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ANTIPROTON-PROTON PHYSICS

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Abstract

We report on the latest developments in the field of low energy antiproton-proton annihilation with emphasis on the $\overline{\mathrm{p}}\mathrm{p}$ annihilation mechanism, on tests of CPT and CP symmetries, and on meson spectroscopy and search for new particles like glueballs, four-quark states, and hybrids.

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1. LEAR and FNAL

Currently low energy antiproton proton annihilations are best studied at the high intensity, low emittance and small momentum uncertainty machines LEAR [1] at CERN and the antiproton accumulator [2] at Fermilab. Especially the dedicated storage ring LEAR was designed to accommodate a variety of experiments, from an internal gas-jet experiment to experiments at external beam lines with momenta ranging from 60 MeV/c to 2 GeV/c. The relative momentum uncertainty can be kept at a very low $\Delta p/p \lessapprox 0.1\%$ level owing to the method of stochastic cooling [3] of the circulating antiprotons. For formation experiments this results in a mass resolution of less than 1 MeV. With jet-target intensities of 4×10^{12} protons/cm^2 (JETSET [4] at LEAR) or 4×10^{13} protons/cm^2 (E760 [5] at FNAL) luminosities of 10^{30}/cm^{2}sec and 10^{31}/cm^{2}sec can be achieved, respectively.

At CERN the antiproton accumulator ACOL allows for a very fast stacking of antiprotons at a rate of up to 10^7/sec. Thus high intensity experiments at external beams may in principle 'consume' antiprotons at this high rate. In general, the beam is extracted over time periods ranging from micro-seconds to 3.5 hours with no micro-structure in the intensity. For example, an extraction of a 200 MeV/c antiproton beam over 3 hours results in an average distance between antiprotons of 100 m; before extraction their average distance was just 0.1μm in the storage ring!

2. Overview of Research Projects

In the following we list all on-going experiments which use low energy antiprotons. Since it is impossible to give due credit to all on-going experiments and since a selection of physics results has to be done, we will in the following briefly list the physics objective of each experiment along with a reference for further reading.

PS185: The experiment PS185 [6] studies total and differential cross sections for hyperon-antihyperon ($\Lambda\overline{\Lambda}$, $\overline{\Lambda}\Sigma^0$, $\Sigma^+\overline{\Sigma^+}$, and $\Sigma\overline{\Sigma^-}$) production near threshold. In addition, hyperon-antihyperon polarizations and spin-correlations are determined [7].

PS194: The aim of this experiment [8] are a study of the stopping power and single ionization cross sections for antiprotons at low energy. For example, this experiments determined [8] the antiproton stopping power of gold to be less than 1/2 of that of protons at an energy of 200 keV (Barkas effect).

PS195: The CPLEAR experiment [9] carries out precision tests of *CP* and *T* symmetries through $K^0\overline{K^0}$ interferometrie. Their latest results will be discussed in section 4.

PS196: The Penning-Trap experiment [10] performs a high precision comparison of proton and antiproton inertial masses using a penning trap. The current status of this experiment is described in section 4.

PS197: The main area of research of the Crystal Barrel experiment [11] concerns the search for new states of matter: glueballs, hybrids, and four-quark states. To unravel new forms of matter requires a detailed knowledge of normal $q\overline{q}$ states, to which this experiment contributes as well. The great strength of this experiment lies in its ability to detect many-photon final states. New results on a possible glueball candidate will be presented in section 5.

PS199: The differential cross section and polarization parameters of the reaction $\overline{p}p \rightarrow \overline{n}n$ have been measured by the PS199 experiment [12] for antiproton momenta ranging from 550 MeV/c to 1300 MeV/c. Such measurements test the spin and isospin structure of the nucleon-antinucleon force. The successor of this completed experiment is PS206, the aim of which are high precision measurements of the differential cross section.

PS200: The design goal of this experiment [13] is a 1% measurement of the *gravitational* mass of the antiproton. This will be achieved by launching ultra-cold antiprotons against the earth's gravitational field and measuring their arrival time spectrum. The experiment intends to prove the feasibility in 1994.

PS201: The OBELIX experiment [14] is designed to study exclusive final states of antiproton and antineutron annihilations at low energies. The physics motivation is very similar to that of the Crystal Barrel experiment (PS 197, see above), except that OBELIX' strength lies in the detection of charged particles in the final state. New results will be presented in section 5. In addition, OBELIX also studies [15] in detail $\overline{p}p$ cross sections as a function of energy and target density. Such studies yield valuable information on the $N\overline{N}$ potential.

PS202: The JETSET experiment [16] utilizes a gas-jet-target intersecting the LEAR antiproton beam. The focus of this experiment is the detection of the $\phi\phi$ final state in the mass region from threshold to 2.43 GeV/c^2. The aim is a search for glueballs. Several candidate states have been previously observed in the decay to $\phi\phi$. New results will be presented in section 5.

PS203: Experiment PS203 [17] studies fission and fragmentation processes of nuclei induced by slow antiprotons. Such investigations result in information on the state of nuclear matter. For example, such studies determine the density of protons and neutrons in nuclei and the neutron halo around a nucleus.

PS205: Following the discovery at KEK of metastable helium atoms, systematic studies of this phenomenon have been carried out by the experiment PS205 [18]. They have recently observed delayed annihilation of antiprotons in liquid and gaseous helium with lifetimes of many μseconds instead of the expected picoseconds. The reason is that from high ℓ-orbitals only radiative decays are allowed, which are slow.

E760: In contrast to all LEAR experiments the E760 experiment [5] at Fermilab takes data at higher center-of-mass energies around the charmonium states. Correspondingly, the main thrust of this experiment is the study of charmonium states in a formation experiment, i.e. $\overline{\mathrm{p}}\mathrm{p} \rightarrow \mathrm{c}\overline{\mathrm{c}}$ like η_c, J/ψ, and χ_c. Results on lower mass $\mathrm{q}\overline{\mathrm{q}}$ states are also available. New results will be reported in section 5. One measurement not reported here is an analysis [19] of the proton electromagnetic form-factor in the time-like region for Q^2 values from 8.9 to 13 GeV^2.

