITEZ 70, ASPELL 74, ESTES 74, and TIMMERMANS 76. The most likely quantum numbers for both the $\Sigma\pi$ and the $\Lambda(1405)\pi$ states are D_{13}. There is also possibly a third Σ, the Σ(1690) in the Listings, the main evidence for which is a large $\Lambda\pi/\Sigma\pi$ branching ratio. These topics have been reviewed by EBERHARD 73 and by MILLER 70.

Formation experiments: Two states are also observed near this mass in formation experiments. One of these, the $\Sigma(1670)D_{13}$, has the same quantum numbers as those observed in production and has a large $\Sigma\pi/\Sigma\pi\pi$ branching ratio; it may well be the Σ(1670) produced at larger angles (see TIMMERMANS 76). The other state, the $\Sigma(1660)P_{11}$, has different quantum numbers from those seen in production, and its $\Sigma\pi/\Sigma\pi\pi$ branching ratio is unknown. Thus its relation to the produced $\Sigma(1670)$'s is obscure.

Σ(1670) D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

Results from production experiments are listed separately in the next entry.

Σ(1670) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1665 to 1685 OUR ESTIMATE				
1665.1± 4.1	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1682 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1670 ± 6	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
1685 ±20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1659 $^{+12}_{-5}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1670 ± 2	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1667 or 1668	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1650	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
1671 ± 3	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
1655 ± 2	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

Σ(1670) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
40 to 80 OUR ESTIMATE	Our best guess is 60 MeV.			
65.0± 7.3	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
79 ±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
56 ±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
50 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
56 ± 3	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
85 ±25	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
32 ±11	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
79 ± 6	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
46 or 46	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
44 ±11	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
76 ± 5	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

Σ(1670) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	7–13 %
Γ_2	$\Lambda\pi$	5–15 %
Γ_3	$\Sigma\pi$	30–60 %
Γ_4	$\Lambda\pi\pi$	
Γ_5	$\Sigma\pi\pi$	
Γ_6	$\Sigma(1385)\pi$	
Γ_7	$\Sigma(1385)\pi$, *S*-wave	
Γ_8	$\Lambda(1405)\pi$	
Γ_9	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

Σ(1670) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.07 to 0.13 OUR ESTIMATE				
0.10±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.11±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08±0.03	GOPAL	77	DPWA	See GOPAL 80
0.07 or 0.07	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.17 ±0.03	[2] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
0.13 ±0.02	[2] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
+0.10 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.06 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.09 ±0.02	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
+0.018±0.060	DEVENISH	74B		Fixed-*t* dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.08 or +0.08	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.05	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
0.08 ±0.01	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
0.17 ±0.01	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.20±0.02	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
+0.21±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.20±0.01	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
+0.21±0.03	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.18 or +0.17	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Gamma(\Lambda\pi\pi)/\Gamma_{\rm total}$ — Γ_4/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.11	ARMENTEROS	68E	HBC	$K^- p$ (Γ_1=0.09)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma(1385)\pi$, *S*-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.11±0.03	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17±0.02	[3] SIMS	68	DBC	$K^- N \to \Lambda\pi\pi$

$\Gamma(\Sigma\pi\pi)/\Gamma_{\rm total}$ — Γ_5/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.14	[4] ARMENTEROS	68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma(\Lambda(1405)\pi)/\Gamma_{\rm total}$ — Γ_8/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	ARMENTEROS	68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma_i\Gamma_f/\Gamma^2_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1405)\pi$ — $\Gamma_1\Gamma_8/\Gamma^2$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.007±0.002	[5] BRUCKER	70	DBC	$K^- N \to \Sigma\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.03	BERLEY	69	HBC	$K^- p$ 0.6–0.82 GeV/*c*

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ — Γ_8/Γ_6

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.23±0.08	BRUCKER	70	DBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.081±0.016	[6] CAMERON	77	DPWA	*P*-wave decay

Σ(1670) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] Results are with and without an S_{11} Σ(1620) in the fit.

[3] SIMS 68 uses only cross-section data. Result used as upper limit only.

[4] Ratio only for $\Sigma 2\pi$ system in I = 1, which cannot be Σ(1385).

[5] Assuming the $\Lambda(1405)\pi$ cross-section bump is due only to $3/2^-$ resonance.

[6] The CAMERON 77 upper limit on *F*-wave decay is 0.03.

Σ(1670) REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEID, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BRUCKER	70	Duke Conf. 155	+Harrison, Sims, Albright, Chandler+	(FSU) I
BERLEY	69	PL 30B 430	+Hart, Rahm, Willis, Yamamoto	(BNL)
ARMENTEROS	68E	PL 28B 521	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFT, BRAN)

Σ(1670) Bumps

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the preceding entry.

Probably there are two states at the same mass with the same quantum numbers, one decaying to $\Sigma\pi$ and $\Lambda\pi$, the other to $\Lambda(1405)\pi$. See the note in front of the preceding entry.

Σ(1670) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1670 ± 4		[1] CARROLL	76	DPWA		Isospin-1 total σ
1675 ± 10		[2] HEPP	76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
1665 ± 1		APSELL	74	HBC		$K^- p$ 2.87 GeV/c
1688 ± 2 or 1683 ± 5	1200	BERTHON	74	HBC	0	Quasi-2-body σ
1670 ± 6		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma\pi\pi$ 4 GeV
1668 ± 10		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma 3\pi$ 4 GeV
1660 ± 10		ALVAREZ	63	HBC	+	$K^- p$ 1.51 GeV/c

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1668 ± 10	150	[3] FERRERSORIA	81	OMEG	−	$\pi^- p$ 9,12 GeV/c
1655 to 1677		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
1665 ± 5		BUGG	68	CNTR		$K^- p$, d total σ
1661 ± 9	70	PRIMER	68	HBC	+	See BARNES 69E
1685		ALEXANDER	62C	HBC	−0	$\pi^- p$ 2–2.2 GeV/c

Σ(1670) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
67.0 ± 2.4		APSELL	74	HBC		$K^- p$ 2.87 GeV/c
110 ± 12		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma\pi\pi$ 4 GeV
135^{+40}_{-30}		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma 3\pi$ 4 GeV
40 ± 10		ALVAREZ	63	HBC	+	

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
90 ± 20	150	[3] FERRERSORIA	81	OMEG	−	$\pi^- p$ 9,12 GeV/c
52		[1] CARROLL	76	DPWA		Isospin-1 total σ
48 to 63		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
30 ± 15		BUGG	68	CNTR		
60 ± 20	70	PRIMER	68	HBC	+	See BARNES 69E
45		ALEXANDER	62C	HBC	−0	

Σ(1670) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma\pi\pi$
Γ_6	$\Sigma(1385)\pi$
Γ_7	$\Lambda(1405)\pi$

Σ(1670) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ Γ_1/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.03		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
<0.10		BERTHON	74	HBC	0	Quasi-2-body σ
<0.2		AGUILAR-...	70B	HBC		
<0.26		BARNES	69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.025		BUGG	68	CNTR	0	Assuming $J = 3/2$
<0.24	0	PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
<0.6		LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
<0.19	0	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c
≥ 0.5 ± 0.25		SMITH	63	HBC	−0	

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ Γ_2/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.76 ± 0.09		ESTES	74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
0.45 ± 0.15		BARNES	69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.15 ± 0.07		HUWE	69	HBC	+	
0.11 ± 0.06	33	BUTTON-...	68	HBC	+	$K^- p$ 1.7 GeV/c

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≤ 0.45 ± 0.07		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
0.55 ± 0.11		BERTHON	74	HBC	0	Quasi-2-body σ
0	0	PRIMER	68	HBC	+	See BARNES 69E
<0.6		LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
1.2	130	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c
1.2		SMITH	63	HBC	−0	

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi)$ Γ_4/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.6		LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
0.56	90	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c
0.17		SMITH	63	HBC	−0	

$\Gamma(\Sigma\pi\pi)/\Gamma(\Sigma\pi)$ Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
largest at small angles		ESTES	74	HBC	0	$K^- p$ 2.1,2.6 GeV/c

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.2		[2] HEPP	76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
0.56	180	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi)$ Γ_7/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.8 ± 0.3 to 0.02 ± 0.07		[3,4] TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
largest at small angles		ESTES	74	HBC	±	$K^- p$ 2.1,2.6 GeV/c
3.0 ± 1.6	50	LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.58 ± 0.20	17	PRIMER	68	HBC	+	See BARNES 69E

$\Gamma(\Sigma\pi)/\Gamma(\Sigma\pi\pi)$ Γ_3/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
varies with prod. angle	[5] APSELL	74	HBC	+	$K^- p$ 2.87 GeV/c
1.39 ± 0.16	BERTHON	74	HBC	0	Quasi-2-body σ
2.5 to 0.24	[4] EBERHARD	69	HBC		$K^- p$ 2.6 GeV/c
<0.4	BIRMINGHAM	66	HBC	+	$K^- p$ 3.5 GeV/c
0.30 ± 0.15	LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi\pi)$ Γ_7/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.97 ± 0.08	TIMMERMANS	76	HBC		$K^- p$ 4.2 GeV/c
1.00 ± 0.02	APSELL	74	HBC		$K^- p$ 2.87 GeV/c
$0.90^{+0.10}_{-0.16}$	EBERHARD	65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ Γ_7/Γ_6

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.8	EBERHARD	65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi\pi)$ Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.35 ± 0.2	BIRMINGHAM	66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi\pi)$ Γ_2/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.2	BIRMINGHAM	66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/[\Gamma(\Lambda\pi) + \Gamma(\Sigma\pi)]$ $\Gamma_2/(\Gamma_2+\Gamma_3)$

VALUE	DOCUMENT ID		TECN
<0.6	AGUILAR-...	70B	HBC

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Sigma\pi)$ Γ_6/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
≤ 0.21 ± 0.05	TIMMERMANS	76	HBC	$K^- p$ 4.2 GeV/c

Σ(1670) QUANTUM NUMBERS (PRODUCTION EXPERIMENTS)

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$J^P = 3/2^-$	400	BUTTON-...	68	HBC	±	$\Sigma^0\pi$
$J^P = 3/2^-$		EBERHARD	67	HBC	+	$\Lambda(1405)\pi$
$J^P = 3/2^+$		LEVEQUE	65	HBC		$\Lambda(1405)\pi$

Σ(1670) FOOTNOTES

[1] Total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.23$.
[2] Enhancements in $\Sigma\pi$ and $\Sigma\pi\pi$ cross sections.
[3] Backward production in the $\Lambda\pi^- K^+$ final state.
[4] Depending on production angle.
[5] APSELL 74, ESTES 74, and TIMMERMANS 76 find strong branching ratio dependence on production angle, as in earlier production experiments.

Σ(1670) REFERENCES (PRODUCTION EXPERIMENTS)

FERRERSORIA 81 NP B178 373 +Treille, Rivet, Volte+ (CERN, CDEF, EPOL, LALO)
CARROLL 76 PRL 37 806 +Chiang, Kycia, Li, Mazur, Michael+ (BNL) I
HEPP 76 NP B115 82 +Braun, Grimm, Stroebele+ (CERN, HEID, MPIM) I
TIMMERMANS 76 NP B112 77 +Engelen+ (NIJM, CERN, AMST, OXF) JP
APSELL 74 PR D10 1419 +Ford, Gourevitch+ (BRAN, UMD, SYRA, TUFT) I
BERTHON 74 NC 21A 146 +Tristram+ (CDEF, RHEL, SACL, STRB)
ESTES 74 LBL-3827 Thesis (LBL)
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
BARNES 69E BNL 13823 +Chung, Eisner, Flaminio+ (BNL, SYRA)
EBERHARD 69 PRL 22 200 +Friedman, Pripstein, Ross (LRL)
HUWE 69 PR 180 1824 (LRL)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
BUTTON-... 68 PRL 21 1123 Button-Shafer (MASA, LRL) JP
PRIMER 68 PRL 20 610 +Goldberg, Jaeger, Barnes, Dornan+ (SYRA, BNL)
EBERHARD 67 PR 163 1446 +Pripstein, Shively, Kruse, Swanson (LRL, ILL) IJP
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) IJ
EBERHARD 65 PRL 14 466 +Shively, Ross, Siegal, Ficenec+ (LRL, ILL) I
LEVEQUE 65 PL 18 69 + (SACL, EPOL, GLAS, LOIC, OXF, RHEL) JP
ALVAREZ 63 PRL 10 184 +Alston, Ferro-Luzzi, Huwe+ (LRL) I
SMITH 63 Athens Conf. 67 (LRL)
ALEXANDER 62C CERN Conf. 320 +Jacobs, Kalbfleisch, Miller+ (LRL) I

Σ(1690) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

See the note preceding the Σ(1670) Listings. Seen in production experiments only, mainly in $\Lambda\pi$.

Σ(1690) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1698±20	70	[1] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1707±20	40	[2] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1698±20	15	ADERHOLZ	69	HBC	+	$\pi^+ p$ 8 GeV/c
1682± 2	46	BLUMENFELD	69	HBC	+	$K^0_L p$
1700±20		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
1694±24	60	[3] PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
1700± 6		[4] SIMS	68	HBC	−	$K^- N \rightarrow \Lambda\pi\pi$
1715±12	30	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

Σ(1690) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
240± 60	70	[1] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
130^{+100}_{-60}	40	[2] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
142± 40	15	ADERHOLZ	69	HBC	+	$\pi^+ p$ 8 GeV/c
25± 10	46	BLUMENFELD	69	HBC	+	$K^0_L p$
130± 25		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
105± 35	60	[3] PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
62± 14		[4] SIMS	68	HBC	−	$K^- N \rightarrow \Lambda\pi\pi$
100± 35	30	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

Σ(1690) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Sigma(1385)\pi$
Γ_5	$\Lambda\pi\pi$ (including $\Sigma(1385)\pi$)

Σ(1690) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.2		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.4±0.25	18	COLLEY	67	HBC	+	6/30 events

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.4	90	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.3±0.3		COLLEY	67	HBC	+	4/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.5	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c

$\Gamma(\Lambda\pi\pi$ (including $\Sigma(1385)\pi))/\Gamma(\Lambda\pi)$ Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.0±0.6	BLUMENFELD	69	HBC	+	31/15 events
0.5±0.25	COLLEY	67	HBC	+	15/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi\pi$ (including $\Sigma(1385)\pi))$ Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
large	SIMS	68	HBC	−	$K^- N \rightarrow \Lambda\pi\pi$
small	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

Σ(1690) FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] From $\pi^+ p \rightarrow (\Lambda\pi^+)K^+$. $J > 1/2$ is not required by the data.
[2] From $\pi^+ p \rightarrow (\Lambda\pi^+)(K\pi)^+$. $J > 1/2$ is indicated, but large background precludes a definite conclusion.
[3] See the Σ(1670) Listings. AGUILAR-BENITEZ 70B with three times the data of PRIMER 68 find no evidence for the Σ(1690).
[4] This analysis, which is difficult and requires several assumptions and shows no unambiguous Σ(1690) signal, suggests $J^P = 5/2^+$. Such a state would lead all previously known Y^* trajectories.

Σ(1690) REFERENCES (PRODUCTION EXPERIMENTS)

GODDARD 79 PR D19 1350 +Key, Luste, Prentice, Yoon, Gordon+ (TNTO, BNL) IJ
AGUILAR-... 70B PRL 25 58 Aguilar-Benitez, Barnes, Bassano+ (BNL, SYRA)
ADERHOLZ 69 NP B11 259 +Bartsch+ (AACH, BERL, CERN, JAGL, WARS) I
BLUMENFELD 69 PL 29B 58 +Kalbfleisch (BNL) I
MOTT 69 PR 177 1966 +Ammar, Davis, Kropac, Slate+ (NWES, ANL) I
Also 67 PRL 18 266 Derrick, Fields, Loken, Ammar+ (ANL, NWES) I
PRIMER 68 PRL 20 610 +Goldberg, Jaeger, Barnes, Dornan+ (SYRA, BNL) I
SIMS 68 PRL 21 1413 +Albright, Bartley, Meer+ (FSU, TUFT, BRAN) I
COLLEY 67 PL 24B 489 (BIRM, GLAS, LOIC, MUNI, OXF, RHEL) I

Σ(1750) S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

There is evidence for this state in many partial-wave analyses, but with wide variations in the mass, width, and couplings. The latest analyses indicated significant couplings to $N\overline{K}$ and $\Lambda\pi$, as well as to $\Sigma\eta$ whose threshold is at 1746 MeV (JONES 74).

Σ(1750) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1730 to 1800 OUR ESTIMATE				
1756±10	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1770±10	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1770±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1800 or 1813	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1715±10	[2] CARROLL	76	DPWA	Isospin-1 total σ
1730	DEBELLEFON	76	IPWA	$K^- p \rightarrow \Lambda\pi^0$
1780±30	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 1)
1700±30	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$ (sol. 2)
1697^{+20}_{-10}	VANHORN	75	DPWA	$K^- p \rightarrow \Lambda\pi^0$
1785±12	CHU	74	DBC	Fits $\sigma(K^- n \rightarrow \Sigma^- \eta)$
1760± 5	[3] JONES	74	HBC	Fits $\sigma(K^- p \rightarrow \Sigma^0 \eta)$
1739±10	PREVOST	74	DPWA	$K^- N \rightarrow \Sigma(1385)\pi$

$\Sigma(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 160 OUR ESTIMATE	Our best guess is 90 MeV.			
64 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
161 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
60 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
117 or 119	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
10	[2] CARROLL	76	DPWA	Isospin-1 total σ
110	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
140 ± 30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
160 ± 50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
66^{+14}_{-12}	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
89 ± 33	CHU	74	DBC	Fits $\sigma(K^-n \to \Sigma^-\eta)$
$92\pm\ 7$	[3] JONES	74	HBC	Fits $\sigma(K^-p \to \Sigma^0\eta)$
108 ± 20	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$\Sigma(1750)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–40 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	<8 %
Γ_4	$\Sigma\eta$	15–55 %
Γ_5	$\Sigma(1385)\pi$	
Γ_6	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1750)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ $\qquad\Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.4 OUR ESTIMATE				
0.14 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.33 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.06 or 0.05	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1750) \to \Lambda\pi$ $\qquad(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$0.04\ \pm0.03$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.10 or -0.09	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
-0.12	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
$-0.12\ \pm0.02$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
$-0.13\ \pm0.03$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
$-0.13\ \pm0.04$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
-0.120 ± 0.077	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma\pi$ $\qquad(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09 ± 0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$+0.06$ or $+0.06$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.13 ± 0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma\eta$ $\qquad(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.23 ± 0.01	[3] JONES	74	HBC	Fits $\sigma(K^-p \to \Sigma^0\eta)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	CLINE	69	DBC	Threshold bump

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma(1385)\pi$ $\qquad(\Gamma_1\Gamma_5)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.18\pm0.15$	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1750) \to \Lambda(1520)\pi$ $\qquad(\Gamma_1\Gamma_6)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.032 ± 0.021	CAMERON	77	DPWA	P-wave decay

$\Sigma(1750)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] A total cross-section bump with $(J+1/2)\ \Gamma_{\text{el}}\ /\ \Gamma_{\text{total}} = 0.30$.

[3] An S-wave Breit-Wigner fit to the threshold cross section with no background and errors statistical only.

$\Sigma(1750)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
CHU	74	NC 20A 35	+Bartley+	(PLAT, TUFT, BRAN) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
JONES	74	NP B73 141		(CHIC) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
CLINE	69	LNC 2 407	+Laumann, Mapp	(WISC)

$\Sigma(1770)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: $*$

OMITTED FROM SUMMARY TABLE

Evidence for this state now rests solely on solution 1 of BAILLON 75, (see the footnotes) but the $\Lambda\pi$ partial-wave amplitudes of this solution are in disagreement with amplitudes from most other $\Lambda\pi$ analyses.

$\Sigma(1770)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1738 ± 10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
1770 ± 20	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1772	[3] KANE	72	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(1770)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
72 ± 10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
80 ± 30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
80	[3] KANE	72	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(1770)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1770)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ $\qquad\Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.14 ± 0.04	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1770) \to \Lambda\pi$ $\qquad(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$<\ 0.04$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.08 ± 0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1770) \to \Sigma\pi$ $\qquad(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$<\ 0.04$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.108	[3] KANE	72	DPWA	$K^-p \to \Sigma\pi$

$\Sigma(1770)$ FOOTNOTES

[1] Required to fit the isospin-1 total cross section of CARROLL 76 in the $\overline{K}N$ channel. The addition of new K^-p polarization and K^-n differential cross-section data in GOPAL 80 find it to be more consistent with the $\Sigma(1660)\ P_{11}$.

[2] From solution 1 of BAILLON 75; not present in solution 2.

[3] Not required in KANE 74, which supersedes KANE 72.

