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MEMORANDUM

To : prof. B. D'Almagne
SPSLC Chairman

From : F. Bradamante
Spokesman of the PS199 and PS206 Experiments

Subject : $N\bar{N}$ scattering at LEAR

At the 3rd LEAR workshop in Tignes, in 1985, the Geneva and the Trieste group proposed an experimental investigation of the charge-exchange $\bar{p}p \to \bar{n}n$ channel. Subsequently two experiments were performed, PS199 and PS206, in collaboration with Cagliari, Saclay, and Turin.

The publishing of the results of the $\bar{p}p$ scattering data obtained by the LEAR experiments, and in particular of our two experiments PS199 and PS206, has aroused a great interest in the scientific community, and has stimulated a considerable theoretical activity. Within the framework of the meson-exchange models, the only successful theory of hadronic interactions at low energy, remarkable progress has been achieved in the description of the $N\bar{N}$ interaction, f.i. by the Nijmegen group [1], the Paris group [2], and the Bonn group [3]. Apart from the quoted references, we would like also to refer to the recent review article which is appended to this Memo.

We believe that the extension to the $N\bar{N}$ sector of the theoretical tools which are so successful in the NN and in the meson-nucleon physics is a scientific goal which should be pursued at LEAR.

In 1990 we proposed four experiments [4]. The scientific motivations for those measurements have only been strengthened five years later, and we reiterate the interest of the Geneva and the Trieste group in this field.

After the experience of PS206 we would like the Committee to know that we can also propose a new measurement of the differential cross section of the $\bar{p}p \to \bar{n}n$ charge-exchange channel capable of providing the most accurate determination of the πNN coupling constant f_c^2 (better than 1%). The value of this constant, which plays a fundamental role in many sectors of Physics (f.i. Goldberger-Treiman relation) is still not agreed upon, and as suggested in the appended paper, LEAR can provide a new standard for its measurement.

F. Bradamante

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EXPERIMENTAL RESULTS ON N$\bar{\text{N}}$ SCATTERING

F. Bradamante
Dipartimento di Fisica dell'Università, Trieste, and INFN,
Sezione di Trieste, Trieste, Italy

Abstract

The experimental situation in N$\bar{\text{N}}$ scattering is reviewed. No new data have been published over the past years in the elastic $\bar{p}p \rightarrow \bar{p}p$ channel, but many results for the differential cross-section, the analysing power, and the target depolarization parameter of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange channel have been obtained at LEAR, the Low Energy Antiproton Ring at CERN by the PS199 and PS206 experiments. The theoretical understanding of these data requires sophisticated meson-exchange-potential models, which succeed in parametrizing the unknown and yet incalculable short-range N$\bar{\text{N}}$ interaction. The agreement between model calculations and the N$\bar{\text{N}}$ database is in general satisfactory, and sometimes excellent. The most recent and very accurate differential cross-section data from the PS206 experiment extrapolate smoothly to the pion pole and allow a precise determination of the πNN coupling constant, an important indication that annihilation and meson-exchange dynamics can be disentangled by precision measurements of N$\bar{\text{N}}$ scattering.

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1 Introduction

At the 3^{rd} LEAR Workshop in Tignes, in 1985, R. Hess and myself proposed [1] an experimental investigation of the charge-exchange $\bar{p}p \rightarrow \bar{n}n$ channel. The ambitious goal was to learn about the $N\bar{N}$ dynamics, as will be quickly reviewed in section 2. The strategy was to focus on spin observables, which are sensitive to the high-partial waves, i.e. to the waves where s-channel resonances were expected and could eventually be revealed. The choice of the charge-exchange reaction was motivated by the 'simple' t-channel exchange structure, which involves only isospin I=1 mesons.

This program had a vigorous start. Experiment PS199 was approved soon after and took data in 1989 and 1990. For the first time analysing power A_{0n} [2, 3, 4, 5] and target depolarization parameter D_{0n0n} data [6, 7] were made available. Also, good quality differential cross-section data [2, 5, 8] were obtained. These results will be reviewed in section 3.

This program was stopped at the Cogne Meeting in 1990, essentially because the CERN Committee did not believe that meaningful physics information could be extracted from this low-energy hadronic system: in particular doubts were expressed about the possibility of disentangling the effects due to meson exchanges and those caused by annihilation. At variance with such a belief, a few months later the Nijmegen group produced a first phase-shift analysis of all the charge-exchange data (including our first results [2, 3]) which showed that one could determine the parameters of the theory [9]. In particular this first analysis provided a value of the charged πNN coupling constant ($f_c^2 = 0.0751 \pm 0.0017$) which compares well with the value one obtains using other more standard methods.