3. Two-Body Branching Ratios and Annihilation Models

Branching ratios for antiproton proton annihilations into two-body final states are particularly well suited to investigate the annihilation mechanism of the antiprotonic atom formed when antiprotons come to rest in liquid or gaseous hydrogen. It is generally accepted that antiprotons are captured by protons in highly excited orbits with $n \simeq \ell \simeq 30$. In collisions with neighboring hydrogen molecules they experience intense electric fields which leads to Stark-mixing of states with different angular momenta. Hence S-wave annihilation should dominate (at least in *liquid* hydrogen), even for high values of the principal quantum number n.

Branching ratios can in addition be used for a variety of tests, which will not be discussed here in detail. Existing analyses concern tests of vector-meson-dominance [20] (via a comparison of $\overline{\mathrm{p}}\mathrm{p} \rightarrow X\pi^0,\ X\eta,\ X\omega,\ X\eta'$ for $X = \gamma,\ \rho^0$, and ω), of chiral perturbation theory [21] (via e.g. a comparison of $\eta \rightarrow \pi^0\pi^0\pi^0$ with $\eta \rightarrow \pi^+\pi^-\pi^0$ yielding a ratio of $3\pi^0/\pi^+\pi^-\pi^0 = 1.47 \pm 0.11$, in good agreement with the prediction of 1.44 ± 0.02 from ChPT [22]), and of extensions [23] of the Standard Model (e.g. via the search for weakly interacting gauge bosons [24] in rare decays of the type $\pi^0 \rightarrow \gamma X$, resulting in an upper limit of 5×10^{-5} at 90% CL for $m_X \in$ [80 MeV, 135 MeV]).

3.1. S-Wave vs. P-Wave Annihilation

The fraction of annihilation from P-states ($\ell = 1$) of the antiprotonic atom has been under intense discussion since the very first measurements of the branching ratios into $\pi^+\pi^-$ and

$\pi^0\pi^0$. Antiproton-proton annihilation into two neutral pseudoscalars is forbidden from states with even orbital angular momentum because of parity and C-parity conservation in strong interactions. The presence of annihilation into $\pi^0\pi^0$ therefore signals contributions from odd angular momenta. Already in 1971 this branching ratio was measured [25] to $(4.8 \pm 1.0) \times 10^{-4}$, from which it was concluded that $(39 \pm 8)\%$ of annihilations to $\pi\pi$ proceed from P-states. Later experiments observed much smaller $\pi^0\pi^0$ branching fractions, leading to a reduced P-wave contribution, in agreement with naive expectation. S-wave dominance was also confirmed by a measurement [26] of $\pi^+\pi^-$ from P-states only, yielding a probability of $(8 \pm 2)\%$ for annihilation from P-states into *any* final state.

The Crystal Barrel experiment with its excellent photon detection capabilities has re-investigated [27] the frequency of $\overline{\mathrm{p}}\mathrm{p}$ annihilation in liquid hydrogen into $\pi^0\pi^0$. They find a branching ratio of $\mathrm{BR}(\overline{\mathrm{p}}\mathrm{p} \to \pi^0\pi^0) = (6.9 \pm 0.2 \pm 0.4) \times 10^{-4}$, resulting in a probability of $(29 \pm 4)\%$ for annihilation from P-wave into $\pi\pi$. The discrepancy between this probability and the probability for annihilation into *any* final state can be explained by assuming that the annihilation probabilities into $\pi^0\pi^0$ are different for different values of the principal quantum number n, see Ref. [27] for a discussion. Furthermore the OBELIX collaboration has used a low density hydrogen target to enhance [28] the fraction of P-wave annihilation. A comparison with an antiprotonium cascade calculation shows reasonably good agreement between data and calculation for cascade times and widths.

3.2. Annihilation Models

A calculation of antiproton proton annihilations in the framework of QCD is still beyond reach. We thus have to confront data with phenomenological models based on e.g. statistical (fireball) methods, on quark-line rules with or without explicit quark-gluon degrees of freedom, on di-quark intermediate states, and on nucleon or meson exchange. Sometimes dynamical selection rules based on spin, angular momentum, and isospin are utilized. The outcome of such a comparison will hopefully yield a connection between the phenomenological $\overline{\mathrm{p}}\mathrm{p}$ description and non-perturbative QCD. A detailed discussion of all phenomenological models along with a comparison with pre-1992 data and an extensive list of references can be found in Ref. [29]. To do justice and to compare the new data on branching ratios given in Table 1 with all existing models would go beyond the frame of this article. It seems best, to accumulate as many new branching ratios as possible and then confront data again with model predictions. Until then Ref. [29] provides a complete review.

Table 1. Two body branching ratios for antiproton proton annihilations in liquid hydrogen, which became available since 1992. All branching ratios are of relevance for studies of the annihilation mechanism. Branching ratios listed in the second part are used for a determination of the pseudoscalar mixing angle; those in the third part determine the strangeness content of the proton; and finally, the radiative branching ratios in the fourth part test vector meson dominance models. In addition, Asterix has published [30] in 1991 branching ratios for specific initial S-wave and P-wave states.