$\Sigma(1770)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
KANE	74	LBL-2452		(LBL) IJP
KANE	72	PR D5 1583		(LBL)

$\Sigma(1775)$ D_{15}

$I(J^P) = 1(\frac{5}{2}^-)$ Status: ∗∗∗∗

Discovered by GALTIERI 63, this resonance plays the same role as cornerstone for isospin-1 analyses in this region as the $\Lambda(1820)$ does in the isospin-0 channel.

For most results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

$\Sigma(1775)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1770 to 1780 OUR ESTIMATE			
1778± 5	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1777± 5	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1774± 5	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1775±10	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
1774±10	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$
1772± 6	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1772 or 1777	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1765	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1775)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
105 to 135 OUR ESTIMATE Our best guess is 120 MeV.			
137±10	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
116±10	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
130±10	GOPAL 77	DPWA	$\overline{K}N$ multichannel
125±15	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
146±18	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$
154±10	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
102 or 103	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
120	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1775)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	37–43%
Γ_2	$\Lambda\pi$	14–20%
Γ_3	$\Sigma\pi$	2–5%
Γ_4	$\Sigma(1385)\pi$	8–12%
Γ_5	$\Sigma(1385)\pi$, D-wave	
Γ_6	$\Lambda(1520)\pi$	17–23%
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

CONSTRAINED FIT INFORMATION

An overall fit to 8 branching ratios uses 16 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 = 26.4$ for 11 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−10			
x_3	−20	2		
x_4	−51	5	10	
x_6	−47	5	9	24
	x_1	x_2	x_3	x_4

$\Sigma(1775)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances. Also, the errors quoted do not include uncertainties due to the parametrization used in the partial-wave analyses and are thus too small.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.37 to 0.43 OUR ESTIMATE			
0.430±0.026 OUR FIT Error includes scale factor of 1.9.			
0.391±0.017 OUR AVERAGE			
0.40 ±0.02	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.37 ±0.03	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.41 ±0.03	GOPAL 77	DPWA	See GOPAL 80
0.37 or 0.36	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.255±0.013 OUR FIT Error includes scale factor of 1.1.			
−0.262±0.015 OUR AVERAGE			
−0.28 ±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.25 ±0.02	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.28\ ^{+0.04}_{-0.05}$	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$
−0.259±0.048	DEVENISH 74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.29 or −0.28	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
−0.30	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.095±0.014 OUR FIT Error includes scale factor of 1.6.			
0.098±0.016 OUR AVERAGE Error includes scale factor of 1.8.			
+0.13 ±0.02	GOPAL 77	DPWA	$\overline{K}N$ multichannel
0.09 ±0.01	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.08 or −0.08	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda(1520)\pi$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.286±0.016 OUR FIT Error includes scale factor of 1.9.			
0.303±0.009 OUR AVERAGE Signs on measurements were ignored.			
−0.305±0.010	[2] CAMERON 77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
0.31 ±0.02	BARLETTA 72	DPWA	$K^- p \to \Lambda(1520)\pi^0$
0.27 ±0.03	ARMENTEROS65C	HBC	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.189±0.010 OUR FIT			
0.188±0.010 OUR AVERAGE Signs on measurements were ignored.			
−0.184±0.011	[3] CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$
+0.20 ±0.02	PREVOST 74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.32 ±0.06	SIMS 68	DBC	$K^- N \to \Lambda\pi\pi$
0.24 ±0.03	ARMENTEROS67C	HBC	$K^- p \to \Lambda\pi\pi$

$\Gamma(\Lambda\pi)/\Gamma(N\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.35±0.04 OUR FIT Error includes scale factor of 1.2.			
0.33±0.05	UHLIG 67	HBC	$K^- p$ 0.9 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.12	[4] ARMENTEROS68C	HDBC	$K^- N \to \Sigma\pi\pi$

$\Gamma(\Sigma(1385)\pi)/\Gamma(N\overline{K})$ Γ_4/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.192±0.031 OUR FIT Error includes scale factor of 1.4.			
0.25 ±0.09	UHLIG 67	HBC	$K^- p$ 0.9 GeV/c

$\Gamma(\Lambda(1520)\pi)/\Gamma(N\overline{K})$ Γ_6/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.44±0.07 OUR FIT Error includes scale factor of 2.3.			
0.28±0.05	UHLIG 67	HBC	$K^- p$ 0.9 GeV/c

$\Sigma(1775)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] This rate combines P-wave- and F-wave decays. The CAMERON 77 results for the separate P-wave- and F-wave decays are -0.303 ± 0.010 and -0.037 ± 0.014. The published signs have been changed here to be in accord with the baryon-first convention.

[3] The CAMERON 78 upper limit on G-wave decay is 0.03.

[4] For about 3/4 of this, the $\Sigma\pi$ system has $I = 0$ and is almost entirely $\Lambda(1520)$. For the rest, the $\Sigma\pi$ has $I = 1$, which is about what is expected from the known $\Sigma(1775) \to \Sigma(1385)\pi$ rate, as seen in $\Lambda\pi\pi$.

Σ(1775) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BARLETTA	72	NP B40 45		(EFI) IJP
Also	66	PRL 17 841	Fenster, Gelfand, Harmsen+	(CHIC, ANL, CERN) IJP
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFT, BRAN)
ARMENTEROS	67C	ZPHY 202 486	+Ferro-Luzzi+	(CERN, HEID, SACL)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL) IJP
GALTIERI	63	PL 6 296	+Hussain, Tripp	(LRL) IJ

$\Sigma(1840)\ P_{13}$

$I(J^P) = 1(\frac{3}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

For the time being, we list together here all resonance claims in the P_{13} wave between 1700 and 1900 MeV.

Σ(1840) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1798 or 1802	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1720± 30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1925±200	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1840± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

Σ(1840) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
93 or 93	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
65^{+50}_{-20}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
120±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

Σ(1840) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(1840) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0 or 0	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.37±0.13	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1840) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 or +0.03	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.11 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.06 ±0.04	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
+0.122±0.078	DEVENISH	74B		Fixed-t dispersion rel.
0.20 ±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1840) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04 or −0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.15±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

Σ(1840) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] From solution 1 of BAILLON 75; not present in solution 2.

Σ(1840) REFERENCES

MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP

$\Sigma(1880)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: **

OMITTED FROM SUMMARY TABLE

A P_{11} resonance is suggested by several partial-wave analyses, but with wide variations in the mass and other parameters. We list here all claims which lie well above the P_{11} Σ(1770).

Σ(1880) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1826±20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1870±10	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
1847 or 1863	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1960±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1985±50	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1898	[3] LEA	73	DPWA	Multichannel K-matrix
~ 1850	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
1950±50	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
1920±30	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
1850	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
1882±40	SMART	68	DPWA	$K^- N \to \Lambda\pi$

Σ(1880) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
86± 15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
80± 10	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
216 or 220	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
260± 40	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
220±140	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
222	[3] LEA	73	DPWA	Multichannel K-matrix
~ 30	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
200± 50	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
170± 40	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
200	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
222±150	SMART	68	DPWA	$K^- N \to \Lambda\pi$

Σ(1880) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$N\overline{K}^*(892)$, S=1/2, P-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, P-wave

Σ(1880) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27 or 0.27	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.31	[3] LEA	73	DPWA	Multichannel K-matrix
0.20	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
0.22	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1880) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24 or −0.24	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.12 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.05\ ^{+0.07}_{-0.02}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
−0.169±0.119	DEVENISH	74B		Fixed-t dispersion rel.
−0.30	[3] LEA	73	DPWA	Multichannel K-matrix
−0.09 ±0.04	BARBARO-...	70	DPWA	$K^- N \to \Lambda\pi$
−0.14 ±0.03	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$
−0.11 ±0.03	SMART	68	DPWA	$K^- N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1880) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.30 or +0.29	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
not seen	[3] LEA 73	DPWA	Multichannel K-matrix

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, $S=1/2$, P-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.05±0.03	[4] CAMERON 78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, $S=3/2$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.11±0.03	CAMERON 78B	DPWA	$K^-p \to N\overline{K}^*$

Σ(1880) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] From solution 1 of BAILLON 75; not present in solution 2.

[3] Only unconstrained states from table 1 of LEA 73 are listed.

[4] The published sign has been changed to be in accord with the baryon-first convention.

Σ(1880) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LEA	73	NP B56 77	+Martin, Moorhouse+	(RHEL, LOUC, GLAS, AARH) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP
BAILEY	69	UCRL 50617 Thesis		(LLL) IJP
SMART	68	PR 169 1330		(LRL) IJP

$\boxed{\Sigma(1915)\ F_{15}}$

$I(J^P) = 1(\frac{5}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66. For results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions in this region used to be listed in in a separate entry immediately following. They may be found in our 1986 edition (Physics Letters 170B).

Σ(1915) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1900 to 1935 OUR ESTIMATE			
1937±20	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
1894± 5	[1] CORDEN 77C		$K^-n \to \Sigma\pi$
1909± 5	[1] CORDEN 77C		$K^-n \to \Sigma\pi$
1920±10	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1900± 4	[2] CORDEN 76	DPWA	$K^-n \to \Lambda\pi^-$
1920±30	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
1914±10	HEMINGWAY 75	DPWA	$K^-p \to \overline{K}N$
1920^{+15}_{-20}	VANHORN 75	DPWA	$K^-p \to \Lambda\pi^0$
1920± 5	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
not seen	DECLAIS 77	DPWA	$\overline{K}N \to \overline{K}N$
1925 or 1933	[3] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1915	DEBELLEFON 76	IPWA	$K^-p \to \Lambda\pi^0$

Σ(1915) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
80 to 160 OUR ESTIMATE	Our best guess is 120 MeV.		
161±20	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
107±14	[1] CORDEN 77C		$K^-n \to \Sigma\pi$
85±13	[1] CORDEN 77C		$K^-n \to \Sigma\pi$
130±10	GOPAL 77	DPWA	$\overline{K}N$ multichannel
75±14	[2] CORDEN 76	DPWA	$K^-n \to \Lambda\pi^-$
70±20	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
85±15	HEMINGWAY 75	DPWA	$K^-p \to \overline{K}N$
102±18	VANHORN 75	DPWA	$K^-p \to \Lambda\pi^0$
162±25	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
171 or 173	[3] MARTIN 77	DPWA	$\overline{K}N$ multichannel
60	DEBELLEFON 76	IPWA	$K^-p \to \Lambda\pi^0$

Σ(1915) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–15 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	<5 %
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$\Sigma(1385)\pi$, F-wave	

The above branching fractions are our estimates, not fits or averages.

Σ(1915) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE			
0.03±0.02	[4] GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
0.14±0.05	ALSTON-... 78	DPWA	$\overline{K}N \to \overline{K}N$
0.11±0.04	HEMINGWAY 75	DPWA	$K^-p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.05±0.03	GOPAL 77	DPWA	See GOPAL 80
0.08 or 0.08	[3] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1915) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.09 ±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.10 ±0.01	[2] CORDEN 76	DPWA	$K^-n \to \Lambda\pi^-$
−0.06 ±0.02	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
−0.09 ±0.02	VANHORN 75	DPWA	$K^-p \to \Lambda\pi^0$
−0.087±0.056	DEVENISH 74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.09 or −0.09	[3] MARTIN 77	DPWA	$\overline{K}N$ multichannel
−0.10	DEBELLEFON 76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.17±0.01	[1] CORDEN 77C		$K^-n \to \Sigma\pi$
−0.15±0.02	[1] CORDEN 77C		$K^-n \to \Sigma\pi$
−0.19±0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
−0.16±0.03	KANE 74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.05 or −0.05	[3] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
<0.01	CAMERON 78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.039±0.009	[5] CAMERON 78	DPWA	$K^-p \to \Sigma(1385)\pi$

Σ(1915) FOOTNOTES

[1] The two entries for CORDEN 77C are from two different acceptable solutions.

[2] Preferred solution 3; see CORDEN 76 for other possibilities.

[3] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[4] The mass and width are fixed to the GOPAL 77 values due to the low elasticity.

[5] The published sign has been changed to be in accord with the baryon-first convention.

Σ(1915) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)

$\Sigma(1940)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

Not all analyses require this state. It is not required by the GOYAL 77 analysis of $K^- n \to (\Sigma\pi)^-$ nor by the GOPAL 80 analysis of $K^- n \to K^- n$. See also HEMINGWAY 75.

$\Sigma(1940)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1900 to 1950 OUR ESTIMATE			
1920 ± 50	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1950 ± 30	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
1949^{+40}_{-60}	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$
1935 ± 80	KANE 74	DPWA	$K^- p \to \Sigma\pi$
1940 ± 20	LITCHFIELD 74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
1950 ± 20	LITCHFIELD 74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1886 or 1893	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
1940	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$, F_{17} wave

$\Sigma(1940)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
150 to 300 OUR ESTIMATE	Our best guess is 220 MeV.		
170 ± 25	CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$
300 ± 80	GOPAL 77	DPWA	$\overline{K}N$ multichannel
150 ± 75	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
160^{+70}_{-40}	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$
330 ± 80	KANE 74	DPWA	$K^- p \to \Sigma\pi$
60 ± 20	LITCHFIELD 74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
70^{+30}_{-20}	LITCHFIELD 74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
157 or 159	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$\Sigma(1940)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	<20 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, S-wave	
Γ_6	$\Lambda(1520)\pi$	seen
Γ_7	$\Lambda(1520)\pi$, P-wave	
Γ_8	$\Lambda(1520)\pi$, F-wave	
Γ_9	$\Delta(1232)\overline{K}$	seen
Γ_{10}	$\Delta(1232)\overline{K}$, S-wave	
Γ_{11}	$\Delta(1232)\overline{K}$, D-wave	
Γ_{12}	$N\overline{K}^*(892)$	seen
Γ_{13}	$N\overline{K}^*(892)$, S=3/2, S-wave	

$\Sigma(1940)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
<0.2 OUR ESTIMATE			
<0.04	GOPAL 77	DPWA	$\overline{K}N$ multichannel
0.14 or 0.13	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.06 ± 0.03	GOPAL 77	DPWA	$\overline{K}N$ multichannel
-0.04 ± 0.02	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.05\ ^{+0.03}_{-0.02}$	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$
-0.153 ± 0.070	DEVENISH 74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •			
-0.15 or -0.14	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.08 ± 0.04	GOPAL 77	DPWA	$\overline{K}N$ multichannel
-0.14 ± 0.04	KANE 74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$+0.16$ or $+0.16$	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
< 0.03	CAMERON 77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
-0.11 ± 0.04	LITCHFIELD 74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, F-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
0.062 ± 0.021	CAMERON 77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
-0.08 ± 0.04	LITCHFIELD 74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, S-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.16 ± 0.05	LITCHFIELD 74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, D-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.14 ± 0.05	LITCHFIELD 74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
$+0.066 \pm 0.025$	[2] CAMERON 78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(1940) \to N\overline{K}^*(892)$ $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
-0.09 ± 0.02	[3] CAMERON 78B	DPWA	$K^- p \to N\overline{K}^*$

$\Sigma(1940)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

[3] Upper limits on the D_1 and D_3 waves are each 0.03.

$\Sigma(1940)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH)
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEID) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEID) IJP

$\Sigma(2000)\ S_{11}$

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

We list here all reported S_{11} states lying above the $\Sigma(1750)\ S_{11}$.

$\Sigma(2000)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1944 ± 15	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
1955 ± 15	GOPAL 77	DPWA	$\overline{K}N$ multichannel
1755 or 1834	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
2004 ± 40	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
215 ± 25	GOPAL 80	DPWA	$\overline{K}N \to \overline{K}N$
170 ± 40	GOPAL 77	DPWA	$\overline{K}N$ multichannel
413 or 450	[1] MARTIN 77	DPWA	$\overline{K}N$ multichannel
116 ± 40	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$

Baryon Full Listings

$\Sigma(2000), \Sigma(2030)$

$\Sigma(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda(1520)\pi$
Γ_5	$N\overline{K}^*(892)$, $S=1/2$, S-wave
Γ_6	$N\overline{K}^*(892)$, $S=3/2$, D-wave

$\Sigma(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ $\qquad\Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.51 ± 0.05	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.44 ± 0.05	GOPAL	77	DPWA	See GOPAL 80
0.62 or 0.57	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2000) \to \Lambda\pi$ $\qquad(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.08 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.19 or -0.18	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.07^{+0.02}_{-0.01}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2000) \to \Sigma\pi$ $\qquad(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.20\pm0.04$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$+0.26$ or $+0.24$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2000) \to \Lambda(1520)\pi$ $\qquad(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.081\pm0.021$	[2] CAMERON	77	DPWA	P-wave decay

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2000) \to N\overline{K}^*(892)$, $S=1/2$, S-wave $\qquad(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.10\pm0.02$	[2] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2000) \to N\overline{K}^*(892)$, $S=3/2$, D-wave $\qquad(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.07 ± 0.03	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Sigma(2000)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(2000)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP

$\boxed{\Sigma(2030)\ F_{17}}$

$I(J^P) = 1(\tfrac{7}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66 and by WOHL 66. For most results published before 1974 (they are now obsolete), see our 1982 edition (Physics Letters 111B).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions around 2030 MeV may be found in our 1984 edition, Rev. Mod. Phys. **56** (April 1984, Part II).

$\Sigma(2030)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2025 to 2040 OUR ESTIMATE				
$2036\pm\ 5$	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2038 ± 10	CORDEN	77B		$K^-N \to N\overline{K}^*$
$2040\pm\ 5$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$2030\pm\ 3$	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
2035 ± 15	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
2038 ± 10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
2042 ± 11	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
$2020\pm\ 6$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
2035 ± 10	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
2020 ± 30	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
2025 ± 10	LITCHFIELD	74D	DPWA	$K^-p \to \Lambda(1820)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2027 to 2057	GOYAL	77	DPWA	$K^-N \to \Sigma\pi$
2030	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(2030)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 200 OUR ESTIMATE	Our best guess is 180 MeV.			
172 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
137 ± 40	CORDEN	77B		$K^-N \to N\overline{K}^*$
190 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$201\pm\ 9$	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
180 ± 20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
172 ± 15	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
178 ± 13	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
$111\pm\ 5$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
160 ± 20	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
200 ± 30	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
260	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
126 to 195	GOYAL	77	DPWA	$K^-N \to \Sigma\pi$
160	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
70 to 125	LITCHFIELD	74D	DPWA	$K^-p \to \Lambda(1820)\pi^0$

$\Sigma(2030)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	17–23 %
Γ_2	$\Lambda\pi$	17–23 %
Γ_3	$\Sigma\pi$	5–10 %
Γ_4	ΞK	<2 %
Γ_5	$\Sigma(1385)\pi$	5–15 %
Γ_6	$\Sigma(1385)\pi$, F-wave	
Γ_7	$\Lambda(1520)\pi$	10–20 %
Γ_8	$\Lambda(1520)\pi$, D-wave	
Γ_9	$\Lambda(1520)\pi$, G-wave	
Γ_{10}	$\Delta(1232)\overline{K}$	10–20 %
Γ_{11}	$\Delta(1232)\overline{K}$, F-wave	
Γ_{12}	$\Delta(1232)\overline{K}$, H-wave	
Γ_{13}	$N\overline{K}^*(892)$	<5 %
Γ_{14}	$N\overline{K}^*(892)$, $S=1/2$, F-wave	
Γ_{15}	$N\overline{K}^*(892)$, $S=3/2$, F-wave	
Γ_{16}	$\Lambda(1820)\pi$, P-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2030)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ $\qquad\Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 to 0.23 OUR ESTIMATE				
0.19 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.18 ± 0.03	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$

• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.24 ± 0.02	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.18 \pm 0.02$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$+0.20 \pm 0.01$	[1] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
$+0.18 \pm 0.02$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.20 \pm 0.01$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
$+0.195 \pm 0.053$	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09 ± 0.01	[2] CORDEN	77C		$K^- n \to \Sigma\pi$
-0.06 ± 0.01	[2] CORDEN	77C		$K^- n \to \Sigma\pi$
-0.15 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.10 ± 0.01	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.085 ± 0.02	[3] GOYAL	77	DPWA	$K^- N \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Xi K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.023	MULLER	69B	DPWA	$K^- p \to \Xi K$
<0.05	BURGUN	68	DPWA	$K^- p \to \Xi K$
<0.05	TRIPP	67	RVUE	$K^- p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1820)\pi$, *P*-wave $(\Gamma_1\Gamma_{16})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.14 ± 0.02	CORDEN	75B	DBC	$K^- n \to N\overline{K}\pi^-$
0.18 ± 0.04	LITCHFIELD	74D	DPWA	$K^- p \to \Lambda(1820)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1520)\pi$, *D*-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.114 \pm 0.010$	[4] CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
0.14 ± 0.03	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ± 0.03	[5] CORDEN	75B	DBC	$K^- n \to N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Lambda(1520)\pi$, *G*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.146 \pm 0.010$	[4] CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
0.02 ± 0.02	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Delta(1232)\overline{K}$, *F*-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.16 ± 0.03	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17 ± 0.03	[5] CORDEN	75B	DBC	$K^- n \to N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Delta(1232)\overline{K}$, *H*-wave $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00 ± 0.02	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.153 \pm 0.026$	[4] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to N\overline{K}^*(892)$, S=1/2, *F*-wave $(\Gamma_1\Gamma_{14})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.06 \pm 0.03$	[4] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
-0.02 ± 0.01	CORDEN	77B		$K^- d \to NN\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2030) \to N\overline{K}^*(892)$, S=3/2, *F*-wave $(\Gamma_1\Gamma_{15})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.04 \pm 0.03$	[6] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
-0.12 ± 0.02	CORDEN	77B		$K^- d \to NN\overline{K}^*$

$\Sigma(2030)$ FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities.