In October '91 a small workshop on 'Antinucleon-Nucleon Scattering and Potential Models' was held in Archamps (France), near Geneva. The idea was to hold a rather informal round-table panel to

- review and look critically at existing and forthcoming data,
- review and look critically at existing models,
- agree on what has been learnt and possibly on what needs to be done.

The workshop was very stimulating and the discussions sometimes very lively, although I have no difficulty to admit that the 'Meeting Report' [10], in spite of the good will of the authors, is not a faithful and unbiased summary of it. I believe that the workshop was useful. The powerful, efficient and universal character of meson-exchange models was underlined in many contributions, and section 4 is devoted to review the most recent work since then. Still, the need was felt that one should use somehow the $N\bar{N}$ scattering data to show that at large distances one really sees one pion, two pions and vector exchanges. We felt that the charge-exchange cross-section was the natural candidate for the first step of this program, i.e. to search for clear manifestation of one-pion exchange, and that LEAR would enable us to obtain the good quality data which are obviously necessary and which have always been lacking in $N\bar{N}$ physics.

Experiment PS206 was proposed to CERN soon after and approved in June '92. It took data in April and May '93, and has amply fulfilled its goals, as I will show in section 5 of this report.

As everybody knows, the investigation of the $\bar{p}p \rightarrow \bar{n}n$ channel is complementary to the investigation of the $\bar{p}p \rightarrow \bar{p}p$ elastic channel: the charge-exchange amplitude is the difference of the I=0 and I=1 amplitudes, while the elastic amplitude is the sum. This talk focuses on the charge-exchange reaction only because since many years no new data have been published on the elastic channel.

2 Physics objectives of Experiment PS199

In the conventional meson-exchange potential (MEP) approach, quite interesting properties have been predicted for the long- and medium-range part of the N$\bar{\text{N}}$ force when it is derived from the NN force by applying the G-parity rule. The basic notion is 'coherence' [11], i.e. the fact that the contributions of the various mesons add up coherently in some parts of the potential, resulting in a much strong central, tensor and quadratic spin-orbit forces in the N$\bar{\text{N}}$ system as compared to the NN one. This coherence leads to a strong N$\bar{\text{N}}$ attraction, which was the starting point for the predictions for N$\bar{\text{N}}$ bound states (baryonium), and which has very striking consequences for the spin observables.

First measurements of spin observables in the charge-exchange $\bar{\text{p}}\text{p} \rightarrow \bar{\text{n}}\text{n}$ reaction were the main objectives of PS199. The necessity for these measurements should be clear to everybody. Since the reaction involves four fermions, five independent complex amplitudes are needed. Using the notation of ref. 12, the scattering matrix can be written in the form:

$$\begin{aligned} M &= \frac{1}{2}[(a+b)+(a-b)(\vec{\sigma}_1\cdot\hat{n})(\vec{\sigma}_2\cdot\hat{n})+(c+d)(\vec{\sigma}_1\cdot\hat{m})(\vec{\sigma}_2\cdot\hat{m})+ \\ &\quad +(c-d)(\vec{\sigma}_1\cdot\hat{l})(\vec{\sigma}_2\cdot\hat{l})+e(\vec{\sigma}_1\cdot\hat{n}+\vec{\sigma}_2\cdot\hat{n})] \end{aligned}$$

where $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are the Pauli spin matrices and $\hat{n}$, $\hat{m}$ and $\hat{l}$ are the 3 directions in the c.m. frame defined respectively by the external product, the difference and the sum of the momenta of the incoming and outgoing antinucleon. The differential cross-section $\mathrm{d}\sigma/\mathrm{d}\Omega$ is given by:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{2}(|a|^2+|b|^2+|c|^2+|d|^2+|e|^2)$$

i.e., it is made up by all the five amplitudes, and only the measurement of spin variables can give the necessary insight into the relative contributions. For instance, the analyzing power A_{0n} is related to the spin-orbit amplitude e, while the measurement of the depolarization parameter D_{0n0n} gives the strength of the spin-spin amplitudes c and d:

$$\begin{aligned} A_{on}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} &= Re(a^{*}e) \\ (1-D_{onon})\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} &= \frac{1}{2}(|c|^2+|d|^2) \end{aligned}$$

This means that A_{0n} and D_{0n0n} are complementary, and both are needed to investigate the full structure of the scattering matrix (the measurements of still other observables, like K_{0nn0}, would of course be also very welcome !). Since the spin-spin amplitudes are linked to the spin-spin part of the potential (at least in the Born approximation), one can thus test with the two-spin observables this crucial and characteristic part of the N$\bar{\text{N}}$ potential.