Decay	Branching Ratio	Reference
$\overline{\mathrm{p}}\mathrm{p} \to \pi^+\pi^-$	$(3.07 \pm 0.13) \times 10^{-3}$	Crystal Barrel [31]
$\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^+\mathrm{K}^-$	$(0.99 \pm 0.05) \times 10^{-3}$	Crystal Barrel [31]
$\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^+\mathrm{K}^-/\pi^+\pi^-$	$(20.5 \pm 1.6)\%$	CPLEAR [32] (15 bar)
$\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^+\mathrm{K}^-/\pi^+\pi^-$	$(16.3 \pm 1.1)\%$	Obelix [33] (in gas, NTP)
$\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^+\mathrm{K}^-/\pi^+\pi^-$	$(10.6 \pm 0.8)\%$	Obelix [34] (in gas, 5mbar)
$\overline{\mathrm{p}}\mathrm{p} \to \pi^0\pi^0$	$(6.93 \pm 0.43) \times 10^{-4}$	Crystal Barrel [27]
$\overline{\mathrm{p}}\mathrm{p} \to \pi^0\eta$	$(2.12 \pm 0.12) \times 10^{-4}$	Crystal Barrel [35]
$\overline{\mathrm{p}}\mathrm{p} \to \pi^0\eta'$	$(1.23 \pm 0.13) \times 10^{-4}$	Crystal Barrel [35]
$\overline{\mathrm{p}}\mathrm{p} \to \eta\eta$	$(1.64 \pm 0.10) \times 10^{-4}$	Crystal Barrel [35]
$\overline{\mathrm{p}}\mathrm{p} \to \eta\eta'$	$(2.16 \pm 0.25) \times 10^{-4}$	Crystal Barrel [35]
$\overline{\mathrm{p}}\mathrm{p} \to \omega\eta$	$(1.51 \pm 0.12) \times 10^{-2}$	Crystal Barrel [35]
$\overline{\mathrm{p}}\mathrm{p} \to \omega\eta'$	$(0.78 \pm 0.08) \times 10^{-2}$	Crystal Barrel [35]
$\overline{\mathrm{p}}\mathrm{p} \to \omega\omega$	$(3.32 \pm 0.34) \times 10^{-2}$	Crystal Barrel [31]
$\overline{\mathrm{p}}\mathrm{p} \to \pi^0\omega$	$(5.73 \pm 0.47) \times 10^{-3}$	Crystal Barrel [31]
$\overline{\mathrm{p}}\mathrm{n} \to \pi^-\phi$	$(7.77 \pm 0.58) \times 10^{-4}$	Obelix [34]
$\overline{\mathrm{p}}\mathrm{n} \to \pi^-\omega$	$(48.2 \pm 13.1) \times 10^{-4}$	Obelix [34]
$\overline{\mathrm{p}}\mathrm{n} \to \pi^-\phi/\pi^-\omega$	$(16.1 \pm 4.5)\%$	Obelix [34]
$\overline{\mathrm{n}}\mathrm{p} \to \pi^+\phi/\pi^+\omega$	$(17.4 \pm 2.3)\%$	Obelix [34]
$\overline{\mathrm{p}}\mathrm{p} \to \pi^0\phi/\eta\phi$	8.3 ± 2.1	Crystal Barrel [21]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\phi/\pi^0\phi$	$(2.9 \pm 0.8)\%$	Crystal Barrel [36]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\phi/\gamma\omega$	$(33 \pm 15)\%$	Crystal Barrel [36]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\pi^0$	$(44 \pm 4) \times 10^{-6}$	Crystal Barrel [20]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\eta$	$(9.3 \pm 1.4) \times 10^{-6}$	Crystal Barrel [20]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\omega$	$(68 \pm 19) \times 10^{-6}$	Crystal Barrel [20]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\eta'$	$< 12 \times 10^{-6}$ (95% CL)	Crystal Barrel [20]
$\overline{\mathrm{p}}\mathrm{p} \to \gamma\gamma$	$< 0.63 \times 10^{-6}$ (95% CL)	Crystal Barrel [20]

3.3. The Pseudoscalar Mixing Angle

Antiproton-proton annihilation at rest into $\pi^0\eta$ and $\pi^0\eta'$, $\eta\eta$ and $\eta\eta'$, and into $\omega\eta$ and $\omega\eta'$ can be used to deduce the pseudoscalar mixing angle $\theta_{\rm PS}$. The assumption here is that the initial state couples only to the $\rm u\overline{u}$ and $\rm d\overline{d}$ component of the η and η' wave function, i.e. that there is a negligible $\rm s\overline{s}$ component in the proton (see, however, the discussion in section 3.4).

From the measured branching ratios in Table 1 the Crystal Barrel collaboration deduces [35] an angle of $\theta_{\rm PS} = (-17 \pm 2)^\circ$, in good agreement with analyses [37] of the Gell-Mann–Okubo mass formula (including one-loop chiral corrections), two-photon decays of η and η', J/ψ radiative and hadronic decays to η and η', and finally η and η' production in π^- p scattering. This agreement confirms on the other hand, that the underlying assumption of negligible $\rm s\overline{s}$ content in the proton is valid. An interesting side result is that centrifugal barrier factors are not necessary for decays of antiprotonium, i.e. phase space is not described by the expected factor $f = q^{2\ell+1}$, but rather [38] $f \simeq 1$.

3.4. Strangeness in the Proton

In the previous section 3.3 it was shown that the assumption of no $\rm s\overline{s}$ content in the proton at low momentum transfer yields a pseudoscalar mixing angle in agreement with other determinations. Another possibility to test for a $\rm s\overline{s}$ component is a comparison of the branching ratios to final states ϕX and ωX. With a deviation of at most 4° from ideal mixing for vector mesons, we obtain the prediction

$$R_X = \frac{\mathrm{BR}(\overline{\rm p}\rm p \to \phi X)}{\mathrm{BR}(\overline{\rm p}\rm p \to \omega X)} = \tan^2(\theta - \theta_{id}) \simeq 0.5\%.$$

A compilation [29] of pre-1993 data on this ratio shows, that for $X = \eta,\ \omega,\ \rho^0$, and $\pi^+\pi^-$ this ratio is not inconsistent with the expected ratio of $R \simeq 0.5\%$. Only for $X = \pi^0$ and π^- (for annihilation on protons and neutrons, respectively), the corresponding ratio exceeds 0.5% by more than a factor of 10. This violation of the OZI-rule was initially explained [39] as being due to a $\rm s\overline{s}$ content in the proton; however, no explanation for the 'normal' behavior of all other ratios can be found. Another attempt [40] involves OZI-allowed production of $\rm K^*\overline{K}$ which re-scatter to form $\pi^0\phi$; but then why is $\pi\pi\phi$ small, since $\rm K^*\overline{K^*}$ is even larger than $\rm K^*\overline{K}$? Finally a sub-threshold crypto-exotic resonance explanation [41] was tried, but again without success.

This year several new branching ratios became available, see Table 1. OBELIX has analyzed [34] the reactions $\overline{\rm p}\rm n \to \pi^-\phi$, $\pi^-\omega$ and $\overline{\rm n}\rm p \to \pi^+\phi$, $\pi^+\omega$ and finds in both cases very large values for R_π of about 17% for annihilations on neutrons and protons. Crystal Barrel has searched [36] for radiative protonium decays to ω and ϕ. In a data set corresponding to 300 million (!) $\overline{\rm p}\rm p$ annihilations they find a very large ratio as well, $R_\gamma = (33 \pm 15)\%$, where the error is the combined statistical and systematic error. At the 90% confidence level this ratio is larger than 6%. In particular this last measurement of large OZI-violations in radiative decays is very surprising; it clearly rules out any subthreshold resonance interpretation. Currently the OZI-violation is not understood theoretically.