[2] The two entries for CORDEN 77C are from two different acceptable solutions.

[3] This coupling is extracted from unnormalized data.

[4] The published sign has been changed to be in accord with the baryon-first convention.

[5] An upper limit.

[6] The upper limit on the G_3 wave is 0.03.

$\Sigma(2030)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CORDEN	77B	NP B121 365	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
CORDEN	75B	NP B92 365	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEID, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEID) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEID) IJP
LITCHFIELD	74D	NP B74 12	+Hemingway, Baillon+	(CERN, HEID) IJP
MULLER	69B	UCRL 19372 Thesis		(LRL)
BURGUN	68	NP B8 447	+Meyer, Pauli, Tallini+	(SACL, CDEF, RHEL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Sigma(2070)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

This state suggested by BERTHON 70B finds support in GOPAL 80 with new $K^- p$ polarization and $K^- n$ angular distributions. The very broad state seen in KANE 72 is not required in the later (KANE 74) analysis of $\overline{K}N \to \Sigma\pi$.

$\Sigma(2070)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2051 ± 25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2057	KANE	72	DPWA	$K^- p \to \Sigma\pi$
2070 ± 10	BERTHON	70B	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(2070)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 ± 30	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
906	KANE	72	DPWA	$K^- p \to \Sigma\pi$
140 ± 20	BERTHON	70B	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(2070)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$

$\Sigma(2070)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(2070) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.104$	KANE	72	DPWA	$K^- p \to \Sigma\pi$
$+0.12 \pm 0.02$	BERTHON	70B	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(2070)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
KANE	74	LBL-2452		(LBL)
KANE	72	PR D5 1583		(LBL)
BERTHON	70B	NP B24 417	+Vrana, Butterworth+	(CDEF, RHEL, SACL) IJP

$\Sigma(2080)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Suggested by some but not all partial-wave analyses across this region.

Σ(2080) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2091 ± 7	[1] CORDEN 76	DPWA	$K^- n \to \Lambda\pi^-$
2070 to 2120	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
2120 ± 40	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
2140 ± 40	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
2082 ± 4	COX 70	DPWA	See CORDEN 76
2070 ± 30	LITCHFIELD 70	DPWA	$K^- N \to \Lambda\pi$

Σ(2080) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
186 ± 48	[1] CORDEN 76	DPWA	$K^- n \to \Lambda\pi^-$
100	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
240 ± 50	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
200 ± 50	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
87 ± 20	COX 70	DPWA	See CORDEN 76
250 ± 40	LITCHFIELD 70	DPWA	$K^- N \to \Lambda\pi$

Σ(2080) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

Σ(2080) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2080) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.10 ± 0.03	[1] CORDEN 76	DPWA	$K^- n \to \Lambda\pi^-$
−0.10	DEBELLEFON 76	IPWA	$K^- p \to \Lambda\pi^0$
−0.13 ± 0.04	BAILLON 75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1 and 2)
−0.16 ± 0.03	COX 70	DPWA	See CORDEN 76
−0.09 ± 0.03	LITCHFIELD 70	DPWA	$K^- N \to \Lambda\pi$

Σ(2080) FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities, including a D_{15} at this mass.

Σ(2080) REFERENCES

CORDEN 76 NP B104 382 +Cox, Dartnell, Kenyon, O'Neale+ (BIRM) IJP
DEBELLEFON 76 NP B109 129 De Bellefon, Berthon (CDEF) IJP
Also 75 NP B90 1 De Bellefon, Berthon, Brunet+ (CDEF, SACL) IJP
BAILLON 75 NP B94 39 +Litchfield (CERN, RHEL) IJP
COX 70 NP B19 61 +Islam, Colley+ (BIRM, EDIN, GLAS, LOIC) IJP
LITCHFIELD 70 NP B22 269 (RHEL) IJP

$\Sigma(2100)$ G_{17}

$I(J^P) = 1(\frac{7}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Σ(2100) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2060 ± 20	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$
2120 ± 30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Σ(2100) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
70 ± 30	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$
135 ± 30	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Σ(2100) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(2100) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2100) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.07 ± 0.02	BARBARO-... 70	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \to \Sigma(2100) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.13 ± 0.02	BARBARO-... 70	DPWA	$K^- p \to \Sigma\pi$

Σ(2100) REFERENCES

BARBARO-... 70 Duke Conf. 173 Barbaro-Galtieri (LRL) IJP

$\Sigma(2250)$

$I(J^P) = 1(?^?)$ Status: ∗∗∗

Results from partial-wave analyses are too weak to warrant separating them from the production and cross-section experiments. LASINSKI 71 in $\overline{K}N$ using a Pomeron + resonances model, and DEBELLEFON 76, DEBELLEFON 77, and DEBELLEFON 78 in energy-dependent partial-wave analyses of $\overline{K}N \to \Lambda\pi$, $\Sigma\pi$, and $N\overline{K}$, respectively, suggest two resonances around this mass.

Σ(2250) MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2210 to 2280 OUR ESTIMATE			
2270 ± 50	DEBELLEFON 78	DPWA	D_5 wave
2210 ± 30	DEBELLEFON 78	DPWA	G_9 wave
2275 ± 20	DEBELLEFON 77	DPWA	D_5 wave
2215 ± 20	DEBELLEFON 77	DPWA	G_9 wave
2300 ± 30	[1] DEBELLEFON 75B	HBC	$K^- p \to \Xi^{*0} K^0$
2251^{+30}_{-20}	VANHORN 75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
2280 ± 14	AGUILAR-... 70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
2237 ± 11	BRICMAN 70	CNTR	Total, charge exchange
2255 ± 10	COOL 70	CNTR	$K^- p$, $K^- d$ total
2250 ± 7	BUGG 68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2260	DEBELLEFON 76	IPWA	D_5 wave
2215	DEBELLEFON 76	IPWA	G_9 wave
2250 ± 20	LU 70	CNTR	$\gamma p \to K^+ Y^*$
2245	BLANPIED 65	CNTR	$\gamma p \to K^+ Y^*$
2299 ± 6	BOCK 65	HBC	$\overline{p}p$ 5.7 GeV/c

$\Sigma(2250)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
60 to 150 OUR ESTIMATE Our best guess is 100 MeV.			
120 ± 40	DEBELLEFON 78	DPWA	D_5 wave
80 ± 20	DEBELLEFON 78	DPWA	G_9 wave
70 ± 20	DEBELLEFON 77	DPWA	D_5 wave
60 ± 20	DEBELLEFON 77	DPWA	G_9 wave
130 ± 20	[1] DEBELLEFON 75B	HBC	$K^- p \rightarrow \Xi^{*0} K^0$
192 ± 30	VANHORN 75	DPWA	$K^- p \rightarrow \Lambda\pi^0$, F_5 wave
100 ± 20	AGUILAR-... 70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
164 ± 50	BRICMAN 70	CNTR	Total, charge exchange
230 ± 20	BUGG 68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •			
100	DEBELLEFON 76	IPWA	D_5 wave
140	DEBELLEFON 76	IPWA	G_9 wave
170	COOL 70	CNTR	$K^- p$, $K^- d$ total
125	LU 70	CNTR	$\gamma p \rightarrow K^+ Y^*$
150	BLANPIED 65	CNTR	$\gamma p \rightarrow K^+ Y^*$
21^{+17}_{-21}	BOCK 65	HBC	$\overline{p}p$ 5.7 GeV/c

$\Sigma(2250)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	<10 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$N\overline{K}\pi$	
Γ_5	$\Xi(1530)K$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2250)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.1 OUR ESTIMATE			
0.08 ± 0.02	DEBELLEFON 78	DPWA	D_5 wave
0.02 ± 0.01	DEBELLEFON 78	DPWA	G_9 wave

$(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.16 ± 0.12	BRICMAN 70	CNTR	Total, charge exchange
0.42	COOL 70	CNTR	$K^- p$, $K^- d$ total
0.47	BUGG 68	CNTR	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2250) \rightarrow \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
-0.16 ± 0.03	VANHORN 75	DPWA	$K^- p \rightarrow \Lambda\pi^0$, F_5 wave
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.11	DEBELLEFON 76	IPWA	D_5 wave
−0.10	DEBELLEFON 76	IPWA	G_9 wave
−0.18	BARBARO-... 70	DPWA	$K^- p \rightarrow \Lambda\pi^0$, G_9 wave

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2250) \rightarrow \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
$+0.06\pm0.02$	DEBELLEFON 77	DPWA	D_5 wave
-0.03 ± 0.02	DEBELLEFON 77	DPWA	G_9 wave
+0.07	BARBARO-... 70	DPWA	$K^- p \rightarrow \Sigma\pi$, G_9 wave

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ Γ_1/Γ_3

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.18	BARNES 69	HBC	1 standard dev. limit

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ Γ_2/Γ_3

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.18	BARNES 69	HBC	1 standard dev. limit

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\text{total}}$ in $N\overline{K} \rightarrow \Sigma(2250) \rightarrow \Xi(1530)K$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.18 ± 0.04	[1] DEBELLEFON 75B	HBC	$K^- p \rightarrow \Xi^{*0} K^0$

$\Sigma(2250)$ FOOTNOTES

[1] Seen in the (initial and final state) D_5 wave. Isospin not determined.

$\Sigma(2250)$ REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
Also	75	NP B90 1	De Bellefon, Berthon, Brunet+	(CDEF, SACL) IJP
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LASINSKI	71	NP B29 125		(EFI) IJP
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
COOL	70	PR D1 1887	+Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)
BARNES	69	PRL 22 479	+Flaminio, Montanet, Samios+	(BNL, SYRA)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
BLANPIED	65	PRL 14 741	+Greenberg, Hughes, Kitching, Lu+	(YALE, CEA)
BOCK	65	PL 17 166	+Cooper, French, Kinson+	(CERN, SACL)

$\Sigma(2455)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is also some slight evidence for Y^* states in this mass region from the reaction $\gamma p \rightarrow K^+ X$ — see GREENBERG 68.

$\Sigma(2455)$ MASS

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
2455 ± 10	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
$2455\pm\ 7$	BUGG 68	CNTR	$K^- p$, $K^- d$ total

$\Sigma(2455)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
140	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
100 ± 20	BUGG 68	CNTR	

$\Sigma(2455)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$

$\Sigma(2455)$ BRANCHING RATIOS

$(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
0.39	ABRAMS 70	CNTR	$K^- p$, $K^- d$ total
0.05 ± 0.05	[1] BRICMAN 70	CNTR	Total, charge exchange
0.3	BUGG 68	CNTR	

$\Sigma(2455)$ FOOTNOTES

[1] Fit of total cross section given by BRICMAN 70 is poor in this region.

$\Sigma(2455)$ REFERENCES

ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	67E	PRL 19 678	Abrams, Cool, Giacomelli, Kycia, Leontic+	(BNL)
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
GREENBERG	68	PRL 20 221	+Hughes, Lu, Minehart+	(YALE)

Σ(2620) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Σ(2620) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2542 ± 22	DIBIANCA	75	DBC	$K^- N \to \Xi K \pi$
2620 ± 15	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

Σ(2620) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
221 ± 81	DIBIANCA	75	DBC	$K^- N \to \Xi K \pi$
175	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

Σ(2620) DECAY MODES

	Mode
Γ_1	$N \overline{K}$

Σ(2620) BRANCHING RATIOS

$(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.32	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.36 ± 0.12	BRICMAN	70	CNTR	Total, charge exchange

Σ(2620) REFERENCES

DIBIANCA 75 NP B98 137 +Endorf (CMU)
ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)
Also 67E PRL 19 678 Abrams, Cool, Giacomelli, Kycia, Leontic+ (BNL)
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)

Σ(3000) Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen as an enhancement in $\Lambda\pi$ and $\overline{K}N$ invariant mass spectra and in the missing mass of neutrals recoiling against a K^0.

Σ(3000) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3000	EHRLICH	66	HBC	0	$\pi^- p$ 7.91 GeV/c

Σ(3000) DECAY MODES

	Mode
Γ_1	$N \overline{K}$
Γ_2	$\Lambda \pi$

Σ(3000) REFERENCES

EHRLICH 66 PR 152 1194 +Selove, Yuta (PENN)

Σ(3170) Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen by AMIRZADEH 79 as a narrow 6.5-standard-deviation enhancement in the reaction $K^- p \to Y^{*+} \pi^-$ using data from independent high statistics bubble chamber experiments at 8.25 and 6.5 GeV/c. The dominant decay modes are multibody, multistrange final states and the production is via isospin-3/2 baryon exchange. Isospin 1 is favored.

Not seen in a $K^- p$ experiment in LASS at 11 GeV/c (ASTON 85B).

Σ(3170) MASS
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3170 ± 5	35	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

Σ(3170) WIDTH
(PRODUCTION EXPERIMENTS)

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<20	35	[1] AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

Σ(3170) DECAY MODES
(PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$\Lambda K \overline{K} \pi$'s
Γ_2	$\Sigma K \overline{K} \pi$'s
Γ_3	$\Xi K \pi$'s

Σ(3170) BRANCHING RATIOS
(PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda K \overline{K} \pi\text{'s})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Gamma(\Sigma K \overline{K} \pi\text{'s})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

$\Gamma(\Xi K \pi\text{'s})/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+} \pi^-$

Σ(3170) FOOTNOTES
(PRODUCTION EXPERIMENTS)

[1] Observed width consistent with experimental resolution.

Σ(3170) REFERENCES
(PRODUCTION EXPERIMENTS)

ASTON 85B PR D32 2270 +Carnegie+ (SLAC, CARL, CNRC, CINC)
AMIRZADEH 79 PL 89B 125 + (BIRM, CERN, GLAS, MSU, LPNP, CAMB+)
Also 80 Toronto Conf. 263 Kinson+ (BIRM, CERN, GLAS, MSU, LPNP)

Ξ BARYONS
$(S = -2,\ I = 1/2)$

$\Xi^0 = uss, \quad \Xi^- = dss$

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

The parity has not actually been measured, but + is of course expected.

Ξ^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN
1314.9±0.6 OUR FIT			
1314.8±0.8 OUR AVERAGE			
1315.2±0.92	49	WILQUET 72	HLBC
1313.4±1.8	1	PALMER 68	HBC

$\Xi^- - \Xi^0$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
6.4±0.6 OUR FIT				
6.3±0.7 OUR AVERAGE				
6.9±2.2	29	LONDON 66	HBC	
6.1±0.9	88	PJERROU 65B	HBC	
6.8±1.6	23	JAUNEAU 63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
6.1±1.6	45	CARMONY 64B	HBC	See PJERROU 65B

Ξ^0 MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID	TECN	COMMENT
2.90±0.09 OUR AVERAGE				
2.83±0.16	6300	[1] ZECH 77	SPEC	Neutral hyperon beam
$2.88^{+0.21}_{-0.19}$	652	BALTAY 74	HBC	1.75 GeV/c $K^- p$
$2.90^{+0.32}_{-0.27}$	157	[2] MAYEUR 72	HLBC	2.1 GeV/c K^-
$3.07^{+0.22}_{-0.20}$	340	DAUBER 69	HBC	
3.0 ±0.5	80	PJERROU 65B	HBC	
$2.5\ ^{+0.4}_{-0.3}$	101	HUBBARD 64	HBC	
$3.9\ ^{+1.4}_{-0.8}$	24	JAUNEAU 63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$3.5\ ^{+1.0}_{-0.8}$	45	CARMONY 64B	HBC	See PJERROU 65B

[1] The ZECH 77 result is $\tau_{\Xi^0} = [2.77-(\tau_\Lambda-2.69)]\times10^{-10}$ s, in which we use $\tau_\Lambda = 2.63\times10^{-10}$ s.

[2] The MAYEUR 72 value is modified by the erratum.

Ξ^0 MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID	TECN
−1.250±0.014 OUR AVERAGE			
−1.253±0.014	270k	COX 81	SPEC
−1.20 ±0.06	42k	BUNCE 79	SPEC

Ξ^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\pi^0$		100 %	
Γ_2	$\Lambda\gamma$		$(1.06\pm0.16)\times10^{-3}$	
Γ_3	$\Sigma^0\gamma$		$(3.6\pm0.4)\times10^{-3}$	
Γ_4	$\Sigma^+e^-\overline{\nu}_e$		$< 1.1 \times10^{-3}$	90%
Γ_5	$\Sigma^+\mu^-\overline{\nu}_\mu$		$< 1.1 \times10^{-3}$	90%
	$\Delta S = \Delta Q$ (SQ) or $\Delta S = 2$ (ΔS) violating modes			
Γ_6	$\Sigma^-e^+\nu_e$	SQ	$< 9 \times10^{-4}$	90%
Γ_7	$\Sigma^-\mu^+\nu_\mu$	SQ	$< 9 \times10^{-4}$	90%
Γ_8	$p\pi^-$	ΔS	$< 4 \times10^{-5}$	90%
Γ_9	$pe^-\overline{\nu}_e$	ΔS	$< 1.3 \times10^{-3}$	
Γ_{10}	$p\mu^-\overline{\nu}_\mu$	ΔS	$< 1.3 \times10^{-3}$	

Ξ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi^0)$ Γ_2/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.06±0.12±0.11	116	JAMES 90	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5 ±5	1	YEH 74	HBC	Effective denom.=200

$\Gamma(\Sigma^0\gamma)/\Gamma(\Lambda\pi^0)$ Γ_3/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
3.56±0.42±0.10		85	TEIGE 89	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 8	90		BENSINGER 88	MPS2	$K^- W$ 6 GeV/c
<65	90	0–1	YEH 74	HBC	Effective denom.=60

$\Gamma(\Sigma^+e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ Γ_4/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 1.1	90	0	YEH 74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.5			DAUBER 69	HBC	
< 7			HUBBARD 66	HBC	
<13			TICHO 63	HBC	

$\Gamma(\Sigma^+\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ Γ_5/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.1	90	0	YEH 74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5			DAUBER 69	HBC	
<7			HUBBARD 66	HBC	

$\Gamma(\Sigma^-e^+\nu_e)/\Gamma(\Lambda\pi^0)$ Γ_6/Γ_1

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.9	90	0	YEH 74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5			DAUBER 69	HBC	
<6			HUBBARD 66	HBC	

$\Gamma(\Sigma^-\mu^+\nu_\mu)/\Gamma(\Lambda\pi^0)$ Γ_7/Γ_1

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.9	90	0	YEH 74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5			DAUBER 69	HBC	
<6			HUBBARD 66	HBC	

$\Gamma(p\pi^-)/\Gamma(\Lambda\pi^0)$ Γ_8/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 3.6	90		GEWENIGER 75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 180	90	0	YEH 74	HBC	Effective denom.=1300
< 90			DAUBER 69	HBC	
< 500			HUBBARD 66	HBC	
<2700			TICHO 63	HBC	

$\Gamma(pe^-\overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
< 1.3			DAUBER 69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 3.4	90	0	YEH 74	HBC	Effective denom.=670
< 6			HUBBARD 66	HBC	
<27			TICHO 63	HBC	

$\Gamma(p\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

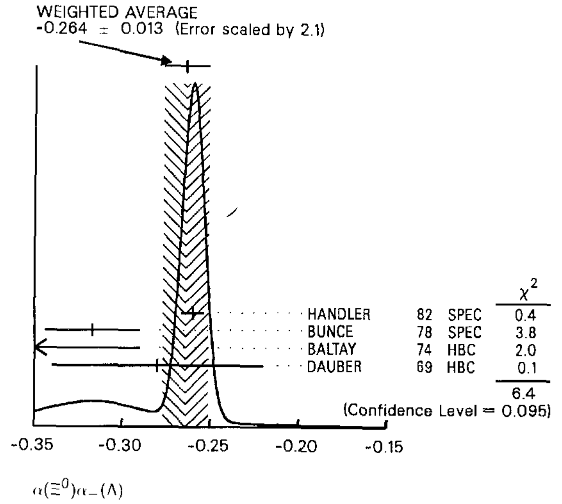
VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.3			DAUBER 69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.5	90	0	YEH 74	HBC	Effective denom.=664
<6			HUBBARD 66	HBC	

Ξ^0 DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings.