3 Results from Experiment PS199

3.1 Old results

Fig. 1 shows the measurement of the analysing power performed by the PS199 collaboration at 8 incident $\bar{\text{p}}$ momenta, ranging from 546 to 1287 MeV/c.

A pentanol polarized target, 12 cm long, has been used. The main difficulty in this kind of experiments is that both the particles in the final state have to be detected, and the detection and identification of neutral particles is much less efficient than for charged ones. The PS199 $\bar{\text{n}}$-counters were designed to unambiguously identify the antineutron and to have a good precision in the reconstruction of the annihilation point, without loosing too much in efficiency. The detectors were made up by iron slabs, in which most of the $\bar{n}$'s annihilations occurred, surrounded by two telescopes of limited streamer tubes to reconstruct the tracks of the charged particles produced in the annihilation. In the off-line program, the $\bar{n}$ candidates were identified by requiring that the reconstructed tracks gave a 'star' pattern centered on one of the iron absorbers. The associated neutron was detected in hodoscopes of vertical scintillator bars; each bar was viewed from each end by a photomultiplier, so that the vertical coordinate of the n interaction point could be obtained from the time-of-flight difference. In the data analysis, once a n and an $\bar{n}$ candidate were found in the corresponding detector, the charge-exchange events on the polarized protons of the target were identified on the basis of the χ^2 of a complete kinematical fit. The most relevant aspects of the experiment have been described in a series of papers, to which I refer the interested reader: the neutron counters [13], the limited streamer tubes system [14], the data acquisition system [15], and the calibration method to measure the efficiency of the $\bar{n}$ detectors [16], most important for the cross-section measurements.

As can be seen in fig. 1 the analyzing power reaches high and positive values at all energies and the angular dependence is remarkable. These data constituted a really new piece of information, since no measurement of spin observables in the charge-exchange channel existed. It turned out to be impossible to reproduce these data using very simple models [17], in which the absorptive potential describing the annihilation process was taken energy and state independent, and thus could be defined with only a few parameters.

The target depolarization parameter D_{0n0n} was measured at two values of the incident $\bar{p}$ momentum, 546 and 875 MeV/c, in two dedicated runs. The D_{0n0n} parameter was obtained from the polarization of the recoiling neutron, which was measured with a suitable polarimeter made up of two neutron counter hodoscopes. Since the polarization of the recoil particle is given by

$$P(\theta) = \frac{A_{on}(\theta) \pm D_{onon}(\theta) \cdot P_T}{1 \pm A_{on}(\theta) \cdot P_T},$$

where P_T is the target polarization and + and − refer to target spin up and target spin down respectively, the value of D_{0n0n} can be estimated from the difference of the recoil neutron polarization measured with the two possible orientations of the target spin. The measurement could be performed only over about half of the angular range because at large scattering angles the small charge-exchange differential cross-section implies a poor statistics, while at small angles the limiting factor is the analysing power of the neutron polarimeter, which decreases with the neutron energy.

The results are shown in fig. 2. Within errors, they suggest that D_{0n0n} is small, which means that the spin-spin amplitudes are important, as suggested by the meson-exchange models.

3.2 New results from Experiment PS199

Fig. 3 shows differential cross-section data, again at many energies. Apart from the data points at 693 MeV/c incident $\bar{p}$ momentum, which were obtained using a liquid hydrogen target, and were published [2] already in 1990, the data are extracted from the run which measured A_{0n}, i.e. using the polarized target. They are not yet published [8] but they can be regarded as final. They have good accuracy, and overlap at low momentum with data from the KEK [18] and the LEAR PS173 [19] experiments, while they extend into an unmeasured region at high momentum. It is known that the backward region is very sensitive to the short-range part of the potential, so we are confident that their contribution to this knowledge will be important.