4. *CPT* and *CP* Tests

The general principle of invariance of local Lagrange theories under proper Lorentz transformation requires invariance under the combined transformation *CPT*. The simplest tests of *CPT* invariance are the equality of masses, lifetimes, and magnetic moments (the latter except for a sign) of a particle and its antiparticle. The best test comes from the mass difference between K^0 and $\overline{K^0}$, which yields a relative mass deviation [42] of 4×10^{-18} at 90% CL. Given that this is a theoretically derived quantity from the observed *CP* violation in the K_S and K_L system, it is clearly desirable to test directly for *CPT* invariance in other systems, like proton and antiproton; this will be discussed in section 4.1.

Given *CPT* invariance, *CP* and *T* violation are equivalent. However, only *CP* violation has been observed up to date in K_L decays. Of particular interest is therefore CPLEAR's new approach to *CP* violation using the eigenstates of the strong interaction, the K^0 and $\overline{K^0}$. This will be discussed in section 4.2.

4.1. *CPT* Tests

Before the advent of cold antiprotons at LEAR the inertial mass of the antiproton was deduced at CERN and at Brookhaven, resulting in a fractional uncertainty of 5×10^{-5}. A thousandfold increase in measurement accuracy has been achieved recently by studying the cyclotron frequencies of protons and antiprotons stored in an ion trap near thermal equilibrium at 4K.

Antiprotons from LEAR at an energy of 5.9 MeV are slowed in a degrader to below 3 keV, caught in an ion trap and cooled via collisions with cold electrons [10]. The measurements of proton and antiproton cyclotron frequencies yield [43] a fractional mass uncertainty of $(2 \pm 4) \times 10^{-8}$, the most precise test of *CPT* made with baryons. In the meantime the group has steadily improved their techniques and systematic errors, and they expect [44] another improvement in the accuracy by more than a factor of 10 by the end of 1993. Most of this improvement will result from their ability to observe a radio signal from a *single* trapped antiproton. For such studies the antiproton's cyclotron energy is excited from 5 eV to 1 keV, which increases the 'relativistic' mass of the antiproton by 10^{-6}. Due to energy dissipation in the trap an exponential decay of the antiproton kinetic energy is observed with a time constant of 55 minutes. Last but not least it should be mentioned that the Trap-group managed to store antiprotons for two months without a observed loss of antiprotons; the resulting antiproton lifetime exceeds [43] 3.4 months.

4.2. *CP* and *T* Tests

Before the advent of the CPLEAR experiment, *CP* violation has been observed in the semi-leptonic decay $\mathrm{K_L} \to \pi^{\mp}\ell^{\pm}\nu_\ell$ and in the non-leptonic decays $\mathrm{K_L} \to \pi^+\pi^-$ and $\mathrm{K_L} \to \pi^0\pi^0$, where the parameters δ, η_{+-} and η_{00} are measured, respectively. If the origin of *CP* violation arises only from $\mathrm{K^0}$–$\overline{\mathrm{K^0}}$ mixing and not from the decay amplitude we have: $\epsilon' = 0$ and $\eta_{+-} = \eta_{00} = \epsilon$, where ϵ is defined as [42]

$$\begin{aligned}
\mathrm{K_S} &\simeq \mathrm{K_1^{CP+}} + \epsilon\, \mathrm{K_2^{CP-}} \\
&\simeq (1+\epsilon)\,\mathrm{K^0} + (1-\epsilon)\,\overline{\mathrm{K^0}} \\
\mathrm{K_L} &\simeq \mathrm{K_2^{CP-}} + \epsilon\, \mathrm{K_1^{CP+}} \\
&\simeq (1+\epsilon)\,\mathrm{K^0} - (1-\epsilon)\,\overline{\mathrm{K^0}}\ .
\end{aligned}$$

Instead of using a pure $\mathrm{K_L}$ beam the CPLEAR experiment starts with a pure $\mathrm{K^0}$ or $\overline{\mathrm{K^0}}$ initial state and observes an asymmetry in the decay time distribution for the difference in rates: $N(\overline{\mathrm{K^0}} \to \pi\pi) - N(\mathrm{K^0} \to \pi\pi)$. The pure initial state of $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ is produced in the 'gold plated' events $\bar{\mathrm{p}}\mathrm{p} \to \pi^-\mathrm{K}^+\overline{\mathrm{K^0}}$ and $\bar{\mathrm{p}}\mathrm{p} \to \pi^+\mathrm{K}^-\mathrm{K}^0$, which both occur with branching ratios of 2×10^{-3}. The resulting asymmetry (for the decay to $\pi^+\pi^-$) is given by [45]

$$\frac{N(\overline{\mathrm{K^0}}) - N(\mathrm{K^0})}{N(\overline{\mathrm{K^0}}) + N(\mathrm{K^0})} = 2\,\mathrm{Re}\,\epsilon - \frac{2\,|\eta_{+-}|\,\exp((\gamma_\mathrm{S} - \gamma_\mathrm{L})t/2)\,\cos(\Delta m\, t - \phi_{+-})}{1 + |\eta_{+-}|^2\,\exp((\gamma_\mathrm{S} - \gamma_\mathrm{L})t)}$$

where $\gamma_{\mathrm{S(L)}}$ are the decay widths of $\mathrm{K_{S(L)}}$, $\Delta m = m_S - m_L$, and ϕ_{+-} is the phase of η_{+-}.