$\alpha(\Xi^0)\ \alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
-0.264 ± 0.013 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.			
$-0.260\pm0.004\pm0.005$	300k	HANDLER 82	SPEC	FNAL hyperons
-0.317 ± 0.027	6075	BUNCE 78	SPEC	FNAL hyperons
$-0.35\ \pm0.06$	505	BALTAY 74	HBC	$K^- p$ 1.75 GeV/c
$-0.28\ \pm0.06$	739	DAUBER 69	HBC	$K^- p$ 1.7–2.6 GeV/c



α FOR $\Xi^0 \rightarrow \Lambda\pi^0$

The above average, $\alpha(\Xi^0)\alpha_-(\Lambda) = -0.264 \pm 0.013$, where the error includes a scale factor of 2.1, divided by our current average $\alpha_-(\Lambda) = 0.642\pm0.013$, gives the following value for $\alpha(\Xi^0)$.

VALUE	DOCUMENT ID
-0.411 ± 0.022 OUR EVALUATION	Error includes scale factor of 2.1.

ϕ ANGLE FOR $\Xi^0 \rightarrow \Lambda\pi^0$ ($\tan\phi = \beta/\gamma$)

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
21 ± 12 OUR AVERAGE				
16 ± 17	652	BALTAY 74	HBC	1.75 GeV/c $K^- p$
38 ± 19	739	[3] DAUBER 69	HBC	
$-\ 8\pm30$	146	[4] BERGE 66	HBC	

[3] DAUBER 69 uses $\alpha_\Lambda = 0.647 \pm 0.020$.

[4] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

α FOR $\Xi^0 \rightarrow \Lambda\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$+0.43\pm0.44$	87	JAMES 90	SPEC	FNAL hyperons

α FOR $\Xi^0 \rightarrow \Sigma^0\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$+0.20\pm0.32\pm0.05$	85	TEIGE 89	SPEC	FNAL hyperons

REFERENCES FOR Ξ^0

JAMES	90	PRL 64 843	+Heller, Border, Dworkin+	(MINN, MICH, WISC, RUTG)
TEIGE	89	PRL 63 2717	+Beretvas, Caracappa, Devlin+	(RUTG, MICH, MINN)
BENSINGER	88	PL B215 195	+Fortner, Kirsch, Piekarz+	(BRAN, DUKE, NDAM, SMAS)
HANDLER	82	PR D25 639	+Grobel, Pondrom+	(WISC, MICH, MINN, RUTG)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
BUNCE	79	PL 86B 386	+Overseth, Cox+	(BNL, MICH, RUTG, WISC)
BUNCE	78	PR D18 633	+Handler, March, Martin+	(WISC, MICH, RUTG)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEID)
GEWENIGER	75	PL 57B 193	+Gjesdal, Presser+	(CERN, HEID)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFT, LOUC)
Also	73	NP B53 268 *erratum*	*Mayeur*	
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFT, LOUC)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
HUBBARD	66	UCRL 11510 Thesis		(LRL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
JAUNEAU	63	PL 4 49	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63C	Siena Conf. 1 1	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)
TICHO	63	BNL Conf. 410		(UCLA)

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

The parity has not actually been measured, but + is of course expected.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

Ξ^- MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1321.32 ± 0.13 OUR FIT				
1321.34 ± 0.14 OUR AVERAGE				
1321.46 ± 0.34	632	DIBIANCA 75	DBC	4.9 GeV/c $K^- d$
1321.12 ± 0.41	268	WILQUET 72	HLBC	
1321.87 ± 0.51	195	[1] GOLDWASSER 70	HBC	5.5 GeV/c $K^- p$
1321.67 ± 0.52	6	CHIEN 66	HBC	6.9 GeV/c $\overline{p}p$
$1321.4\ \pm1.1$	299	LONDON 66	HBC	
$1321.3\ \pm0.4$	149	PJERROU 65B	HBC	
$1321.1\ \pm0.3$	241	[2] BADIER 64	HBC	
$1321.4\ \pm0.4$	517	[2] JAUNEAU 63D	FBC	
$1321.1\ \pm0.65$	62	[2] SCHNEIDER 63	HBC	

[1] GOLDWASSER 70 uses $m(\Lambda) = 1115.58$ MeV.

[2] These masses have been increased 0.09 MeV because the Λ mass increased.

$\overline{\Xi}^+$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1321.32 ± 0.13 OUR FIT				
1321.20 ± 0.33 OUR AVERAGE				
$1321.6\ \pm0.8$	35	VOTRUBA 72	HBC	10 GeV/c $K^+ p$
$1321.2\ \pm0.4$	34	STONE 70	HBC	
1320.69 ± 0.93	5	CHIEN 66	HBC	6.9 GeV/c $\overline{p}p$

Ξ^- MEAN LIFE

Measurements with an error $> 0.2\times10^{-10}$ s or with systematic errors not included have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID	TECN	COMMENT
1.639 ± 0.015 OUR AVERAGE				
1.652 ± 0.051	32k	BOURQUIN 84	SPEC	Hyperon beam
1.665 ± 0.065	41k	BOURQUIN 79	SPEC	Hyperon beam
1.609 ± 0.028	4286	HEMINGWAY 78	HBC	4.2 GeV/c $K^- p$
$1.67\ \pm0.08$		DIBIANCA 75	DBC	4.9 GeV/c $K^- d$
$1.63\ \pm0.03$	4303	BALTAY 74	HBC	1.75 GeV/c $K^- p$
$1.73\ ^{+0.08}_{-0.07}$	680	MAYEUR 72	HLBC	2.1 GeV/c K^-
$1.61\ \pm0.04$	2610	DAUBER 69	HBC	
$1.80\ \pm0.16$	299	LONDON 66	HBC	
$1.70\ \pm0.12$	246	PJERROU 65B	HBC	
$1.69\ \pm0.07$	794	HUBBARD 64	HBC	
$1.86\ ^{+0.15}_{-0.14}$	517	JAUNEAU 63D	FBC	

$\overline{\Xi}^+$ MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID	TECN	COMMENT
$1.6\ \pm0.3$	34	STONE 70	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.55^{+0.35}_{-0.20}$	35	[3] VOTRUBA 72	HBC	10 GeV/c $K^+ p$
$1.9\ ^{+0.7}_{-0.5}$	12	[3] SHEN 67	HBC	
1.51 ± 0.55	5	[3] CHIEN 66	HBC	6.9 GeV/c $\overline{p}p$

[3] The error is statistical only.

Ξ^- MAGNETIC MOMENT

See the Note on Baryon Magnetic Moments in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID	TECN	COMMENT
-0.679 ± 0.031 OUR AVERAGE				
$-0.661\pm0.036\pm0.036$	44k	TROST 89	SPEC	Ξ^- ~ 250 GeV/c
$-0.69\ \pm0.04$	218k	RAMEIKA 84	SPEC	400 GeV pBe
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$2.1\ \pm0.8$	2436	COOL 74	OSPK	1.8 GeV/c $K^- p$
$-0.1\ \pm2.1$	2724	BINGHAM 70B	OSPK	1.8 GeV/c $K^- p$

Ξ^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\pi^-$		100 %	
Γ_2	$\Sigma^-\gamma$		$(2.3\pm1.0)\times10^{-4}$	
Γ_3	$\Lambda e^-\overline{\nu}_e$		$(5.5\pm0.3)\times10^{-4}$	
Γ_4	$\Lambda\mu^-\overline{\nu}_\mu$		$(3.5\pm3.5)\times10^{-4}$	
Γ_5	$\Sigma^0 e^-\overline{\nu}_e$		$(8.7\pm1.7)\times10^{-5}$	
Γ_6	$\Sigma^0\mu^-\overline{\nu}_\mu$		$< 8 \times10^{-4}$	90%
Γ_7	$\Xi^0 e^-\overline{\nu}_e$		$< 2.3 \times10^{-3}$	90%

$\Delta S = 2$ (ΔS) violating modes

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_8	$n\pi^-$	ΔS	$< 1.9 \times10^{-5}$	90%
Γ_9	$ne^-\overline{\nu}_e$	ΔS	$< 3.2 \times10^{-3}$	90%
Γ_{10}	$n\mu^-\overline{\nu}_\mu$	ΔS	< 1.5 %	90%
Γ_{11}	$p\pi^-\pi^-$	ΔS	$< 4 \times10^{-4}$	90%
Γ_{12}	$p\pi^-e^-\overline{\nu}_e$	ΔS	$< 4 \times10^{-4}$	90%
Γ_{13}	$p\pi^-\mu^-\overline{\nu}_\mu$	ΔS	$< 4 \times10^{-4}$	90%

Ξ^- BRANCHING RATIOS

A number of early results have been omitted.

$\Gamma(\Sigma^-\gamma)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_2/\Gamma_1$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.27±1.02	9	BIAGI	87B	SPEC	SPS hyperon beam

$\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_3/\Gamma_1$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.550±0.030 OUR AVERAGE					
0.564±0.031	2857	BOURQUIN	83	SPEC	SPS hyperon beam
0.30 ±0.13	11	THOMPSON	80	ASPK	Hyperon beam

$\Gamma(\Lambda\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_4/\Gamma_1$

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.35±0.35		1	YEH	74	HBC	Effective denom.=2859
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.3	90	0	THOMPSON	80	ASPK	Effective denom.=1017
<1.3			DAUBER	69	HBC	
<12			BERGE	66	HBC	

$\Gamma(\Sigma^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_5/\Gamma_1$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.087±0.017	154	BOURQUIN	83	SPEC	SPS hyperon beam

$\Gamma(\Sigma^0\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_6/\Gamma_1$

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.76	90	0	YEH	74	HBC	Effective denom.=3026
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5			BERGE	66	HBC	

$[\Gamma(\Lambda e^-\overline{\nu}_e) + \Gamma(\Sigma^0 e^-\overline{\nu}_e)]/\Gamma(\Lambda\pi^-)$ $\qquad(\Gamma_3+\Gamma_5)/\Gamma_1$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.651±0.031	3011	[4] BOURQUIN	83	SPEC	SPS hyperon beam
0.68 ±0.22	17	[5] DUCLOS	71	OSPK	

[4] See the separate BOURQUIN 83 values for $\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ and $\Gamma(\Sigma^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ above.

[5] DUCLOS 71 cannot distinguish Σ^0's from Λ's. The Cabibbo theory predicts the Σ^0 rate is about a factor 6 smaller than the Λ rate.

$\Gamma(\Xi^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_7/\Gamma_1$

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	0	YEH	74	HBC	Effective denom.=1000

$\Gamma(n\pi^-)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_8/\Gamma_1$

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.019	90		BIAGI	82B	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.0	90	0	YEH	74	HBC	Effective denom.=760
<1.1			DAUBER	69	HBC	
<5.0			FERRO-LUZZI	63	HBC	

$\Gamma(ne^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_9/\Gamma_1$

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.2	90	0	YEH	74	HBC	Effective denom.=715
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<10	90		BINGHAM	65	RVUE	

$\Gamma(n\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_{10}/\Gamma_1$

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<15.3	90	0	YEH	74	HBC	Effective denom.=150

$\Gamma(p\pi^-\pi^-)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_{11}/\Gamma_1$

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p\pi^-e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_{12}/\Gamma_1$

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p\pi^-\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ $\qquad\Gamma_{13}/\Gamma_1$

ΔS=2. Forbidden in first-order weak interaction.

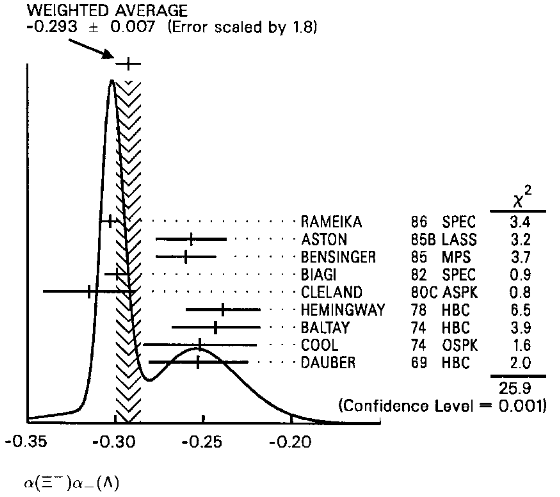
VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

Ξ^- DECAY PARAMETERS

See the Note on Baryon Decay Parameters in the neutron Listings.

$\alpha(\Xi^-)\alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.293±0.007 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
−0.303±0.004±0.004	192k	RAMEIKA	86	SPEC	400 GeV pBe
−0.257±0.020	11k	ASTON	85B	LASS	11 GeV/c K^-p
−0.260±0.017	21k	BENSINGER	85	MPS	5 GeV/c K^-p
−0.299±0.007	150k	BIAGI	82	SPEC	SPS hyperon beam
−0.315±0.026	9046	CLELAND	80C	ASPK	BNL hyperon beam
−0.239±0.021	6599	HEMINGWAY	78	HBC	4.2 GeV/c K^-p
−0.243±0.025	4303	BALTAY	74	HBC	1.75 GeV/c K^-p
−0.252±0.032	2436	COOL	74	OSPK	1.8 GeV/c K^-p
−0.253±0.028	2781	DAUBER	69	HBC	



α FOR $\Xi^- \to \Lambda\pi^-$

The above average, $\alpha(\Xi^-)\ \alpha_-(\Lambda) = -0.293 \pm 0.007$, where the error includes a scale factor of 1.8, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^-)$.

VALUE	DOCUMENT ID
−0.456±0.014 OUR EVALUATION	Error includes scale factor of 1.8.

ϕ ANGLE FOR $\Xi^- \to \Lambda\pi^-$ $\qquad(\tan\phi = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
4 ± 4 OUR AVERAGE					
5 ±10	11k	ASTON	85B	LASS	K^-p
14.7±16.0	21k	[6] BENSINGER	85	MPS	5 GeV/c K^-p
11 ± 9	4303	BALTAY	74	HBC	1.75 GeV/c K^-p
5 ±16	2436	COOL	74	OSPK	1.8 GeV/c K^-p
−26 ±30	2724	BINGHAM	70B	OSPK	
−14 ±11	2781	DAUBER	69	HBC	Uses $\alpha_\Lambda = 0.647\pm0.020$
0 ±12	1004	[7] BERGE	66	HBC	
0 ±20.4	364	[7] LONDON	66	HBC	Using $\alpha_\Lambda = 0.62$
54 ±30	356	[7] CARMONY	64B	HBC	

[6] BENSINGER 85 used $\alpha_\Lambda = 0.642 \pm 0.013$.

[7] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

g_A / g_V FOR $\Xi^- \rightarrow \Lambda e^- \overline{\nu}_e$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.25 ± 0.05	1992	[8] BOURQUIN	83	SPEC	SPS hyperon beam

[8] BOURQUIN 83 assumes that $g_2 = 0$. Also, the sign has been changed to agree with our conventions, given in the Note on Baryon Decay Parameters in the neutron Listings.

REFERENCES FOR Ξ^-

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

TROST	89	PR D40 1703	+McCliment, Newsom, Hseuh, Mueller+	(FNAL-715 Collab.)
BIAGI	87B	ZPHY C35 143	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
RAMEIKA	86	PR D33 3172	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BENSINGER	85	NP B252 561	+	(CHIC, ELMT, FNAL, ISU, LENI, SMAS)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEID, LALO, RAL, STRB)
RAMEIKA	84	PRL 52 581	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEID, LALO, RL, STRB)
BIAGI	82	PL 112B 265	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RL)
BIAGI	82B	PL 112B 277	+	(LOQM, GEVA, RL, HEID, CAMB, LAUS, BRIS)
CLELAND	80C	PR D21 12	+Cooper, Dris, Engels, Herbert+	(PITT, BNL)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
BOURQUIN	79	PL 87B 297	+	(BRIS, GEVA, HEID, ORSA, RHEL, STRB)
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
COOL	74	PR D10 792	+Giacomelli, Jenkins, Kycia, Leontic, Li+	(BNL)
Also	72	PRL 29 1630	Cool, Giacomelli, Jenkins, Kycia, Leontic+	(BNL)
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFT, LOUC)
VOTRUBA	72	NP B45 77	+Safder, Ratcliffe	(BIRM, EDIN)
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFT, LOUC)
DUCLOS	71	NP B32 493	+Freytag, Heintze, Heinzelmann, Jones+	(CERN)
BINGHAM	70B	PR D1 3010	+Cook, Humphrey, Sander+	(UCSD, WASH)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
STONE	70	PL 32B 515	+Berlinghieri, Bromberg, Cohen, Ferbel+	(ROCH)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL) J
SHEN	67	PL 25B 443	+Firestone, Goldhaber	(UCB, LRL)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
BINGHAM	65	PRSL 285 202		(CERN)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
BADIER	64	Dubna Conf. 1 593	+Demoulin, Barloutaud+	(EPOL, SACL, ZEEM)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA) J
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
FERRO-LUZZI	63	PR 130 1568	+Alston-Garnjost, Rosenfeld, Wojcicki	(LRL)
JAUNEAU	63D	Siena Conf. 4	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63B	PL 5 261	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)
SCHNEIDER	63	PL 4 360		(CERN)

OTHER RELATED PAPERS

PONDROM	85	PRPL 122 57	(WISC)

Review of FNAL hyperon experiments.

NOTE ON Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) they are produced with small cross sections (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus our early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in recent years have electronic experiments made significant contributions. However, there is nothing at all new on Ξ resonances since our 1988 edition.

For a detailed earlier review, see Meadows.[1]

References

1. B.T. Meadows, in *Proceedings of the IVth International Conference on Baryon Resonances* (Toronto, 1980), ed. N. Isgur, p. 283.

Table 1. The status of the Ξ resonances. Only those with an overall status of *** or **** are included in the Baryon Summary Table.

			Status as seen in —				
Particle	$L_{2I\cdot 2J}$	Overall status	$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	P_{11}	****					Decays weakly
$\Xi(1530)$	P_{13}	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	D_{13}	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$	1	***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$	1	**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

****	Good, clear, and unmistakable.
***	Good, but in need of clarification or not absolutely certain.
**	Not established; needs confirmation.
*	Evidence weak; could disappear.

$\Xi(1530)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ****

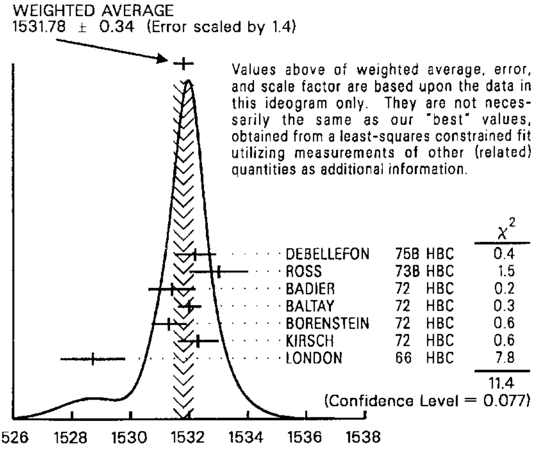
This is the only Ξ resonance whose properties are all reasonably well known. Spin-parity $3/2^+$ is favored by the data.

We use only those determinations of the mass and width that are accompanied by some discussion of systematics and resolution.

$\Xi(1530)$ MASSES

$\Xi(1530)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1531.80±0.32 OUR FIT Error includes scale factor of 1.3.					
1531.78±0.34 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
1532.2 ±0.7		DEBELLEFON	75B	HBC	$K^- p \rightarrow \Xi^- \overline{K} \pi$
1533 ±1		ROSS	73B	HBC	$K^- p \rightarrow \Xi \overline{K} \pi (\pi)$
1531.4 ±0.8	59	BADIER	72	HBC	$K^- p$ 3.95 GeV/c
1532.0 ±0.4	1262	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
1531.3 ±0.6	324	BORENSTEIN	72	HBC	$K^- p$ 2.2 GeV/c
1532.3 ±0.7	286	KIRSCH	72	HBC	$K^- p$ 2.87 GeV/c
1528.7 ±1.1	76	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1532.1 ±0.4	1244	ASTON	85B	LASS	$K^- p$ 11 GeV/c
1532.1 ±0.6	2700	[1] BAUBILLIER	81B	HBC	$K^- p$ 8.25 GeV/c
1530 ±1	450	BIAGI	81	SPEC	SPS hyperon beam
1527 ±6	80	SIXEL	79	HBC	$K^- p$ 10 GeV/c
1535 ±4	100	SIXEL	79	HBC	$K^- p$ 16 GeV/c
1533.6 ±1.4	97	BERTHON	74	HBC	Quasi-2-body σ



$\Xi(1530)^0$ mass (MeV)

Ξ(1530)⁻ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1535.0±0.6 OUR FIT					
1535.2±0.8 OUR AVERAGE					
1534.5±1.2		DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1535.3±2.0		ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
1536.2±1.6	185	KIRSCH	72	HBC	$K^- p$ 2.87 GeV/c
1535.7±3.2	38	LONDON	66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1540 ±3	48	BERTHON	74	HBC	Quasi-2-body σ
1534.7±1.1	334	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c

Ξ(1530)⁻ – Ξ(1530)⁰ MASS DIFFERENCE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3.2±0.6 OUR FIT				
2.9±0.9 OUR AVERAGE				
2.7±1.0	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
2.0±3.2	MERRILL	66	HBC	$K^- p$ 1.7–2.7 GeV/c
5.7±3.0	PJERROU	65B	HBC	$K^- p$ 1.8–1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9±1.8	[2] KIRSCH	72	HBC	$K^- p$ 2.87 GeV/c
7 ±4	[2] LONDON	66	HBC	$K^- p$ 2.24 GeV/c

Ξ(1530) WIDTHS

Ξ(1530)⁰ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
9.1±0.5 OUR AVERAGE					
9.5±1.2		DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
9.1±2.4		ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
11 ±2		BADIER	72	HBC	$K^- p$ 3.95 GeV/c
9.0±0.7		BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
8.4±1.4		BORENSTEIN	72	HBC	$\Xi^- \pi^+$
11.0±1.8		KIRSCH	72	HBC	$\Xi^- \pi^+$
7 ±7		BERGE	66	HBC	$K^- p$ 1.5–1.7 GeV/c
8.5±3.5		LONDON	66	HBC	$K^- p$ 2.24 GeV/c
7 ±2		SCHLEIN	63B	HBC	$K^- p$ 1.8, 1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12.8±1.0	2700	[1] BAUBILLIER	81B	HBC	$K^- p$ 8.25 GeV/c
19 ±6	80	[3] SIXEL	79	HBC	$K^- p$ 10 GeV/c
14 ±5	100	[3] SIXEL	79	HBC	$K^- p$ 16 GeV/c

Ξ(1530)⁻ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$9.9^{+1.7}_{-1.9}$ OUR AVERAGE				
9.6±2.8	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
8.3±3.6	ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi (\pi)$
$7.8^{+3.5}_{-7.8}$	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
16.2±4.6	KIRSCH	72	HBC	$\Xi^- \pi^0$, $\Xi^0 \pi^-$

Ξ(1530) POLE POSITIONS

Ξ(1530)⁰ REAL PART

VALUE	DOCUMENT ID	COMMENT
1531.6±0.4	LICHTENBERG74	Using HABIBI 73

Ξ(1530)⁰ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
4.45±0.35	LICHTENBERG74	Using HABIBI 73

Ξ(1530)⁻ REAL PART

VALUE	DOCUMENT ID	COMMENT
1534.4±1.1	LICHTENBERG74	Using HABIBI 73

Ξ(1530)⁻ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
$3.9^{+1.75}_{-3.9}$	LICHTENBERG74	Using HABIBI 73

Ξ(1530) DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Xi \pi$	100 %	
Γ_2	$\Xi \gamma$	<4 %	90%

Ξ(1530) BRANCHING RATIOS

$\Gamma(\Xi\gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	KALBFLEISCH	75	HBC	$K^- p$ 2.18 GeV/c

Ξ(1530) FOOTNOTES

[1] BAUBILLIER 81B is a fit to the inclusive spectrum. The resolution (5 MeV) is not unfolded.

[2] Redundant with data in the mass Listings.

[3] SIXEL 79 doesn't unfold the experimental resolution of 15 MeV.

Ξ(1530) REFERENCES

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BAUBILLIER	81B	NP B192 1	+	(BIRM, CERN, GLAS, MSU, LPNP)
BIAGI	81	ZPHY C9 305	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
SIXEL	79	NP B159 125	+Bottcher+	(AACH, BERL, CERN, LOIC, VIEN)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
LICHTENBERG	74	PR D10 3865		(IND)
Also	74B	Private Comm.	Lichtenberg	(IND)
HABIBI	73	Nevis 199 Thesis		(COLU)
ROSS	73B	Purdue Conf. 355	+Lloyd, Radojicic	(OXF)
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)
BALTAY	72	PL 42B 129	+Bridgewater, Cooper, Gershwin+	(COLU, BING)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
KIRSCH	72	NP B40 349	+Schmidt, Chang+	(BRAN, UMD, SYRA, TUFT) I
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL) I
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJ
MERRILL	66	UCRL 16455 Thesis		(LRL) JP
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
SCHLEIN	63B	PRL 11 167	+Carmony, Pjerrou, Slater, Stork, Ticho	(UCLA) IJP

OTHER RELATED PAPERS

MAZZUCATO	81	NP B178 1	+Pennino+	(AMST, CERN, NIJM, OXF)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFT)
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFT)
HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
BUTTON-...	66	PR 142 883	Button-Shafer, Lindsey, Murray, Smith	(LRL) JP

Ξ(1620)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

What little evidence there is consists of weak signals in the $\Xi\pi$ channel. A number of other experiments (e.g., BORENSTEIN 72 and HASSALL 81) have looked for but not seen any effect.

Ξ(1620) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1624± 3	31	BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
1633±12	34	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1606± 6	29	ROSS	72	HBC	$K^- p$ 3.1–3.7 GeV/c

Ξ(1620) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
22.5	31	[1] BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
40 ±15	34	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
21 ± 7	29	ROSS	72	HBC	$K^- p \to$ $\Xi^- \pi^+ K^{*0}(892)$

Ξ(1620) DECAY MODES

	Mode
Γ_1	$\Xi \pi$

Ξ(1620) FOOTNOTES

[1] The fit is insensitive to values between 15 and 30 MeV.

Ξ(1620) REFERENCES

HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAMB, MSU)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFT)
Also	70	Duke Conf. 317	Briefel+	(BRAN, UMD, SYRA, TUFT)
Also	75	PR D12 1859	Briefel, Gourevitch+	(BRAN, UMD, SYRA, TUFT)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
ROSS	72	PL 38B 177	+Buran, Lloyd, Mulvey, Radojicic	(OXF) I

OTHER RELATED PAPERS

HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
SCHMIDT	73	Purdue Conf. 363		(BRAN)
KALBFLEISCH	70	Duke Conf. 331		(BNL) I
APSELL	69	PRL 23 884	+	(BRAN, UMD, SYRA, TUFT)
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

DIONISI 78 sees a threshold enhancement in both the neutral and negatively charged $\Sigma\overline{K}$ mass spectra in $K^- p \rightarrow (\Sigma\overline{K})K\pi$ at 4.2 GeV/c. The data from the $\Sigma\overline{K}$ channels alone cannot distinguish between a resonance and a large scattering length. Weaker evidence at the same mass is seen in the corresponding $\Lambda\overline{K}$ channels, and a coupled-channel analysis yields results consistent with a new Ξ.

BIAGI 81 sees an enhancement at 1700 MeV in the diffractively produced ΛK^- system. A peak is also observed in the $\Lambda\overline{K}^0$ mass spectrum at 1660 MeV that is consistent with a 1720 MeV resonance decaying to $\Sigma^0\overline{K}^0$, with the γ from the Σ^0 decay not detected.

BIAGI 87 provides further confirmation of this state in diffractive dissociation of Ξ^- into ΛK^-. The significance claimed is 6.7 standard deviations.

$\Xi(1690)$ MASSES

$\Xi(1690)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1699±5	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
1684±5	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1691.1± 1.9±2.0	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
1700 ±10	150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
1694 ± 6	45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ WIDTHS

$\Xi(1690)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
44±23	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
20± 4	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)^-$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 8	90	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
47±14		150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
26± 6		45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	seen
Γ_2	$\Sigma\overline{K}$	seen
Γ_3	$\Xi\pi$	
Γ_4	$\Xi^-\pi^+\pi^0$	
Γ_5	$\Xi^-\pi^+\pi^-$	
Γ_6	$\Xi(1530)\pi$	

$\Xi(1690)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	104	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.7±0.9	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c
3.1±1.4	DIONISI	78	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^-\pi^+\pi^0)/\Gamma(\Sigma\overline{K})$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	4	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV

$\Gamma(\Xi^-\pi^+\pi^-)/\Gamma(\Sigma\overline{K})$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.03	DIONISI	78	HBC	−	K p 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Sigma\overline{K})$ — Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.06	DIONISI	78	HBC	−	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ FOOTNOTES

[1] From a fit to the $\Sigma^+ K^-$ spectrum.

[2] From a coupled-channel analysis of the $\Sigma^+ K^-$ and $\Lambda\overline{K}^0$ spectra.

[3] A fit to the inclusive spectrum from $\Xi^- N \rightarrow \Lambda K^- X$.

[4] From a coupled-channel analysis of the $\Sigma^0 K^-$ and ΛK^- spectra.

$\Xi(1690)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL) I
BIAGI	81	ZPHY C9 305	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
DIONISI	78	PL 80B 145	+Diaz, Armenteros+	(CERN, AMST, NIJM, OXF) I

$\Xi(1820)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

The clearest evidence is an 8-standard-deviation peak in ΛK^- seen by GAY 76. TEODORO 78 favors J=3/2, but cannot make a parity discrimination. BIAGI 87C is consistent with J=3/2 and favors negative parity for this J value.

$\Xi(1820)$ MASS

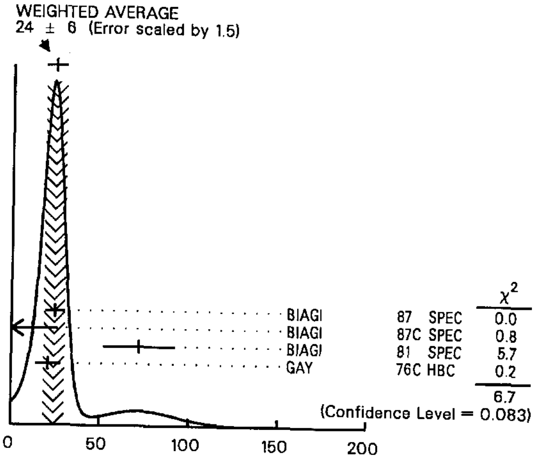
We only average the measurements that appear to us to be most significant and best determined.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1823 ± 5 OUR ESTIMATE						
1823.4± 1.4 OUR AVERAGE						
1819.4± 3.1±2.0	280	[1] BIAGI	87	SPEC	0	Ξ^- Be $\rightarrow$ (ΛK^-) X
1826 ± 3 ±1	54	BIAGI	87C	SPEC	0	Ξ^- Be $\rightarrow$ $(\Lambda\overline{K}^0)$ X
1822 ± 6		JENKINS	83	MPS	−	$K^- p \rightarrow K^+$ (MM)
1830 ± 6	300	BIAGI	81	SPEC	−	SPS hyperon beam
1823 ± 2	130	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1797 ±19	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
1829 ± 9	68	BRIEFEL	77	HBC	−0	$\Xi(1530)\pi$
1860 +14	39	BRIEFEL	77	HBC	−	$\Sigma^-\overline{K}^0$
1870 ± 9	44	BRIEFEL	77	HBC	0	$\Lambda\overline{K}^0$
1813 + 4	57	BRIEFEL	77	HBC	−	ΛK^-
1807 +27		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
1762 ± 8	28	[2] BADIER	72	HBC	−0	$\Xi\pi$, $\Xi\pi\pi$, YK
1838 + 5	38	[2] BADIER	72	HBC	−0	$\Xi\pi$, $\Xi\pi\pi$, YK
1830 ±10	25	[3] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
1826 ±12		[4] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
1830 ±10	40	ALITTI	69	HBC	−	Λ, $\Sigma\overline{K}$
1814 ± 4	30	BADIER	65	HBC	0	$\Lambda\overline{K}^0$
1817 ± 7	29	SMITH	65C	HBC	−0	$\Lambda\overline{K}^0$, ΛK^-
1770		HALSTEINSLID	63	FBC	−0	K^- freon 3.5 GeV/c

$\Xi(1820)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
24 $^{+15}_{-10}$ OUR ESTIMATE						
24 ± 6 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.						
24.6± 5.3	280	[1] BIAGI	87	SPEC	0	Ξ^- Be $\rightarrow$ (ΛK^-) X
12 ±14 ±1.7	54	BIAGI	87C	SPEC	0	Ξ^- Be $\rightarrow$ $(\Lambda\overline{K}^0)$ X
72 ±20	300	BIAGI	81	SPEC	−	SPS hyperon beam
21 ± 7	130	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
99 ±57	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
52 ±34	68	BRIEFEL	77	HBC	−0	$\Xi(1530)\pi$
72 ±17	39	BRIEFEL	77	HBC	−	$\Sigma^-\overline{K}^0$
44 ±11	44	BRIEFEL	77	HBC	0	$\Lambda\overline{K}^0$
26 ±11	57	BRIEFEL	77	HBC	−	ΛK^-
85 ±58		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
51 ±13		[2] BADIER	72	HBC	−0	Lower mass

58 ±13	[2] BADIER	72	HBC	−0	Higher mass
103^{+38}_{-24}	[3] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
48^{+36}_{-19}	[4] CRENNELL	70B	DBC	−0	3.6, 3.9 GeV/c
55^{+40}_{-20}	ALITTI	69	HBC	−	Λ, $\Sigma\overline{K}$
12 ± 4	BADIER	65	HBC	0	$\Lambda\overline{K}^0$
30 ± 7	SMITH	65B	HBC	−0	$\Lambda\overline{K}$
< 80	HALSTEINSLID	63	FBC	−0	K^- freon 3.5 GeV/c



Ξ(1820) width (MeV)

Ξ(1820) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	large
Γ_2	$\Sigma\overline{K}$	small
Γ_3	$\Xi\pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi\pi\pi$ (not $\Xi(1530)\pi$)	

Ξ(1820) BRANCHING RATIOS

The dominant modes seem to be $\Lambda\overline{K}$ and (perhaps) $\Xi(1530)\pi$, but the branching fractions are very poorly determined.

$\Gamma(\Lambda\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi\pi)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.10±0.10	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Lambda\overline{K})$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.36	95	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
0.20±0.20		BADIER	65	HBC	0	$K^- p$ 3 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$1.5^{+0.6}_{-0.4}$	APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

$\Gamma(\Sigma\overline{K})/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	*TRIPP*	*67*	*RVUE*		Use SMITH 65C

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.24±0.10	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	ASTON	85B	LASS		$K^- p$ 11 GeV/c
not seen	[5] HASSALL	81	HBC		$K^- p$ 6.5 GeV/c
<0.25	[6] DAUBER	69	HBC		$K^- p$ 2.7 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Lambda\overline{K})$ Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.38±0.27 OUR AVERAGE	Error includes scale factor of 2.3.				
1.0 ±0.3	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
0.26±0.13	SMITH	65C	HBC	−0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi\pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Lambda\overline{K})$ Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.20	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.14	[7] BADIER	65	HBC	0	1 st. dev. limit
>0.1	SMITH	65C	HBC	−0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi\pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ Γ_5/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
consistent with zero	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.3±0.5	[8] APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

Ξ(1820) FOOTNOTES

[1] BIAGI 87 also sees weak signals in the in the $\Xi^- \pi^+ \pi^-$ channel at 1782.6 ± 1.4 MeV (Γ = 6.0 ± 1.5 MeV) and 1831.9 ± 2.8 MeV (Γ = 9.6 ± 9.9 MeV).

[2] BADIER 72 adds all channels and divides the peak into lower and higher mass regions. The data can also be fitted with a single Breit-Wigner of mass 1800 MeV and width 150 MeV.

[3] From a fit to inclusive $\Xi\pi$, $\Xi\pi\pi$, and ΛK^- spectra.

[4] From a fit to inclusive $\Xi\pi$ and $\Xi\pi\pi$ spectra only.

[5] *Including* $\Xi\pi\pi$.

[6] DAUBER 69 uses in part the same data as SMITH 65C.

[7] For the decay mode $\Xi^- \pi^+ \pi^0$ only. This limit includes $\Xi(1530)\pi$.

[8] Or less. Upper limit for the 3-body decay.

Ξ(1820) REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
BIAGI 87C ZPHY C34 175 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL) JP
ASTON 85B PR D32 2270 +Carnegie+ (SLAC, CARL, CNRC, CINC)
JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
BIAGI 81 ZPHY C9 305 + (BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAMB, MSU)
TEODORO 78 PL 77B 451 +Diaz, Dionisi, Blokzijl+ (AMST, CERN, NIJM, OXF) JP
BRIEFEL 77 PR D16 2706 +Gourevitch, Chang+ (BRAN, UMD, SYRA, TUFT)
Also 69 PRL 23 884 Apsell+ (BRAN, UMD, SYRA, TUFT)
GAY 76 NC 31A 593 +Jeanneret, Bogdanski+ (NEUC, LAUS, LIVP, LPNP)
GAY 76C PL 62B 477 +Armenteros, Berge+ (AMST, CERN, NIJM) IJ
DIBIANCA 75 NP B98 137 +Endorf (CMU)
BADIER 72 NP B37 429 +Barrelet, Charlton, Videau (EPOL)
APSELL 70 PRL 24 777 + (BRAN, UMD, SYRA, TUFT) I
CRENNELL 70B PR D1 847 +Karshon, Lai, O'Neall, Scarr, Schumann (BNL)
ALITTI 69 PRL 22 79 +Barnes, Flaminio, Metzger+ (BNL, SYRA) I
DAUBER 69 PR 179 1262 +Berge, Hubbard, Merrill, Miller (LRL)
TRIPP 67 NP B3 10 +Leith+ (LRL, SLAC, CERN, HEID, SACL)
BADIER 65 PL 16 171 +Demoulin, Goldberg+ (EPOL, SACL, AMST) I
SMITH 65B Athens Conf. 251 +Lindsey (LRL)
SMITH 65C PRL 14 25 +Lindsey, Button-Shafer, Murray (LRL) IJP
HALSTEINSLID 63 Siena Conf. 1 73 + (BERG, CERN, EPOL, RHEL, LOUC) I

OTHER RELATED PAPERS

TEODORO 78 PL 77B 451 +Diaz, Dionisi, Blokzijl+ (AMST, CERN, NIJM, OXF) JP
BRIEFEL 75 PR D12 1859 +Gourevitch+ (BRAN, UMD, SYRA, TUFT)
SCHMIDT 73 Purdue Conf. 363 (BRAN)
MERRILL 68 PR 167 1202 +Shafer (LRL)
SMITH 64 PRL 13 61 +Lindsey, Murray, Button-Shafer+ (LRL) IJP

$\Xi(1950)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

We list here everything reported between 1875 and 2000 MeV. The accumulated evidence for a Ξ near 1950 MeV seems strong enough to include a $\Xi(1950)$ in the main Baryon Table, but not much can be said about its properties. In fact, there may be more than one Ξ near this mass.