The CPLEAR experiment presented [46] in 1993 updated results on this asymmetry for the decay into two charged pions. The result is shown in Fig. 1. Here they plot the modified asymmetry

$$A'_{+-} = \frac{2\,|\eta_{+-}|\,\cos(\Delta m\, t - \phi_{+-})}{1 + |\eta_{+-}|^2\,\exp((\gamma_\mathrm{S} - \gamma_\mathrm{L})t)}\ .$$

A fit to the modified asymmetry results in the following values:

$$\begin{aligned}
|\eta_{+-}| &= (2.25 \pm 0.07) \times 10^{-3} \\
\phi_{+-} &= (44.7 \pm 1.3)^\circ\ ,
\end{aligned}$$

where only statistical errors are quoted. These values are in good agreement with those of the Particle Data Group [42] [2.268 ± 0.023) × 10^{-3} and (44.6 ± 1.2)°, resp.], and with a

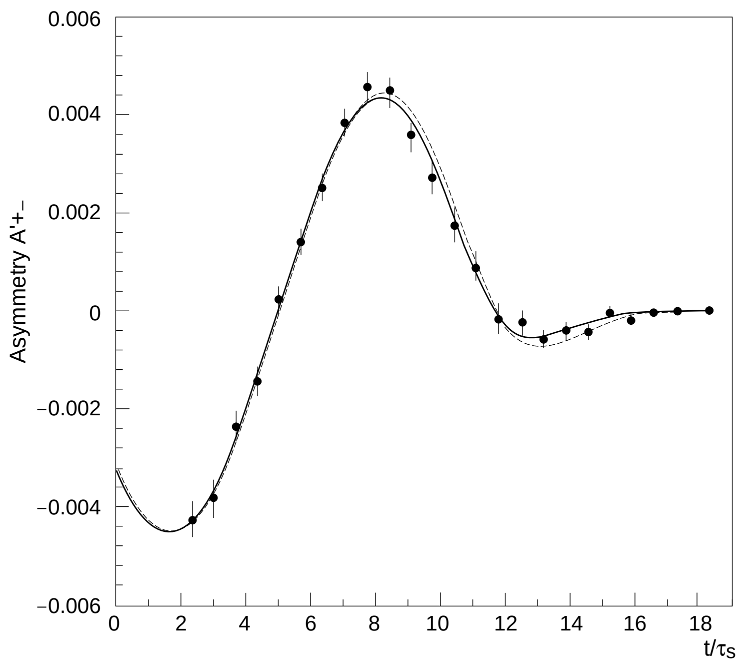

Figure 1. The modified asymmetry A'_{+-} as defined in the text for the decay of K^0 and $\overline{\mathrm{K}^0}$ to charged pions as a function of the decay time (in units of the $\mathrm{K_S}$ decay time). The solid curve is a fit to the data, the dotted curve shows the expectation based on the known values of the *CP* violating parameters $|\eta_{+-}|$, ϕ_{+-}, Δm and $\gamma_\mathrm{S} - \gamma_\mathrm{L}$

recent determination [47] of ϕ_{+-} by E731 at Fermilab [$(42.2 \pm 1.4)°$]. An analysis of final states with two neutral pions is in progress [46].

CPLEAR has also started to investigate semileptonic decays of neutral kaons. A measurement of T violation is possible by an observation of a rate difference for transitions $\mathrm{K}^0 \to \overline{\mathrm{K}^0}$ and $\overline{\mathrm{K}^0} \to \mathrm{K}^0$. One possibility to observe such transitions proceeds via the wrong sign semileptonic decays $\overline{\mathrm{K}^0} \to \pi^-\mathrm{e}^+\nu_e$ and $\mathrm{K}^0 \to \pi^+\mathrm{e}^-\nu_e$. From an analysis of the difference in rates as a function of the lifetime CPLEAR determines [46] an asymmetry of $A_T = (0 \pm 4 \pm 8) \times 10^{-3}$. Using *CPT* invariance one expects $A_T \simeq 4\,\mathrm{Re}\,\epsilon \simeq 7 \times 10^{-3}$.

Furthermore CPLEAR studies the $\pi^+\pi^-\pi^0$ channel, which consists of a *CP* conserving (from $\mathrm{K_L}$ and $\mathrm{K_S}$) and a *CP* violating (from $\mathrm{K_S}$ only) amplitude. Since the *CP* values correspond to different angular momentum configurations of the three pions, the *CP* conserving part from $\mathrm{K_S}$ is anti-symmetric w.r.t. $(E_{\pi^+} - E_{\pi^-})$, and thus vanishes in rate asymmetries. Therefore a fit to the rate asymmetry is sensitive directly to the *CP* violating parameters η_{+-0} and yields [46]

$$\mathrm{Re}\,\eta_{+-0} \quad = \quad 0.002 \pm 0.016$$

$$\text{Im}\,\eta_{+-0} \;=\; 0.044 \pm 0.026\ ,$$

where only statistical errors are being quoted for the time being. By studying separately events with ($E_{\pi^+} > E_{\pi^-}$) and vice versa, one can extract the ratio of decay rates:

$$\frac{\Gamma(\mathrm{K_S} \to (\pi^+\pi^-\pi^0)^{CP+})}{\Gamma(\mathrm{K_L} \to (\pi^+\pi^-\pi^0)^{CP-})} \;=\; (2.1 \pm 1.2) \times 10^{-3}\ ,$$

where again only the statistical error is stated.

Given an expected running time until the end of 1995 the CPLEAR collaboration expects the following final uncertainties on CP violating quantities (most of which will be better than the current total error of those quantities as compiled by the Particle Data Group [42]): $\sigma(\eta_{+-}) \simeq 2 \times 10^{-5}$, $\sigma(\phi_{+-}) \simeq 0.4^\circ$, $\sigma(A_T) \simeq 1 \times 10^{-3}$, and on other quantities [46] which were not discussed here. Note that the estimated error on A_T will allow for a first observation of T violation!

5. Meson Spectroscopy

In the 60's and 70's meson spectroscopy was a very active area of research and many particles have been discovered which finally lead to the general acceptance of the constituent quark model. Since the advent of *perturbative* QCD, a *calculable* theory of strong interactions, emphasis had shifted from low energy hadron spectroscopy to high energy phenomena, from which, for example, the strong coupling constant can be evaluated and shown to be running, i.e. dependent on the energy scale of the process.

Owing to its non-abelian character another fundamental prediction of QCD is the existence of glueballs, particles made completely out of gluons. Ratios of glueball masses can today be estimated rather reliably with the help of lattice calculations [48]; further guidelines are provided by phenomenological models such as the bag model [49], the flux-tube model [50], and the potential model [51]. But in order to establish the existence and the absolute mass of glueballs requires experimental searches. Given the importance of glueballs for QCD it is evident that a new effort had to be launched after the promising J/ψ radiative decays had not unambiguously uncovered a glueball. The effort concentrated mostly at LEAR, where large rates and a new detector generation promised access to this new land. In addition, the searches concentrate as well on four-quark states and on hybrids.

It is now after two years of data taking at LEAR that we may have uncovered a sign of the lowest lying scalar glueball. This will be reported in section 5.1. A possible candidate for the lowest lying $\mathrm{q\overline{q}}$ meson with $J^{PC} = 2^{++}$ and isospin 1 will be discussed in section 5.2. The status of the search for glueballs decaying to $\phi\phi$ is the subject of section 5.3. Finally, in section 5.4 we will report on charmonium spectroscopy, which is exclusively being performed at Fermilab and has yielded the last missing charmonium state, the $h_c(3526)$.

5.1. Sign of a Scalar Glueball?

In 1991 the Crystal Barrel collaboration published [52] an *Observation of a 2^{++} Resonance at 1515 MeV in Proton Antiproton Annihilations into $3\pi^0$*, a state which was found earlier by the Asterix collaboration [53] in the final state $\pi^+\pi^-\pi^0$. Afterwards the Crystal Barrel collaboration found [54] in the final state $\pi^0\eta\eta$ a 0^{++} resonance at 1560 MeV decaying into $\eta\eta$, albeit with a substantially larger width, 245 MeV vs. 120 MeV. Since that time the Crystal Barrel group has increased the statistics in the $3\pi^0$ final state from 55k events to well above 400k events (the latter being extracted from an 'all neutral' triggered data set of 11M events corresponding to 300M $\bar{p}p$ annihilations). The Dalitz plot of this high statistics data set is shown in Fig. 2a.

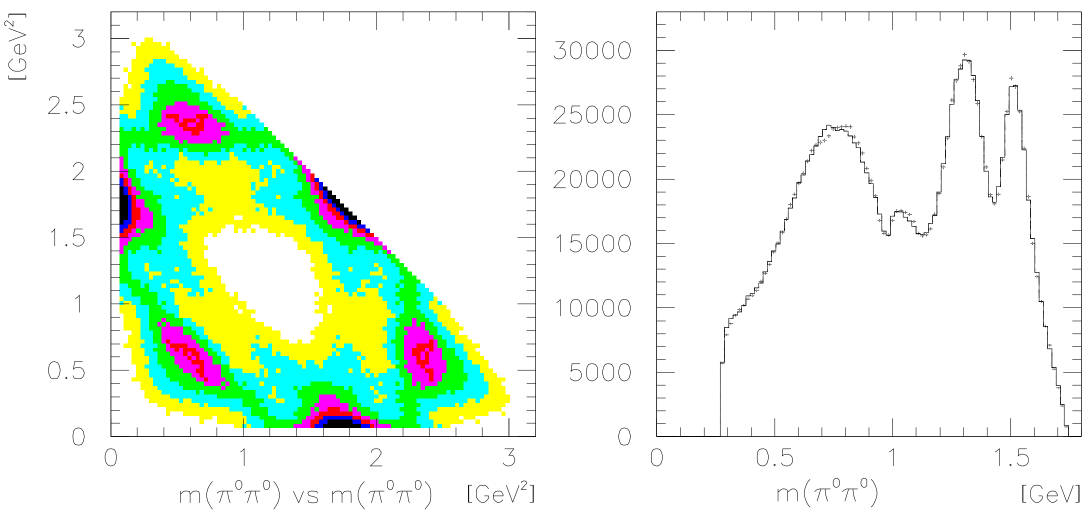

Figure 2. a) Dalitz plot for $3\pi^0$ events. b) $\pi^0\pi^0$ invariant mass distribution (the solid line corresponds to the best fit). The scalar amplitude $f_0(\sim 1500)$ corresponds to the narrow bands that cross the Dalitz plot at around 2.3 GeV^2.

The new Crystal Barrel data set has now been analyzed [23] under two differing assumptions concerning the initial $\bar{p}p$ state. The first Dalitz plot analysis follows closely the original one [52] by assuming final state interactions and the isobar model. One striking result is (and was) a large contribution of annihilation from initial P-waves ($J^{PC} = 1^{++}$ and 2^{++}). The second analysis, which fits simultaneously $\pi^0\pi^0\pi^0$ and $\pi^0\pi^0\eta$, assumes only initial S-wave annihilation and allows for a change of the $\pi\pi$ S-wave scattering amplitude. This was done in order to take re-scattering in the final state into account, which modifies the $\pi\pi$ S-wave taken originally in the parametrization as deduced by Ref. [55].

Both analyses achieve a very good description of the Dalitz plot, see e.g. Fig. 2b for the fit result of the first analysis. Aside from the $\pi\pi$ S-wave both preliminary analyses [23] yield the following poles (here for simplicity denoted in a resonance notation):

- 3 $J^{PC} = 0^{++}$ poles: $f_0(975)$, $f_0(1400)$, and a new resonance $f_0(\sim1500)$ with a width $\Gamma(\sim 130)$;
- 2 $J^{PC} = 2^{++}$ poles: $f_2(1275)$ and a new resonance $f_2(\sim1600)$ with an ill defined width.

Thus two new features are being established, an $f_2(\sim1600)$ with an ill defined width between 150 and 450 MeV (thus probably ruling out a resonance interpretation) and a $f_0(\sim1500)$ with a width between 100 and 150 MeV (the range in widths still reflect that the analyses are preliminary). It is the latter resonance, decaying into $\pi^0\pi^0$ *and* $\eta\eta$, which is of interest. First of all it replaces (together with the ill defined $f_2(\sim1600)$) the previously observed tensor meson. More important, if fully established, this resonance will be a prime candidate for the scalar glueball, since it is seen to decay in approximate equal strengths to $\pi^0\pi^0$ and $\eta\eta$: exactly what is expected of a SU(3) flavor singlet. It should be mentioned, that GAMS also observed [56] a state at 1590 MeV to decay to $\eta\eta$. The interpretation as a glueball candidate was strengthened here by the fact that this state was observed in charge exchange reactions as well as in (gluon rich) central production. Most likely the states observed by GAMS and by Crystal Barrel are one and the some particle.