$\Xi(1950)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1950±15 OUR ESTIMATE					
1944± 9	129	BIAGI	87	SPEC	$\Xi^- \mathrm{Be} \to (\Xi^- \pi^+)\pi^- X$
1963± 5±2	63	BIAGI	87C	SPEC	$\Xi^- \mathrm{Be} \to (\Lambda \overline{K}^0) X$
1937± 7	150	BIAGI	81	SPEC	SPS hyperon beam
1961±18	139	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^- \pi^+ X$
1936±22	44	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^0 \pi^- X$
1964±10	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
1900±12		DIBIANCA	75	DBC	$\Xi\pi$
1952±11	25	ROSS	73C		$(\Xi\pi)^-$
1956± 6	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
1955±14	21	GOLDWASSER	70	HBC	$\Xi\pi$
1894±18	66	DAUBER	69	HBC	$\Xi\pi$
1930±20	27	ALITTI	68	HBC	$\Xi^- \pi^+$
1933±16	35	BADIER	65	HBC	$\Xi^- \pi^+$

$\Xi(1950)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
60±20 OUR ESTIMATE					
100±31	129	BIAGI	87	SPEC	$\Xi^- \mathrm{Be} \to (\Xi^- \pi^+)\pi^- X$
25±15±1.2	63	BIAGI	87C	SPEC	$\Xi^- \mathrm{Be} \to (\Lambda \overline{K}^0) X$
60± 8	150	BIAGI	81	SPEC	SPS hyperon beam
159±57	139	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^- \pi^+ X$
87±26	44	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^0 \pi^- X$
60±39	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
63±78		DIBIANCA	75	DBC	$\Xi\pi$
38±10		ROSS	73C		$(\Xi\pi)^-$
35±11	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
56±26	21	GOLDWASSER	70	HBC	$\Xi\pi$
98±23	66	DAUBER	69	HBC	$\Xi\pi$
80±40	27	ALITTI	68	HBC	$\Xi^- \pi^+$
140±35	35	BADIER	65	HBC	$\Xi^- \pi^+$

$\Xi(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	seen
Γ_2	$\Sigma\overline{K}$	possibly seen
Γ_3	$\Xi\pi$	seen
Γ_4	$\Xi(1530)\pi$	
Γ_5	$\Xi\pi\pi$ (not $\Xi(1530)\pi$)	

$\Xi(1950)$ BRANCHING RATIOS

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ Γ_2/Γ_1

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2.3	90	0	BIAGI	87C	SPEC	Ξ^- Be 116 GeV

$\Gamma(\Sigma\overline{K})/\Gamma_{\mathrm{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
possibly seen	17	HASSALL	81	HBC	$K^- p$ 6.5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ Γ_3/Γ_4

VALUE	*DOCUMENT ID*		*TECN*
$2.8^{+0.7}_{-0.6}$	APSELL	70	HBC

$\Gamma(\Xi\pi\pi\ (\mathrm{not}\ \Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ Γ_5/Γ_4

VALUE	*DOCUMENT ID*		*TECN*
0.0±0.3	APSELL	70	HBC

$\Xi(1950)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
BIAGI	87C	ZPHY C34 175	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
BIAGI	81	ZPHY C9 305	+	(BRIS, CAMB, GEVA, HEID, LAUS, LOQM, RHEL)
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAMB, MSU)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFT)
Also	70	Duke Conf. 317	Briefel+	(BRAN, UMD, SYRA, TUFT)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ROSS	73C	Purdue Conf. 345	+Lloyd, Radojicic	(OXF)
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)
APSELL	70	PRL 24 777	+	(BRAN, UMD, SYRA, TUFT)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
ALITTI	68	PRL 21 1119	+Flaminio, Metzger, Radojicic+	(BNL, SYRA)
BADIER	65	PL 16 171	+Demoulin, Goldberg+	(EPOL, SACL, AMST)

$\Xi(2030)$

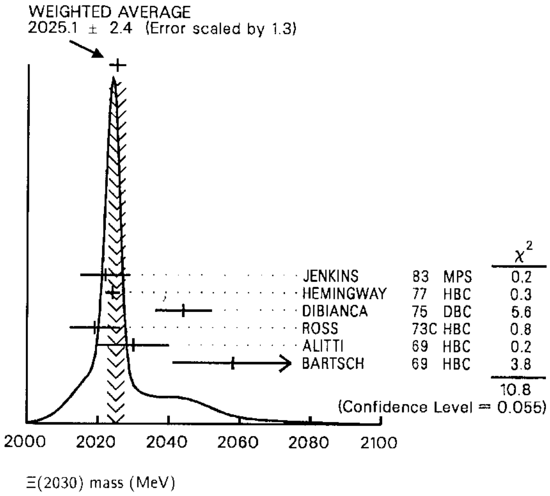
$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$Status: ∗∗∗

The evidence for this state has been much improved by HEMINGWAY 77, who see an eight standard deviation enhancement in $\Sigma\overline{K}$ and a weaker coupling to $\Lambda\overline{K}$. ALITTI 68 and HEMINGWAY 77 observe no signals in the $\Xi\pi\pi$ (or $\Xi(1530)\pi$) channel, in contrast to DIBIANCA 75. The decay $(\Lambda/\Sigma)\overline{K}\pi$ reported by BARTSCH 69 is also not confirmed by HEMINGWAY 77.

A moments analysis of the HEMINGWAY 77 data indicates at a level of three standard deviations that $J \geq 5/2$.

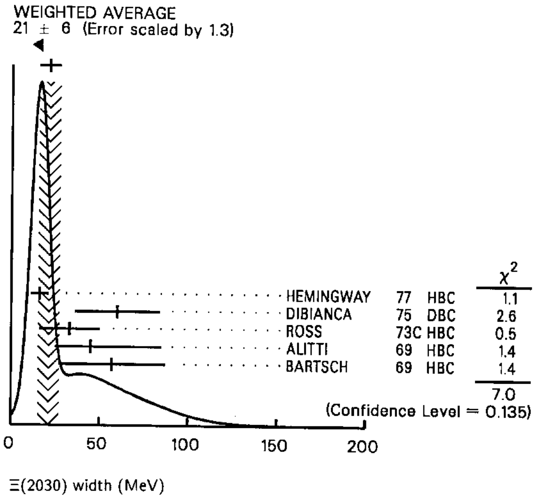
$\Xi(2030)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2025 ± 5 OUR ESTIMATE						
2025.1± 2.4 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
2022 ± 7		JENKINS	83	MPS	−	$K^- p \to K^+ \mathrm{MM}$
2024 ± 2	200	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c
2044 ± 8		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
2019 ± 7	15	ROSS	73C	HBC	−0	$\Sigma\overline{K}$
2030 ±10	42	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
2058 ±17	40	BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c



$\Xi(2030)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
20^{+15}_{-5} **OUR ESTIMATE**						
21± 6 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
16± 5	200	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c
60+24		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
33±17	15	ROSS	73C	HBC	−0	$\Sigma\overline{K}$
45^{+40}_{-20}		ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
57+30		BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c



Ξ(2030) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	~ 20 %
Γ_2	$\Sigma\overline{K}$	~ 80 %
Γ_3	$\Xi\pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi\pi\pi$ (not $\Xi(1530)\pi$)	small
Γ_6	$\Lambda\overline{K}\pi$	small
Γ_7	$\Sigma\overline{K}\pi$	small

Ξ(2030) BRANCHING RATIOS

$\Gamma(\Xi\pi)/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ $\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	ALITTI	69	HBC	−	1 standard dev. limit

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.19	95	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K})/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ $\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.25±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Lambda\overline{K})/\Gamma(\Sigma\overline{K})$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.22±0.09	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K})/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75±0.20	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi\pi) + \Gamma(\Xi(1530)\pi)]$ $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	ALITTI	69	HBC	−	1 standard dev. limit

$[\Gamma(\Xi(1530)\pi) + \Gamma(\Xi\pi\pi\ (\text{not}\ \Xi(1530)\pi))]/\Gamma(\Sigma\overline{K})$ $(\Gamma_4+\Gamma_5)/\Gamma_2$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.11	95	[1] HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Lambda\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.32	95	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Sigma\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ Γ_7/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	95	[2] HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

Ξ(2030) FOOTNOTES

[1] For the decay mode $\Xi^- \pi^+ \pi^-$ only.

[2] For the decay mode $\Sigma^\pm K^- \pi^\mp$ only.

Ξ(2030) REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
HEMINGWAY 77 PL 68B 197 +Armenteros+ (AMST, CERN, NIJM, OXF) ||
Also 76C PL 62B 477 Gay, Armenteros, Berge+ (AMST, CERN, NIJM)
DIBIANCA 75 NP B98 137 +Endorf (CMU)
ROSS 73C Purdue Conf. 345 +Lloyd, Radojicic (OXF)
ALITTI 69 PRL 22 79 +Barnes, Flaminio, Metzger+ (BNL, SYRA) |
BARTSCH 69 PL 28B 439 + (AACH, BERL, CERN, LOIC, VIEN)
ALITTI 68 PRL 21 1119 +Flaminio, Metzger, Radojicic+ (BNL, SYRA)

Ξ(2120)

$I(J^P) = \frac{1}{2}(?^?)$ Status: *

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

Ξ(2120) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2137±4	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
2123±7		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

Ξ(2120) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
<20	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
25±12		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

Ξ(2120) DECAY MODES

	Mode
Γ_1	$\Lambda\overline{K}$

Ξ(2120) BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[1] CHLIAPNIK...	79	HBC	$K^+ p \to (\overline{\Lambda} K^+)\ X$
seen	[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

Ξ(2120) FOOTNOTES

[1] CHLIAPNIKOV 79 does not uniquely identify the K^+ in the $(\overline{\Lambda} K^+)\ X$ final state. It also reports bumps with fewer events at 2240, 2540, and 2830 MeV.

[2] GAY 76C sees a 4-standard deviation signal. However, HEMINGWAY 77, with more events from the same experiment points out that the signal is greatly reduced if a cut is made on the 4-momentum u. This suggests an anomalous production mechanism if the Ξ(2120) is real.

Ξ(2120) REFERENCES

CHLIAPNIK... 79 NP B158 253 Chliapnikov, Gerdyukov+ (CERN, BELG, MONS)
HEMINGWAY 77 PL 68B 197 +Armenteros+ (AMST, CERN, NIJM, OXF)
GAY 76C PL 62B 477 +Armenteros, Berge+ (AMST, CERN, NIJM)

Ξ(2250)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The evidence for this state is mixed. BARTSCH 69 sees a bump of not much statistical significance in $\Lambda\overline{K}\pi$, $\Sigma\overline{K}\pi$, and $\Xi\pi\pi$ mass spectra. GOLDWASSER 70 sees a narrower bump in $\Xi\pi\pi$ at a higher mass. Not seen by HASSALL 81 with 45 events/μb at 6.5 GeV/c. Seen by JENKINS 83. Perhaps seen by BIAGI 87.

Ξ(2250) MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2189 ± 7	66	BIAGI	87	SPEC	−	Ξ^- Be → ($\Xi^-\pi^+\pi^-$) X
2214 ± 5		JENKINS	83	MPS	−	$K^- p \rightarrow K^+$ MM
2295 ± 15	18	GOLDWASSER	70	HBC	−	$K^- p$ 5.5 GeV/c
2244 ± 52	35	BARTSCH	69	HBC		$K^- p$ 10 GeV/c

Ξ(2250) WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
46 ± 27	66	BIAGI	87	SPEC	−	Ξ^- Be → ($\Xi^-\pi^+\pi^-$) X
< 30		GOLDWASSER	70	HBC	−	$K^- p$ 5.5 GeV/c
130 ± 80		BARTSCH	69	HBC		

Ξ(2250) DECAY MODES

	Mode
Γ_1	$\Xi\pi\pi$
Γ_2	$\Lambda\overline{K}\pi$
Γ_3	$\Sigma\overline{K}\pi$

Ξ(2250) REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM, RAL)
JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAMB, MSU)
GOLDWASSER 70 PR D1 1960 +Schultz (ILL)
BARTSCH 69 PL 28B 439 + (AACH, BERL, CERN, LOIC, VIEN)

Ξ(2370)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

Ξ(2370) MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2356 ± 10		JENKINS	83	MPS	−	$K^- p \rightarrow K^+$ MM
2370	50	HASSALL	81	HBC	−0	$K^- p$ 6.5 GeV/c
2373 ± 8	94	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c
2392 ± 27		DIBIANCA	75	DBC		$\Xi 2\pi$

Ξ(2370) WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
80	50	HASSALL	81	HBC	−0	$K^- p$ 6.5 GeV/c
80 ± 25	94	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c
75 ± 69		DIBIANCA	75	DBC		$\Xi 2\pi$

Ξ(2370) DECAY MODES

	Mode
Γ_1	$\Lambda\overline{K}\pi$ Includes $\Gamma_4 + \Gamma_6$.
Γ_2	$\Sigma\overline{K}\pi$ Includes $\Gamma_5 + \Gamma_6$.
Γ_3	$\Omega^- K$
Γ_4	$\Lambda\overline{K}^*(892)$
Γ_5	$\Sigma\overline{K}^*(892)$
Γ_6	$\Sigma(1385)\overline{K}$

Ξ(2370) BRANCHING RATIOS

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
seen	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
seen	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c

$\left[\Gamma(\Lambda\overline{K}\pi) + \Gamma(\Sigma\overline{K}\pi)\right]/\Gamma_{\text{total}}$ $(\Gamma_1+\Gamma_2)/\Gamma$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
seen	50	HASSALL	81	HBC	−0	$K^- p$ 6.5 GeV/c

$\Gamma(\Omega^- K)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.09 ± 0.04	[1] KINSON	80	HBC	−	$K^- p$ 8.25 GeV/c

$\left[\Gamma(\Lambda\overline{K}^*(892)) + \Gamma(\Sigma\overline{K}^*(892))\right]/\Gamma_{\text{total}}$ $(\Gamma_4+\Gamma_5)/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.22 ± 0.13	[1] KINSON	80	HBC	−	$K^- p$ 8.25 GeV/c

$\Gamma(\Sigma(1385)\overline{K})/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.12 ± 0.08	[1] KINSON	80	HBC	−	$K^- p$ 8.25 GeV/c

Ξ(2370) FOOTNOTES

[1] KINSON 80 is a reanalysis of AMIRZADEH 80 with 50% more events.

Ξ(2370) REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAMB, MSU)
AMIRZADEH 80 PL 90B 324 + (BIRM, CERN, GLAS, MSU, LPNP) I
KINSON 80 Toronto Conf. 263 + (BIRM, CERN, GLAS, MSU, LPNP) I
DIBIANCA 75 NP B98 137 +Endorf (CMU)

Ξ(2500)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The ALITTI 69 peak might be instead the Ξ(2370) or might be neither the Ξ(2370) nor the Ξ(2500).

Ξ(2500) MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2505 ± 10		JENKINS	83	MPS	−	$K^- p \rightarrow K^+$ MM
2430 ± 20	30	ALITTI	69	HBC	−	$K^- p$ 4.6–5 GeV/c
2500 ± 10	45	BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c

Ξ(2500) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*
150^{+60}_{-40}	ALITTI	69	HBC	−
59 ± 27	BARTSCH	69	HBC	−0

Ξ(2500) DECAY MODES

	Mode
Γ_1	$\Xi\pi$
Γ_2	$\Lambda\overline{K}$
Γ_3	$\Sigma\overline{K}$
Γ_4	$\Xi\pi\pi$
Γ_5	$\Xi(1530)\pi$
Γ_6	$\Lambda\overline{K}\pi + \Sigma\overline{K}\pi$

Ξ(2500) BRANCHING RATIOS

$\Gamma(\Xi\pi)/\left[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)\right]$ $\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.5	ALITTI	69	HBC	1 standard dev. limit

$\Gamma(\Lambda\overline{K})/\left[\Gamma(\Xi\pi) + \Gamma(\Lambda\overline{K}) + \Gamma(\Sigma\overline{K}) + \Gamma(\Xi(1530)\pi)\right]$ $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*
0.5 ± 0.2	ALITTI	69	HBC	−

$\Gamma(\Sigma\overline{K})/[\Gamma(\Xi\pi)+\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi(1530)\pi)]$ $\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	*DOCUMENT ID*		*TECN*	*CHG*
0.5 ± 0.2	ALITTI	69	HBC	–

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Xi\pi)+\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi(1530)\pi)]$ $\Gamma_5/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.2	ALITTI	69	HBC	1 standard dev. limit

$\Gamma(\Xi\pi\pi)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*
seen	BARTSCH	69	HBC	−0

$[\Gamma(\Lambda\overline{K}\pi)+\Gamma(\Sigma\overline{K}\pi)]/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE	*DOCUMENT ID*		*TECN*	*CHG*
seen	BARTSCH	69	HBC	−0

$\Xi(2500)$ REFERENCES

JENKINS 83 PRL 51 951 +Albright, Diamond+ (FSU, BRAN, LBL, CINC, SMAS)
ALITTI 69 PRL 22 79 +Barnes, Flaminio, Metzger+ (BNL, SYRA) I
BARTSCH 69 PL 28B 439 + (AACH, BERL, CERN, LOIC, VIEN)

Ω BARYONS
$(S=-3,\ I=0)$
$\Omega^- = sss$

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$

The unambiguous discovery in both production and decay was by BARNES 64. The quantum numbers have not actually been measured, but follow from the assignment of the particle to the baryon decuplet. DEUTSCHMANN 78 and BAUBILLIER 78 rule out $J=1/2$ and find consistency with $J=3/2$.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

Ω^- MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1672.43±0.32 OUR AVERAGE					
$1673\ \pm1$	100	HARTOUNI	85	SPEC	80–280 GeV K^0_L C
$1673.0\ \pm0.8$	41	BAUBILLIER	78	HBC	8.25 GeV/c K^-p
$1671.7\ \pm0.6$	27	HEMINGWAY	78	HBC	4.2 GeV/c K^-p
$1673.4\ \pm1.7$	4	[1] DIBIANCA	75	DBC	4.9 GeV/c K^-d
$1673.3\ \pm1.0$	3	PALMER	68	HBC	K^-p 4.6, 5 GeV/c
$1671.8\ \pm0.8$	3	SCHULTZ	68	HBC	K^-p 5.5 GeV/c
$1674.2\ \pm1.6$	5	SCOTTER	68	HBC	K^-p 6 GeV/c
$1672.1\ \pm1.0$	1	[2] FRY	55	EMUL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1671.43 ± 0.78	13	[3] DEUTSCH...	73	HBC	K^-p 10 GeV/c
$1671.9\ \pm1.2$	6	[3] SPETH	69	HBC	See DEUTSCHMANN 73
$1673.0\ \pm8.0$	1	ABRAMS	64	HBC	$\to\Xi^-\pi^0$
$1670.6\ \pm1.0$	1	[2] FRY	55B	EMUL	
1615	1	[4] EISENBERG	54	EMUL	

[1] DIBIANCA 75 gives a mass for each event. We quote the average.

[2] The FRY 55 and FRY 55B events were identified as Ω^- by ALVAREZ 73. The masses assume decay to ΛK^- at rest. For FRY 55B, decay from an atomic orbit could Doppler shift the K^- energy and the resulting Ω^- mass by several MeV. This shift is negligible for FRY 55 because the Ω decay is approximately perpendicular to its orbital velocity, as is known because the Λ strikes the nucleus (L.Alvarez, private communication 1973). We have calculated the error assuming that the orbital n is 4 or larger.

[3] Excluded from the average; the Ω^- lifetimes measured by the experiments differ significantly from other measurements.

[4] The EISENBERG 54 mass was calculated for decay in flight. ALVAREZ 73 has shown that the Ω interacted with an Ag nucleus to give $K^-\Xi$Ag.

$\overline{\Omega}^+$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1672.6±0.7 OUR AVERAGE					
$1672\ \pm1$	72	HARTOUNI	85	SPEC	80–280 GeV K^0_L C
1673.1 ± 1.0	1	FIRESTONE	71B	HBC	12 GeV/c K^+d

Ω^- MEAN LIFE

Measurements with an error $>0.1\times10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.822±0.012 OUR AVERAGE					
0.811 ± 0.037	1096	LUK	88	SPEC	pBe 400 GeV
0.823 ± 0.013	12k	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.822 ± 0.028	2437	BOURQUIN	79B	SPEC	See BOURQUIN 84

Ω^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	ΛK^-	(67.8 ± 0.7) %	
Γ_2	$\Xi^0\pi^-$	(23.6 ± 0.7) %	
Γ_3	$\Xi^-\pi^0$	(8.6 ± 0.4) %	
Γ_4	$\Xi^-\pi^+\pi^-$	$(4.3^{+3.4}_{-1.3})\times10^{-4}$	
Γ_5	$\Xi(1530)^0\pi^-$	$(6.4^{+5.1}_{-2.0})\times10^{-4}$	
Γ_6	$\Xi^0e^-\overline{\nu}_e$	$(5.6\pm2.8)\times10^{-3}$	
Γ_7	$\Xi^-\gamma$	$<2.2\ \times10^{-3}$	90%
	$\Delta S=2$ (ΔS) violating modes		
Γ_8	$\Lambda\pi^-$	ΔS $<1.9\ \times10^{-4}$	90%

Ω^- BRANCHING RATIOS

The BOURQUIN 84 values (which include results of BOURQUIN 79B, a separate experiment) are much more accurate than any other results, and so the other results have been omitted.

$\Gamma(\Lambda K^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.678±0.007	14k	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.686 ± 0.013	1920	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^0\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.236±0.007	1947	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.234 ± 0.013	317	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\pi^0)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.086±0.004	759	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.080 ± 0.008	145	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_4/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$4.3^{+3.4}_{-1.3}$	4	BOURQUIN	84	SPEC	SPS hyperon beam

$\Gamma(\Xi(1530)^0\pi^-)/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$6.4^{+5.1}_{-2.0}$	4	[5] BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 20	1	BOURQUIN	79B	SPEC	See BOURQUIN 84

[5] The same 4 events as in the previous mode, with the isospin factor to take into account $\Xi(1530)^0\to\Xi^0\pi^0$ decays included.