The other scalar resonance seen to decay to $\pi^0\pi^0$ and to $\eta\eta$, the $f_0(1400)$, is a clear candidate for the 0^{++} $q\overline{q}$ state. This state has been observed in its decay to $\pi^+\pi^-\pi^+\pi^-$ by OBELIX [34,57] at a mass of 1345 ± 45 MeV and by Crystal Barrel [58] in the decay $\pi^+\pi^0\pi^-\pi^0$ at a mass of 1347 ± 38 MeV; the widths, however, vary between 300 and 400 MeV. The remaining $f_0(975)$ is most likely a $K\overline{K}$ molecule [59,60]. The missing $q\overline{q}$ state in the scalar sector (composed of nearly pure $s\overline{s}$) may well be the state claimed by LASS [61] at a mass of 1525 MeV decaying to K_SK_S. This would complete the scalar $q\overline{q}$ sector and leave the $f_0(\sim1500)$ as a candidate for something new.

Finally it should be noted that the E760 experiment at Fermilab also investigated the final states $\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$, and $\pi^0\eta\eta$ at center-of-mass energies around 3 GeV (which makes a Dalitz plot analysis very difficult and has not yet been tried). In mass projections they find [62] striking peaks, both in $\pi^0\pi^0$ and in $\eta\eta$, around 1500 MeV and with a width of 105 MeV, consistent with Crystal Barrel's observation.

5.2. An $a_0(1450)$?

The Crystal Barrel collaboration has also extracted [23] the final state $\pi^0\pi^0\eta$ from the same 11M 'all-neutral' data set and found 150k such events. The Dalitz plot, shown in Fig. 3, shows many structures; this is indicative of strong interferences in the final state. A preliminary partial wave analysis [23] achieves a very good description of the Dalitz plot with the following contributions:

- 1 $J^{PC} = 0^{++}$ $\pi\pi$ pole: $f_0(975)$ ($\pi\pi$ S-wave) ;
- 2 $J^{PC} = 0^{++}$ $\pi\eta$ poles: $a_0(980)$ and a new resonance $a_0(\sim 1450)$ with a width $\Gamma(\sim 250)$;
- 1 $J^{PC} = 1^{-+}$ $\pi\eta$ non-resonant P-wave with a mass in the range 1200 to 1900 MeV and a width between 400 and 1000 MeV;
- 2 $J^{PC} = 2^{++}$ $\pi\eta$ poles: $a_2(1320)$ and an additional term parametrized as a resonance of mass around 1600 MeV and width around 250 MeV.

Figs. 3b,c show the $\pi^0\pi^0$ and $\pi^0\eta$ mass projections along with the result of the best fit. There is clearly good agreement between data and analysis. The necessity for the new resonance $a_0(\sim 1450)$ is best demonstrated by Fig. 3d, which shows the $\pi^0\eta$ invariant mass along with the best fit excluding an $a_0(\sim 1450)$. Obviously this state is necessary to describe the data. Its interpretation is as the lowest lying $J^{PC} = 2^{++}$ iso-vector resonance. Again such an interpretation leaves the $a_0(980)$ as a candidate for a $K\overline{K}$ molecule [59,60].

5.3. Search for Glueballs above 2 GeV/c^2

The internal jet-target experiment JETSET concentrates its effort on the detection of ϕ-pairs produced exclusively in $\overline{p}p$ annihilations. Since the maximum momentum of LEAR is 2 GeV/c this search is limited in mass between threshold and 2.43 GeV/c^2. The challenge of this experiment is to separate a small $\phi\phi$ signal from the huge background, which is at least 4 orders of magnitude larger. But the reward is a glance at what structures are present in this mass region, where pion production experiments [63] have found evidence for three $\phi\phi$ resonances: $f_2(2010)$, $f_2(2300)$, and $f_2(2340)$. Furthermore, a narrow structure, the $f_4(2220)$, had been observed [42] by Mark III, GAMS, E147 at Serpukhov, and by LASS in this mass range. This structure is most likely a $s\overline{s}$ state in a $^3F_4$ configuration.

The JETSET collaboration has now presented [64] data on the cross section $\overline{p}p \to \phi\phi$, showing the cross section to be about 1.5 μb. The analysis of the 9 data points taken in a first coarse scan of the mass region from 2.15 to 2.43 GeV/c^2 reveals no apparent structure. Next they concentrated their effort on a fine scan of 7 points around the $f_4(2220)$: again no apparent structure. With increased luminosity the JETSET collaboration hopes to fill the gaps between the existing data points and to resolve possible structures.

A search for the $f_4(2220)$ has also been carried out by the PS185 collaboration in the reaction $\overline{p}p \to K_SK_S$. No structure was seen [65] in the cross section, which is about 2 μb, at the position of this resonance.