$\Gamma(\Xi^0e^-\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_6/Γ

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
5.6 ± 2.8	14	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 10	3	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\gamma)/\Gamma_{\text{total}}$ Γ_7/Γ

VALUE (units 10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2.2	90	9	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.1	90	0	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Lambda\pi^-)/\Gamma_{\text{total}}$ Γ_8/Γ

$\Delta S=2$. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.9	90	0	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<13	90	0	BOURQUIN	79B	SPEC	See BOURQUIN 84

Ω^- DECAY PARAMETERS

α FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.026±0.026 OUR AVERAGE					
−0.034±0.079	1743	LUK	88	SPEC	pBe 400 GeV
−0.025±0.028	12k	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^0 \pi^-$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.09±0.14	1630	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^- \pi^0$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.05±0.21	614	BOURQUIN	84	SPEC	SPS hyperon beam

REFERENCES FOR Ω^-

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

LUK	88	PR D38 19	+Beretvas, Deck+	(RUTG, WISC, MICH, MINN)
HARTOUNI	85	PRL 54 628	+Atiya, Holmes, Knapp, Lee+	(COLU, ILL, FNAL)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEID, LALO, RAL, STRB)
Also	79	PL 87B 297	Bourquin+	(BRIS, GEVA, HEID, ORSA, RHEL, STRB)
BOURQUIN	79B	PL 88B 192	+	(BRIS, GEVA, HEID, LALO, RAL)
BAUBILLIER	78	PL 78B 342	+	(BIRM, CERN, GLAS, MSU, LPNP) J
DEUTSCH...	78	PL 73B 96	Deutschmann+	(AACH, BERL, CERN, INNS, LOIC+) J
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ALVAREZ	73	PR D8 702		(LBL)
DEUTSCH...	73	NP B61 102	Deutschmann, Kaufmann, Besliv+	(ABCLV Collab.)
FIRESTONE	71B	PRL 26 410	+Goldhaber, Lissauer, Sheldon, Trilling	(LRL)
SPETH	69	PL 29B 252	+	(AACH, BERL, CERN, LOIC, VIEN)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
SCHULTZ	68	PR 168 1509	+	(ILL, ANL, NWES, WISC)
SCOTTER	68	PL 26B 474	+	(BIRM, GLAS, LOIC, MUNI, OXF)
ABRAMS	64	PRL 13 670	+Burnstein, Glasser+	(UMD, NRL)
BARNES	64	PRL 12 204	+Connolly, Crennell, Culwick+	(BNL)
FRY	55	PR 97 1189	+Schneps, Swami	(WISC)
FRY	55B	NC 2 346	+Schneps, Swami	(WISC)
EISENBERG	54	PR 96 541		(CORN)

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$ Status: ∗∗∗

$\Omega(2250)^-$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2252± 9 OUR AVERAGE					
2253±13	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
2251± 9±8	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
55±18 OUR AVERAGE					
81±38	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
48±20	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^- \pi^+ K^-$	seen
Γ_2	$\Xi(1530)^0 K^-$	seen

$\Omega(2250)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0 K^-)/\Gamma(\Xi^- \pi^+ K^-)$ Γ_2/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
~ 1.0	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
0.70±0.20	49	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2250)^-$ REFERENCES

ASTON	87B	PL B194 579	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)
BIAGI	86B	ZPHY C31 33	+	(LOQM, GEVA, RAL, HEID, LAUS, BRIS, CERN)

$\Omega(2380)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Omega(2380)^-$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2384±9±8	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
26±23	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ DECAY MODES

	Mode
Γ_1	$\Xi^- \pi^+ K^-$
Γ_2	$\Xi(1530)^0 K^-$
Γ_3	$\Xi^- \overline{K}^*(892)^0$

$\Omega(2380)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0 K^-)/\Gamma(\Xi^- \pi^+ K^-)$ Γ_2/Γ_1

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.44	90	9	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Gamma(\Xi^- \overline{K}^*(892)^0)/\Gamma(\Xi^- \pi^+ K^-)$ Γ_3/Γ_1

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.5±0.3	21	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2380)^-$ REFERENCES

BIAGI	86B	ZPHY C31 33	-	(LOQM, GEVA, RAL, HEID, LAUS, BRIS, CERN)

$\Omega(2470)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

A peak in the $\Omega^- \pi^+ \pi^-$ mass spectrum with a signal significance claimed to be at least 5.5 standard deviations. There is no reason to seriously doubt the existence of this state, but unless the evidence is overwhelming we usually wait for confirmation from a second experiment before elevating peaks to the Summary Table.

$\Omega(2470)^-$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2474±12	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
72±33	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ DECAY MODES

	Mode
Γ_1	$\Omega^- \pi^+ \pi^-$

$\Omega(2470)^-$ REFERENCES

ASTON	88G	PL B215 799	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, TOKY)

CHARMED BARYONS
$(C = +1)$

$\Lambda_c^+ = udc,\ \Sigma_c^{++} = uuc,\ \Sigma_c^+ = udc,\ \Sigma_c^0 = ddc,$
$\Xi_c^+ = usc,\ \Xi_c^0 = dsc,\ \Omega_c^0 = ssc$

NOTE ON CHARMED BARYONS

Figures 1(a) and 1(b) show the SU(4) multiplets that have as their "ground floors" (a) the SU(3) octet that contains the nucleon and (b) the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only charmed baryons that have been discovered each contain one charmed quark and belong to the first floor of the multiplet shown in Figure 1(a). Figure 2 shows this first floor, pulled apart into two SU(3) multiplets, a $\overline{\mathbf{3}}$ that contains the $\Lambda_c(2285)$ and the $\Xi_c(2470)$, both of which decay weakly, and a **6** that contains the $\Sigma_c(2455)$, which decays strongly to $\Lambda_c\pi$. A second Ξ_c and an Ω_c remain to be discovered to fill out the **6**, and a host of other baryons with one or more charmed quarks are needed to fill out the full SU(4) multiplets in Figure 1. Furthermore, *every* N or Δ baryon resonance "starts" a multiplet like that in Figure 1(a) or 1(b), so the woods are full of charmed baryons, most of which no doubt will forever remain undiscovered.

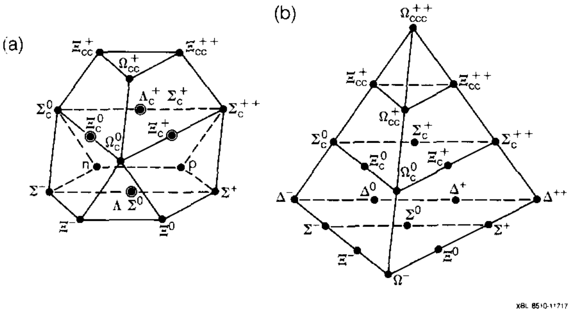


Figure 1. SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet on the "ground floor." (b) The 20-plet with an SU(3) decuplet on the ground floor.

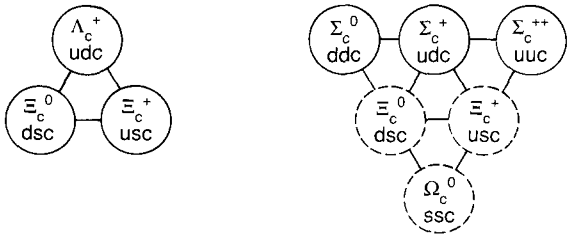


Figure 2. The SU(3) multiplets on the "first floor" of the SU(4) multiplet of Figure 1(a). The particles in dashed circles have yet to be discovered.

The states of the $\overline{\mathbf{3}}$ multiplet are antisymmetric under interchange of the two light quarks (the u, d, and s quarks), and the states of the **6** multiplet are symmetric under interchange of these quarks. Actually, there is probably some mixing between the pure $\overline{\mathbf{3}}$ and **6** Ξ_c states (they have all the same ordinary quantum numbers) to form the physical Ξ_c states.

It need hardly be said that the flavor symmetries Figure 1 displays are very badly broken, but the figure is the simplest way to see what charmed baryons should exist. For an entry into the literature on models of charmed baryons, see Ref. 1.

References

1. K. Maltman and N. Isgur, Phys. Rev. **D22**, 1701 (1980); S. Capstick and N. Isgur, Phys. Rev. **D34**, 2809 (1986); W. Kwong, J.L. Rosner, and C. Quigg, Ann. Rev. Nucl. Part. Sci. **37**, 325 (1987); and S. Fleck and J.M. Richard, Part. World **1**, 67 (1990).

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$

J has not actually been measured yet. $J = 1/2$ is of course expected. The quark content is udc.

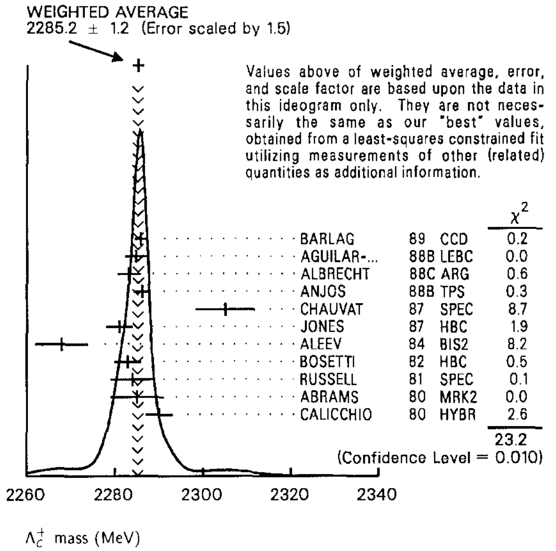
We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1986 edition (Physics Letters 170B) or in earlier editions.

Λ_c^+ MASS

We only average the measurements with an error less than 10 MeV. It seems clear that the early values around 2260 MeV were too low.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2285.2± 1.2 OUR FIT	Error includes scale factor of 1.5.			
2285.2± 1.2 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.			
2285.8± 0.6± 1.2	101	BARLAG 89	CCD	$pK^-\pi^+$ + c.c.
2284.7± 2.3± 0.5	5	AGUILAR-... 88B	LEBC	$pK^-\pi^+$ + c.c.
2283.1± 1.7± 2.0	628	ALBRECHT 88C	ARG	$pK^-\pi^+$, $p\overline{K}^0$, $\Lambda 3\pi$
2286.2± 1.7± 0.7	97	ANJOS 88B	TPS	$pK^-\pi^+$ + c.c.
2305 ± 3 ± 6	621	CHAUVAT 87	SPEC	pp 63 GeV ISR
2281 ± 3	2	JONES 87	HBC	$pK^-\pi^+$
2268 ± 6	187	ALEEV 84	BIS2	$\Lambda\pi^+\pi^+\pi^-$, $pK_S^0\pi^+\pi^-$
2283 ± 3	3	BOSETTI 82	HBC	$pK^-\pi^+$
2284 ± 5	55	RUSSELL 81	SPEC	$p\overline{K}^0$ + c.c.
2285 ± 6	39	ABRAMS 80	MRK2	$pK^-\pi^+$ + c.c.
2290 ± 3	1	CALICCHIO 80	HYBR	$pK^-\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2301 ±17	4	ADAMOVICH 87	EMUL	γA 20–70 GeV/c
2285.6± 1.1	14	BARLAG 87	CCD	See BARLAG 89
2293 ± 6 ±30	78	DIESBURG 87	SPEC	$nA \sim 600$ GeV
2300 ±25	1	AMMAR 86	EMUL	$\Sigma^+\pi^+\pi^-$
2266 ±13	8	USHIDA 86	EMUL	Wideband ν
2270 ±15	3	KITAGAKI 82	DBC	$\Sigma^0\pi^+$
2260 ±20	1	ALLASIA 80	EMUL	$pK^-\pi^+$
2275 ±10	19	KITAGAKI 80	DBC	$\Lambda\pi^+$, $p\overline{K}^0$
2257 ±10	6	BALTAY 79	HLBC	$\Lambda\pi^+$
2254 ±12	1	CNOPS 79	DBC	$pK^*(892)^-\pi^+$
2262 ±10	30	[1] GIBONI 79	SPEC	$pK^-\pi^+$
2260 ±10	60	KNAPP 76	SPEC	$\overline{\Lambda}2\pi^-\pi^+$
2260 ±20	1	CAZZOLI 75	HBC	$\Lambda 2\pi^+\pi^-$

[1] GIBONI 79 has been changed from 2255 ± 4 MeV by the authors; see KERNAN 79.



Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our "best" values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

Λ_c^+ MEAN LIFE

Measurements with an error $> 1.0 \times 10^{-13}$ s have been omitted.

VALUE (10^{-13} s)	EVTS	DOCUMENT ID	TECN	COMMENT
$1.91^{+0.17}_{-0.13}$ OUR AVERAGE				
$1.96^{+0.23}_{-0.20}$	101	BARLAG 89	CCD	$pK^- \pi^+$ + c.c.
$1.2\ ^{+0.5}_{-0.3}$	9	AGUILAR-... 88B	LEBC	
$2.2\ \pm 0.3\ \pm 0.2$	97	ANJOS 88B	TPS	$pK^- \pi^+$ + c.c.
$2.3\ ^{+0.9}_{-0.6}\ \pm 0.4$	11	ADAMOVICH 87	EMUL	γA 20–70 GeV/c
$1.1\ ^{+0.8}_{-0.4}$	9	AMENDOLIA 87	SPEC	γ Ge-Si, $pK^- \pi^+ \pi^0$
$2.0\ ^{+0.7}_{-0.5}$	13	USHIDA 86	EMUL	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.4\ ^{+0.5}_{-0.3}\ \pm 0.3$	14	BARLAG 87	CCD	See BARLAG 89

Λ_c^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\overline{K}^0$	(1.6 ± 0.6) %
Γ_2	$pK^- \pi^+$	(2.8 ± 0.8) %
Γ_3	$p\overline{K}^*(892)^0$	[a] $(6.0 \pm 3.1) \times 10^{-3}$
Γ_4	$\Delta(1232)^{++} K^-$	$(5.7 \pm 2.8) \times 10^{-3}$
Γ_5	$p\overline{K}^0 \pi^+ \pi^-$	(8.1 ± 3.5) %
Γ_6	$pK^- \pi^+ \pi^0$	seen
Γ_7	$pK^*(892)^- \pi^+$	seen
Γ_8	$\Delta(1232)\overline{K}^*(892)$	seen
Γ_9	Λ anything	(27 ± 9) %
Γ_{10}	$\Lambda \pi^+$	seen
Γ_{11}	$\Lambda \pi^+ \pi^+ \pi^-$	(1.9 ± 0.7) %
Γ_{12}	$\Sigma^0 \pi^+$	seen
Γ_{13}	$\Sigma^\pm$ anything	(10 ± 5) %
Γ_{14}	$\Sigma^+ \pi^0$	
Γ_{15}	$\Sigma^+ \pi^+ \pi^-$	(10 ± 8) %
Γ_{16}	e^+ anything	(4.5 ± 1.7) %
Γ_{17}	pe^+ anything	(1.8 ± 0.9) %
Γ_{18}	$p\overline{K}^0 \pi^- \pi^0 e^+ \nu$	
Γ_{19}	Λe^+ anything	(1.1 ± 0.8) %
Γ_{20}	p hadrons	
Γ_{21}	all except Γ_1, Γ_2, Γ_5, and Γ_{11}	[b] (86 ± 5) %

[a] Corrected for the $\overline{K}^*(892)^0 \to \overline{K}^0 \pi^0$ mode.

[b] A dummy mode used by the fit.

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 9 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 = 1.6$ for 5 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	84			
x_5	51	61		
x_{11}	66	79	78	
x_{21}	−70	−79	−96	−88
	x_1	x_2	x_5	x_{11}

Λ_c^+ BRANCHING RATIOS

$\Gamma(pK^- \pi^+)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.028 ± 0.008 OUR FIT					
0.025 ± 0.009 OUR AVERAGE					
0.041 ± 0.024		208	[2] ALBRECHT 88E	ARG	
0.022 ± 0.010		39	ABRAMS 80	MRK2	$e^+ e^-$ 5.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.044	90	6	[3] AGUILAR-... 88B	LEBC	pp 27.4 GeV

[2] ALBRECHT 88E use their result $B(B \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to pK^- \pi^+) = (0.30 \pm 0.12 \pm 0.06)$% plus $B(B \to \Lambda_c^+ X) = (7.4 \pm 2.9)$% from other measurements of inclusive proton and Λ yields in B decays.

[3] The AGUILAR-BENITEZ 88B lower limit is, on the face of it, in disagreement with the ABRAMS 80 measurement. However, the limit assumes that $\tau(\Lambda_c) = 1.2 \times 10^{-13}$ s, and it "decreases by 20% [to >0.035] assuming a lifetime of 1.7×10^{-13} s instead." Our average for $\tau(\Lambda_c)$ is still higher, $(1.91^{+0.17}_{-0.13}) \times 10^{-13}$ s (see the mean-life section), which if correct would further reduce the limit. The two experiments then do not disagree so badly. Given the very limited statistics and the uncertainties all around, we include the ABRAMS 80 result, which claims to be a measurement rather than a limit, in our average.

$\Gamma(p\overline{K}^0)/\Gamma(pK^- \pi^+)$ — Γ_1/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.58 ± 0.11 OUR FIT					
0.58 ± 0.11 OUR AVERAGE					
$0.55 \pm 0.17 \pm 0.14$		45	ANJOS 90	TPS	γ Be 70–260 GeV
$0.62 \pm 0.15 \pm 0.03$		73	ALBRECHT 88C	ARG	$e^+ e^-$ 10 GeV
$0.5\ \pm 0.25$		12	WEISS 80	MRK2	$e^+ e^-$ 5.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.67	90	50	RUSSELL 81	SPEC	Photoproduction

$\Gamma(p\overline{K}^*(892)^0)/\Gamma(pK^- \pi^+)$ — Γ_3/Γ_2

Corrected for the $\overline{K}^{*0} \to \overline{K}^0 \pi^0$ mode.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.22 ± 0.09 OUR AVERAGE				
0.42 ± 0.24	12	BASILE 81B	CNTR	$pp \to \Lambda_c^+ e^- X$
0.18 ± 0.10		WEISS 80	MRK2	$e^+ e^-$ 5.2 GeV

$\Gamma(\Delta(1232)^{++} K^-)/\Gamma(pK^- \pi^+)$ — Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.20 ± 0.08 OUR AVERAGE Error includes scale factor of 1.3.				
0.40 ± 0.17	17	BASILE 81B	CNTR	$pp \to \Lambda_c^+ e^- X$
0.17 ± 0.07		WEISS 80	MRK2	$e^+ e^-$ 5.2 GeV

$\Gamma(p\overline{K}^0 \pi^+ \pi^-)/\Gamma(p\overline{K}^0)$ — Γ_5/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.3	90	45	RUSSELL 81	SPEC	Photoproduction

$\Gamma(p\overline{K}^0 \pi^+ \pi^-)/\Gamma(pK^- \pi^+)$ — Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	90	ANJOS 90	TPS	γ Be 70–260 GeV

$\Gamma(pK^- \pi^+ \pi^0)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	44	AMENDOLIA 87	SPEC	γ Ge-Si

$\Gamma(pK^*(892)^- \pi^+)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	1	CNOPS 79	DBC	νN in BNL 7-ft

$\Gamma(\Delta(1232)\overline{K}^*(892))/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	35	AMENDOLIA 87	SPEC	γ Ge-Si

$\Gamma(\Lambda\,\text{anything})/\Gamma_{\text{total}}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.27±0.09 OUR AVERAGE				
0.49±0.24		ADAMOVICH 87	EMUL	γA 20–70 GeV/c
0.23±0.10	8	[4] ABE 86	HYBR	20 GeV γp

[4] ABE 86 includes Λ's from Σ^0 decay.

$\Gamma(\Lambda\pi^+)/\Gamma(p\overline{K}^0)$ Γ_{10}/Γ_1

We regard this mode as seen, but with a limit given by the ALBRECHT 88C result.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
seen OUR EVALUATION					
<0.26	90		[5] ALBRECHT 88C	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	40	RUSSELL 81	SPEC	Photoproduction
$0.51^{+0.62}_{-0.27}$		9	KITAGAKI 80	DBC	$\nu\, d$ in FNAL 15-ft
$0.67^{+0.78}_{-0.35}$		5	[6] BALTAY 79	HLBC	ν Ne-H in 15-ft

[5] This ALBRECHT 88C result is redundant with their limit on $\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$, below.

[6] Calculated by KITAGAKI 80 from BALTAY 79 results.

$\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$ Γ_{10}/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.16	90	ALBRECHT 88C	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.33	90	ANJOS 90	TPS	γBe 70–260 GeV
<0.8	90	WEISS 80	MRK2	e^+e^- 5.2 GeV

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.019±0.007 OUR FIT				
0.028±0.007±0.011	70	[7] BOWCOCK 85	CLEO	e^+e^- 10.5 GeV

[7] See BOWCOCK 85 for assumptions made on charm production and Λ_c production from charm to get this result.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(p\overline{K}^0)$ Γ_{11}/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.1	90	220	RUSSELL 81	SPEC	Photoproduction

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ Γ_{11}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.68±0.15 OUR FIT					
0.64±0.15 OUR AVERAGE					
0.82±0.29±0.27		44	ANJOS 90	TPS	γBe 70–260 GeV
0.61±0.16±0.04		105	ALBRECHT 88C	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90		WEISS 80	MRK2	e^+e^- 5.2 GeV

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(\Lambda\pi^+\pi^+\pi^-)$ Γ_5/Γ_{11}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
4.3±1.2 OUR FIT				
4.3±1.2	130	ALEEV 84	BIS2	nC 40–70 GeV

$\Gamma(\Sigma^\pm\,\text{anything})/\Gamma_{\text{total}}$ Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.1±0.05	5	ABE 86	HYBR	20 GeV γp

$\Gamma(\Sigma^0\pi^+)/\Gamma_{\text{total}}$ Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
seen	3	KITAGAKI 82	DBC	$\nu\, d$ in FNAL 15-ft

$\Gamma(\Sigma^+\pi^+\pi^-)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.10±0.08		ADAMOVICH 87	EMUL	γA 20–70 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	1	AMMAR 86	EMUL	νA

$\Gamma(p\,\text{hadrons})/\Gamma_{\text{total}}$ Γ_{20}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.41±0.24	ADAMOVICH 87	EMUL	γA 20–70 GeV/c

$\Gamma(pe^+\,\text{anything})/\Gamma_{\text{total}}$ Γ_{17}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.018±0.009	[8] VELLA 82	MRK2	e^+e^- 4.5–6.8 GeV

[8] VELLA 82 includes protons from Λ decay.

$\Gamma(\Lambda e^+\,\text{anything})/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.011±0.008			[9] VELLA 82	MRK2	e^+e^- 4.5–6.8 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.022	90	1	BALLAGH 81	HYBR	ν Ne-H in 15-ft

[9] VELLA 82 includes Λ's from Σ^0 decay.

$\Gamma(\Lambda e^+\,\text{anything})/\Gamma(\Lambda\,\text{anything})$ Γ_{19}/Γ_9

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.027±0.017	[10] SON 82	DBC	$\nu\, d$ in FNAL 15-ft

[10] SON 82 uses own data and $\Lambda\mu^- e^+$ events of MURTAGH 79.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(\Lambda e^+\,\text{anything})$ Γ_{11}/Γ_{19}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.7	90	KLEIN 89	MRK2	e^+e^- 29 GeV

$\Gamma(e^+\,\text{anything})/\Gamma_{\text{total}}$ Γ_{16}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.045±0.017	VELLA 82	MRK2	e^+e^- 4.5–6.8 GeV

REFERENCES FOR Λ_c^+

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1986 edition (Physics Letters **170B**) or in earlier editions.

ANJOS	90	PR D41 801	+Appel, Bean+	(Tagged Photon Spectrometer Collab.)
BARLAG	89	PL B218 374	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
KLEIN	89	PRL 62 2444	+Himel, Abrams, Amidei, Baden+	(Mark II Collab.)
AGUILAR-...	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	87	PL B189 254	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	87B	PL B199 462	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	88	SJNP 48 833 Translated from YAF 48 1310.	Begalli, Otter, Schulte, Gensch+	(LEBC-EHS Collab.)
ALBRECHT	88C	PL B207 109	+	(ARGUS Collab.)
ALBRECHT	88E	PL B210 263	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88B	PRL 60 1379	+Appel+	(Tagged Photon Spectrometer Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
Also	87	SJNP 46 447 Translated from YAF 46 799.	Viaggi, Gessaroli+	(Photon Emulsion Collab.)
AMENDOLIA	87	ZPHY C36 513	+Bagliesi, Batignani, Beck+	(CERN NA1 Collab.)
BARLAG	87	PL B184 283	+	(MPIM, CERN, RAL, ANIK, BRIS, CRAC+)
CHAUVAT	87	PL B199 304	+Cousins, Hayes+	(CERN, UCLA, SACL, UDCF)
DIESBURG	87	PRL 59 2711	+Ladbury+	(COLO, ILL, FNAL, BGNA, MILA, INFN)
JONES	87	ZPHY C36 593	+Jones+	(BIRM, CERN, LOIC, MPIM, OXF, LOUC)
ABE	86	PR D33 1	+	(SLAC Hybrid Facility Photon Collab.)
AMMAR	86	JETPL 43 515 Translated from ZETFP 43 401.	+Ammosov, Bakic, Baranov, Burnett+	(ITEP)
USHIDA	86	PRL 56 1767	+Kondo+	(AICH, FNAL, GIFU, GYEO, KOBE, SEOU+)
BOWCOCK	85	PRL 55 923	+Giles, Hassard, Kinoshita+	(CLEO Collab.)
ALEEV	84	ZPHY C23 333	+Arefiev, Balandin, Berdyshev+	(BIS-2 Collab.)
BOSETTI	82	PL 109B 234	+Graessler+	(AACH, BONN, CERN, MPIM, OXF)
KITAGAKI	82	PRL 48 299	+Tanaka, Yuta+	(TOHO, IIT, UMD, STON, TUFT)
SON	82	PRL 49 1128	+Snow, Chang+	(UMD, IIT, STON, TOHO, TUFT)
VELLA	82	PRL 48 1515	+Trilling, Abrams, Alam+	(SLAC, LBL, UCB)
BALLAGH	81	PR D24 7	+Bingham+	(LBL, UCB, FNAL, HAWA, WASH, WISC)
BASILE	81B	NC 62A 14	+Romeo+	(CERN, BGNA, PGIA, FRAS)
RUSSELL	81	PRL 46 799	+Avery, Butler, Gladding+	(ILL, FNAL, COLU)
ABRAMS	80	PRL 44 10	+Alam, Blocker, Boyarski+	(SLAC, LBL)
ALLASIA	80	NP B176 13	+	(ANKA, LIBH, CERN, DUUC, LOUC, KEYN+)
CALICCHIO	80	PL 93B 521	+	(BARI, BIRM, BRUX, CERN, EPOL, RHEL+)
KITAGAKI	80	PRL 45 955	+Tanaka, Yuta+	(TOHO, IIT, UMD, STON, TUFT)
WEISS	80	Toronto Conf. 319		(SLAC)
BALTAY	79	PRL 42 1721	+Caroumbalis, French, Hibbs+	(COLU, BNL)
CNOPS	79	PRL 42 197	+Connolly, Kahn, Kirk, Murtagh, Palmer+	(BNL)
GIBONI	79	PL 85B 437	+	(AACH, CERN, HARV, MUNI, NWES, UCR)
KERNAN	79	Lepton Conf. FNAL		(UCR)
MURTAGH	79	Fermilab Symp. 277		(FNAL)
KNAPP	76	PRL 37 882	+Lee, Leung, Smith+	(COLU, HAWA, ILL, FNAL)
CAZZOLI	75	PRL 34 1125	+Cnops, Connolly, Louttit, Murtagh+	(BNL)

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$

J^P not confirmed. $1/2^+$ is the quark model prediction.

$\Sigma_c(2455)$ MASSES

The mass measurements in this section are redundant with the mass difference measurements that follow. We get the masses by adding the $\Sigma_c(2455) - \Lambda_c^+$ mass differences to the Λ_c^+ mass.

$\Sigma_c(2455)^{++}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
2453.0± 1.2 OUR FIT Error includes scale factor of 1.4.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2449 ± 3	2	JONES 87	HBC	++	νp in BEBC
2480	1	ADAMOVICH 84	EMUL	++	γA (OMEGA)
2454 ± 5	1	BOSETTI 82	HBC	++	See JONES 87
2425 ±10	6	BALTAY 79	HLBC	++	ν Ne-H in 15-ft
>2439	1	BARISH 77B	DBC	++	νd in 12-ft
2426 ±12	1	CAZZOLI 75	HBC	++	νp in BNL 7-ft

$\Sigma_c(2455)^{+}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
2453.2±3.2 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2457 ±4	1	CALICCHIO 80	HBC	+	νp in BEBC-TST

$\Sigma_c(2455)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2452.7± 1.3 OUR FIT Error includes scale factor of 1.4.						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2462 ±26	1	AMMAR	86	EMUL	0	νA
~ 2460	9	KNAPP	76	SPEC	0	γBe

$\Sigma_c(2455) - \Lambda_c^+$ MASS DIFFERENCES

$\Sigma_c^{++} - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
167.8± 0.4 OUR FIT						
167.7± 0.4 OUR AVERAGE						
167.8± 0.4±0.3	54	BOWCOCK	89	CLEO	++	$e^+ e^-$ 10 GeV
168.2± 0.5±1.6	92	ALBRECHT	88D	ARG	++	$e^+ e^-$ 10 GeV
167.4± 0.5±2.0	46	DIESBURG	87	SPEC	++	nA ~ 600 GeV
167 ± 1	2	JONES	87	HBC	++	νp in BEBC
168 ± 3	6	BALTAY	79	HLBC	++	ν Ne-H in 15-ft
• • • We do not use the following data for averages, fits, limits, etc. • • •						
166 ± 1	1	BOSETTI	82	HBC	++	See JONES 87
166 ±15	1	CAZZOLI	75	HBC	++	νp in BNL 7-ft

$\Sigma_c^{+} - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
168.0±3.0 OUR FIT						
168 ±3	1	CALICCHIO	80	HBC	+	νp in BEBC-TST

$\Sigma_c^{0} - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
167.6±0.6 OUR FIT Error includes scale factor of 1.1.						
168.4±1.0±0.3	14	ANJOS	89D	TPS	0	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
167.9±0.5±0.3	48	[1] BOWCOCK	89	CLEO	0	$e^+ e^-$ 10 GeV
167.0±0.5±1.6	70	[1] ALBRECHT	88D	ARG	0	$e^+ e^-$ 10 GeV
178.2±0.4±2.0	85	[2] DIESBURG	87	SPEC	0	nA ~ 600 GeV
163 ±2	1	AMMAR	86	EMUL	0	νA

[1] This result enters the fit through the $\Sigma_c^{++} - \Sigma_c^0$ mass difference given in the next section.

[2] See the note in the $\Sigma_c^{++} - \Sigma_c^0$ mass difference section below.

$\Sigma_c(2455)$ MASS DIFFERENCES

$\Sigma_c^{++} - \Sigma_c^0$ MASS DIFFERENCE

DIESBURG 87 is completely incompatible with the other experiments, which is surprising since it agrees with them about the $\Sigma_c(2455)^{++} - \Lambda_c^+$ mass difference. We go with the majority here.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.2±0.5 OUR FIT Error includes scale factor of 1.2.				
0.4±0.6 OUR AVERAGE Error includes scale factor of 1.3.				
− 0.1±0.6±0.1	BOWCOCK	89	CLEO	$e^+ e^-$ 10 GeV
+ 1.2±0.7±0.3	ALBRECHT	88D	ARG	$e^+ e^-$ ~ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 10.8±2.9	DIESBURG	87	SPEC	nA ~ 600 GeV

$\Sigma_c(2455)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+ \pi$	100 %

$\Sigma_c(2455)$ REFERENCES

ANJOS 89D PRL 62 1721 +Appel, Bean, Bracker, Browder+ (TPS Collab.)
BOWCOCK 89 PRL 62 1240 +Kinoshita, Pipkin, Procario, Wilson+ (CLEO Collab.)
ALBRECHT 88D PL B211 489 +Boeckmann, Glaeser+ (ARGUS Collab.)
DIESBURG 87 PRL 59 2711 +Ladbury+ (COLO, ILL, FNAL, BGNA, MILA, INFN)
JONES 87 ZPHY C36 593 +Jones+ (BIRM, CERN, LOIC, MPIM, OXF, LOUC)
AMMAR 86 JETPL 43 515 +Ammosov, Bakic, Baranov, Burnett+ (ITEP)
Translated from ZETFP 43 401.
ADAMOVICH 84 PL 140B 119 +Alexandrov, Bolta, Bravo+ (WA58 Collab.)
BOSETTI 82 PL 109B 234 +Graessler+ (AACH, BONN, CERN, MPIM, OXF)
CALICCHIO 80 PL 93B 521 + (BARI, BIRM, BRUX, CERN, EPOL, RHEL+)
BALTAY 79 PRL 42 1721 +Caroumbalis, French, Hibbs+ (COLU, BNL)
BARISH 77B PR D15 1 +Derrick, Dombeck, Musgrave+ (ANL, PURD)
KNAPP 76 PRL 37 882 +Lee, Leung, Smith+ (COLU, HAWA, ILL, FNAL)
CAZZOLI 75 PRL 34 1125 +Cnops, Connolly, Louttit, Murtagh+ (BNL)

Ξ_c^+

According to the quark model, the Ξ_c^+ (quark content usc) and Ξ_c^0 form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Ξ_c^+ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2466.8± 2.4 OUR FIT					
2466.5± 2.5 OUR AVERAGE					
2467 ± 3 ± 4	23	ALAM	89	CLEO	$e^+ e^-$ 10.6 GeV
2466.5± 2.7± 1.2	5	BARLAG	89C	CCD	π^- Cu 230 GeV
2459 ± 5 ±30	56	[1] COTEUS	87	SPEC	nA ~ 600 GeV
2460 ±25	82	BIAGI	83	SPEC	Σ^- Be 135 GeV

[1] Although COTEUS 87 claims to agree well with BIAGI 83 on the mass and width, there appears to be a discrepancy between the two experiments. BIAGI 83 sees a single peak (stated significance about 6 standard deviations) in the $\Lambda K^- \pi^+ \pi^+$ mass spectrum. COTEUS 87 sees *two* peaks in the same spectrum, one at the Ξ_c^+ mass, the other 75 MeV lower. The latter is attributed to $\Xi_c^+ \rightarrow \Sigma^0 K^- \pi^+ \pi^+ \rightarrow (\Lambda\gamma) K^- \pi^+ \pi^+$, with the γ unseen. The *combined* significance of the double peak is stated to be 5.5 standard deviations. But the absence of any trace of a lower peak in BIAGI 83 seems to us to throw into question the interpretation of the lower peak of COTEUS 87.

Ξ_c^+ MEAN LIFE

VALUE (10^{-13} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$3.0^{+1.0}_{-0.6}$ OUR AVERAGE Error includes scale factor of 1.1.					
$2.0^{+1.1}_{-0.6}$	6	BARLAG	89C	CCD	π^- (K^-) Cu 230 GeV
$4.0^{+1.8+1.0}_{-1.2-1.0}$		COTEUS	87	SPEC	nA ~ 600 GeV
$4.8^{+2.9}_{-1.8}$	53	BIAGI	85C	SPEC	Σ^- Be 135 GeV

Ξ_c^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K^- \pi^+ \pi^+$	seen
Γ_2	$\Sigma^0 K^- \pi^+ \pi^+$	seen
Γ_3	$\Xi^- \pi^+ \pi^+$	seen
Γ_4	$\Sigma^+ K^- \pi^+$	seen

Ξ_c^+ BRANCHING RATIOS

$\Gamma(\Lambda K^- \pi^+ \pi^+)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	82	[2] BIAGI	83	SPEC	Σ^- Be 135 GeV

[2] BIAGI 85B look for but do not see the Ξ_c^+ in $p K^- \overline{K}^0 \pi^+$ (branching fraction <0.08 with 90% CL), $p 2K^- 2\pi^+$ (<0.03, 90% CL), $\Omega^- K^+ \pi^+$, $\Lambda K^{*0} \pi^+$, and $\Sigma(1385)^+ K^- \pi^+$.

$\Gamma(\Sigma^0 K^- \pi^+ \pi^+)/\Gamma(\Lambda K^- \pi^+ \pi^+)$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.84±0.36	102	COTEUS	87	SPEC	nA ~ 600 GeV

$\Gamma(\Xi^- \pi^+ \pi^+)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	23	ALAM	89	CLEO	$e^+ e^-$ 10.6 GeV

$\Gamma(\Sigma^+ K^- \pi^+)/\Gamma(\Xi^- \pi^+ \pi^+)$ Γ_4/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.09^{+0.13+0.03}_{-0.06-0.02}$	5	BARLAG	89C	CCD	2 $\Sigma^+ K^- \pi^+$, 3 $\Xi^- \pi^+ \pi^+$

REFERENCES FOR Ξ_c^+

ALAM 89 PL B226 401 +Katayama, Kim, Li, Lou, Sun, Bortoletto+ (CLEO Collab.)
BARLAG 89C PL B233 522 +Boehringer, Bosman+ (ACCMOR Collab.)
COTEUS 87 PRL 59 1530 +Binkley+ (COLO, ILL, FNAL, BGNA, MILA, INFN)
BIAGI 85B ZPHY C28 175 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)
BIAGI 85C PL 150B 230 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)
BIAGI 83 PL 122B 455 + (BRIS, CERN, GEVA, HEID, LAUS, LOQM+)

Ξ_c^0

According to the quark model, the Ξ_c^0 (quark content dsc) and Ξ_c^+ form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Ξ_c^0 MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2473.0±2.0 OUR FIT				
2473.1±2.0 OUR AVERAGE				
2473.3±1.9±1.2	4	BARLAG 90	CCD	π^- (K^-) Cu 230 GeV
2472 ±3 ±4	19	ALAM 89	CLEO	e^+e^- 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2471 ±3 ±4	14	AVERY 89	CLEO	See ALAM 89

$\Xi_c^0 - \Xi_c^+$ MASS DIFFERENCE

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
6.2±2.6 OUR FIT			
6.1±2.6 OUR AVERAGE			
+6.8±3.3±0.5	BARLAG 90	CCD	π^- (K^-) Cu 230 GeV
+5 ±4 ±1	ALAM 89	CLEO	$\Xi_c^0 \to \Xi^-\pi^+$, $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

Ξ_c^0 MEAN LIFE

VALUE (10^{-13} s)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$0.82^{+0.59}_{-0.30}$	4	BARLAG 90	CCD	π^- (K^-) Cu 230 GeV

Ξ_c^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^-\pi^+$	seen
Γ_2	$pK^-\overline{K}^*(892)^0$	seen

REFERENCES FOR Ξ_c^0

BARLAG	90	PL B236 495	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun, Bortoletto+	(CLEO Collab.)
AVERY	89	PRL 62 863	+Besson, Garren, Yelton, Bowcock+	(CLEO Collab.)

Ω_c^0

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

OMITTED FROM SUMMARY TABLE

A cluster of three $\Xi^- K^- \pi^+ \pi^+$ events. The $\Omega_c^0 - \Xi_c^+$ mass difference is 280 ± 10 MeV. The existence of the effect and its interpretation as being the Ω_c^0 (quark content ssc) need confirmation.

Ω_c^0 MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2740±20	3	BIAGI 85B	SPEC	Σ^- Be $\to$

REFERENCES FOR Ω_c^0

BIAGI	85B	ZPHY C28 175	+	(BRIS, CERN, GEVA, HEID, LAUS, LOQM+)

BOTTOM (BEAUTY) BARYON

$(B = -1)$

$\Lambda_b^0 = udb$

Λ_b^0

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The claim by BASILE 81 to have discovered the Λ_b^0 (quark content udb) is hotly disputed by DRIJARD 82. BASILE 82 is the reply, and DRIJARD 82B is the reply to that.

The decay of the Λ_b^0 to the final state observed by ARENTON 86 is Cabibbo suppressed, whereas the decay of a Ξ_b^0 to this final state is allowed. ARENTON 86 thus only claims to have observed a baryon which probably has a b quark and which has a D^0 among the decay products, not necessarily the Λ_b^0.

Λ_b^0 MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
~ 5750	4	ARENTON 86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$
5425^{+175}_{-75}		BASILE 81	SFM	62 GeV pp

Λ_b^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$pD^0\pi^-$	seen
Γ_2	$\Lambda K^0 2\pi^+ 2\pi^-$	seen

Λ_b^0 BRANCHING RATIOS

$\Gamma(pD^0\pi^-)/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	*DOCUMENT ID*	*TECN*	*COMMENT*
seen	BASILE 81	SFM	$D^0 \to K^-\pi^+$

$\Gamma(\Lambda K^0 2\pi^+ 2\pi^-)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
seen	4	ARENTON 86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$

REFERENCES FOR Λ_b^0

ARENTON	86	NP B274 707	+Chen, Cormell, Dieterle+	(ARIZ, NDAM, VAND)
BASILE	82	NC 68A 289	+Bonvicini, Romeo+	(CERN, BGNA, FRAS)
DRIJARD	82	PL 108B 361	+	(CERN, CDEF, DORT, HEID, LAPP, WARS)
DRIJARD	82B	CERN-EP/82-31	+	(CERN, CDEF, DORT, HEID, LAPP, WARS)
BASILE	81	LNC 31 97	+Bonvicini, Romeo+	(CERN, BGNA, FRAS, PGIA)

NOTE ON DIBARYON RESONANCES

Dibaryons were reviewed in our 1986 edition[1] and have been reviewed more extensively by Locher, Sainio, and Svarc.[2] We no longer compile data on dibaryons. See our 1988 edition[3] for our last compilation.

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