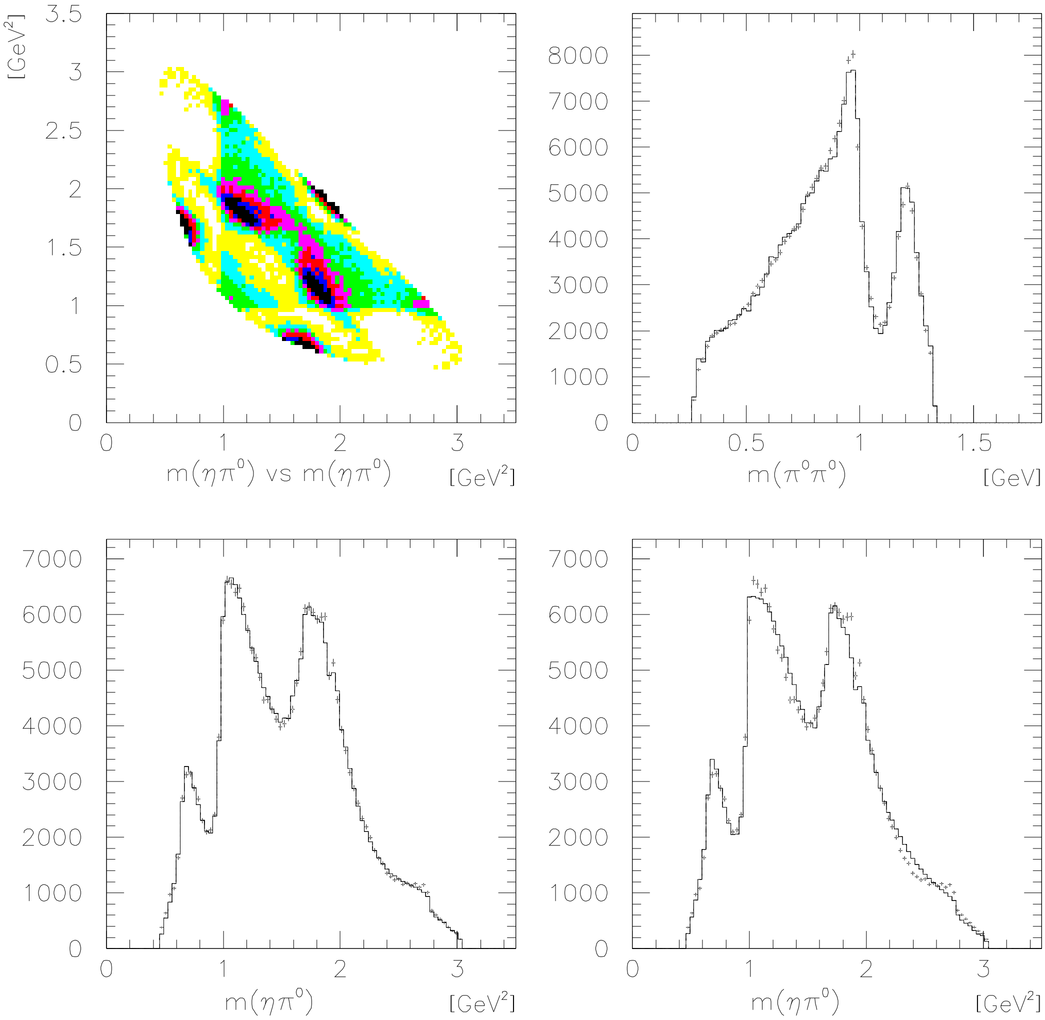

Figure 3. a) Dalitz plot for $\eta\pi^0\pi^0$ events. b) $\pi^0\pi^0$ invariant mass distribution (the solid line corresponds to the best fit). c) $\eta\pi^0$ invariant mass square distribution (the solid line corresponds to the best fit). d) $\eta\pi^0$ invariant mass square distribution (the solid line corresponds to the best fit without the $a_0(\sim 1450)$.

5.4. Charmonium Spectroscopy

The E760 experiment at Fermilab is unique with respect to their significantly higher energy over LEAR. This allows the experiment to study the formation of charmonium states. But whereas the JETSET collaboration had to fight background/ signal at about 10^4, E760 in its search for charm has to suppress background at the 10^7 level, i.e. the cross section for the formation of charmonium is on the order of nanobarns! Using a detector with Cherenkov counters they trigger on electron-positron pairs from the decay of the J/ψ or ψ', or on photon-pairs from the decay of the η_c and χ_c states.

The main result of E760's research concerns the discovery [66] of the last missing charmonium state, the $h_c(3526)$. In a scan around the center-of-gravity of the χ_c triplet P-states the E760 collaboration found an enhancement at a mass of 3526.2 ± 0.3 MeV when analyzing the reaction $\overline{p}p \to J/\psi\pi^0 \to e^+e^-\gamma\gamma$. Although the significance of the peak does at first glance not seem overwhelming, their likelihood analysis shows that such a peak arises as a statistical fluctuation only with a probability of 1/400. Thus they interpret the peak as being due to the h_c, the $^1P_1$ state of charmonium. The other state in the charmonium system left to be checked by another experiment is the η_c', seen only be the Crystal Ball [67] experiment.

Furthermore the E760 group has made precision measurement [68] of the charmonium states J/ψ, χ_1, χ_2, and ψ'. Table 2 collects the relevant results. It is worth noting that the mass measurements are more accurate than all previous determinations from e^+e^- colliders combined. Also the measurement of the width of χ_2 and ψ' are more accurate, whereas for the width of the χ_1 only an upper limit existed previously. The total widths of, for example, the χ_c states can be used to test QCD calculations (to first order in α_s) of the gluonic widths. To this end one needs a better measurement of the total width of the χ_0 state, which E760 will attack in the next running period.

Table 2. Results from E760's scans over charmonium resonances. Given are their new mass and widths determinations.

Resonance	Mass [GeV/c^2]	Width [keV]
J/ψ	3096.87 ± 0.04	99 ± 13
χ_1	3510.53 ± 0.13	880 ± 136
χ_2	3556.15 ± 0.14	1980 ± 184
ψ'	3686 (input)	306 ± 39

In a formation experiment one measures the product branching ratio $BR(c\overline{c} \to p\overline{p}) \times BR(c\overline{c} \to \text{final state})$. Therefore E760 also provides the (partly) unknown branching ratios $BR(c\overline{c} \to p\overline{p})$ for the $c\overline{c}$ states, see Ref. [68]. Finally E760 also studied the angular distributions in the decay of the χ_2 state, $\overline{p}p \to \chi_2 \to J/\psi\,\gamma \to e^+e^-\,\gamma$. Such studies allow tests of perturbative QCD, which for massless quarks predicts that zero helicity is forbidden, of quadrupole and octupole contributions to the radiative decay, and of the presence of an anomalous magnetic moment of the charm quark. The results of their analysis [69] are as follows:

- small contribution of the zero helicity amplitude in the formation process;
- quadrupole contribution consistent with vanishing anomalous magnetic moment of the charm quark; and

- vanishing octupole contribution in the radiative decay.

This experiment improves the accuracy of the measurements over existing data by more than a factor of five and thus strengthens the above conclusions.

6. Summary and Outlook

Experiments at LEAR and Fermilab have greatly contributed over the last years to our understanding of light meson and charmonium spectroscopy, of CP violation, of CPT tests via a comparison of antiproton and proton inertial mass, of the $\mathrm{N\overline{N}}$ annihilation mechanism and the $\mathrm{N\overline{N}}$ potential, of the question of a strangeness content in the proton at small momentum transfer, and last but not least may have provided us with a very strong candidate for the long sought after scalar glueball. The years ahead will certainly offer many more insights into the items addressed above; in particular we hope for a definitive answer regarding the origin of CP violation and the existence and the mass of the scalar glueball. In addition, LEAR and Fermilab experiments will further our knowledge on light and heavy meson spectroscopy.

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