In fig. 4 new measurements of A_{0n} at 546 MeV/c and 875 MeV/c are shown. They have been obtained automatically (the data, not the results...) when measuring D_{0n0n}, and they compare well with the previous results of ref. 4. The statistical accuracy of the new A_{0n} data is very good, particularly for the new points at 875 MeV/c in the backward hemisphere, which were obtained with a different technique, relying on the detection of the $\bar{n}$'s only [5].

The same data in the backward hemisphere at 875 MeV/c have been analyzed to give the differential cross-section values [5] which are shown in fig. 5, together with the data already given in fig. 3. The two sets of data are completely independent, and have been obtained at different times and with different techniques, but the results exhibit an excellent agreement.

4 Theoretical understanding

4.1 Rejection of inconsistent data

A most delicate and important point when comparing data with theoretical model calculations is the treatment of inconsistent data. The published $N\bar{N}$ scattering data at low energies (say incident antiproton momentum up to $\simeq$ 900 MeV/c, i.e. about the one-pion production threshold) total about 5000 points, and it is not a big surprise that some of the data are not consistent with each other. The case of the differential cross-section of the elastic $\bar{p}p \rightarrow \bar{p}p$ channel is an exemplary one, as stressed by many authors [17, 20, 21], but by far it is not the only one. The procedure usually adopted by theorists is essentially to reject from the data base those data which give a large contribution to the overall χ^2 of a global fit to their model calculation. While agreeing that one cannot enter a fit with inconsistent data, as an experimentalist I cannot be happy with this procedure. Either one has very solid theoretical (or experimental !) arguments to motivate that one set of data is wrong (this has happened many times in the past, and has also lead to important findings), or one has to accept the fact that our knowledge of some observables is neither as good as we think, nor as good as the authors of a single experiment think, and one has to re-estimate the errors correspondingly. Rejecting a set of data just on the χ^2 criterion leaves the outside observer with the prejudice that by substituting in the data base one 'accepted' data set with a 'rejected' one an acceptable solution can still be found, without running into unsurmountable difficulties or contradicting first principles.

Obviously the ideal way out is new dedicated measurements at LEAR, a point on which both theorists and experimentalists active in the field can only agree upon. This is a must for the differential cross-section of the elastic channel: experiments PS172 and PS198 used polarized target and provided differential cross-section values only as a byproduct. And the absence of really accurate $\bar{p}p \rightarrow \bar{n}n$ differential cross-section data, covering the full angular range in the energy region of the PS199 experiment, was one strong motivation for proposing the PS206 experiment.

4.2 The Nijmegen phase-shift-analysis

Most of the theoretical work in the $N\bar{N}$ scattering sector is at present being carried out by the Nijmegen group. A dedicated talk at this Conference is given by J. de Swart [22], therefore here I will just mention the highlights of their work. Following their original work of ref. 9, they have performed the first multi-energy partial-wave analysis [21] of all the available $\bar{p}p$ scattering data below 925 MeV/c antiproton laboratory momentum.

The Schrödinger equation for the coupled antiproton-proton and antineutron-neutron channels is solved. The short-range interaction, including the coupling to the mesonic annihilation channels, is taken into account by applying to each individual partial wave an energy-dependent complex boundary condition at a given radius (r = 1.3 fm). The long-range interaction consists of the Coulomb potential, the magnetic-momentum interaction, and the one-pion exchange potential. The tail of the heavy-boson-exchange part of the Nijmegen potential is used as intermediate-range interaction. By fitting 30 short-range parameters and about 100 normalization constants over the whole database (after some filtering to avoid inconsistencies in the data, they use about 4000 data points), they obtain excellent fits (total χ^2/ndf=1.043). The quality of this result can be appreciated by inspection of fig. 6, where the A_{0n} data from experiment PS199 are compared, at a few energies, with the results [21] of their fits. As mentioned in section 3.1, it was not easy to reproduce the trend of these data with 'simple' models, but apparently this is not a problem for the Nijmegen analysis.

An extremely important result of this phase-shift analysis is the determination of f_c^2, the charged pion-nucleon coupling constant. As mentioned in the introduction, this constant could be fitted in the preliminary phase-shift analysis of ref. 9, which was based on 884 charge-exchange data points between 400 and 950 MeV/c. This analysis was repeated on the full 1993 N$\bar{\text{N}}$ data base, obtaining a value $f_c^2 = 0.0732 \pm 0.0011$, which provides further evidence for a 'low' and approximately charge-independent nucleon pion-coupling constant. Given the interest of knowing precisely the value of this quantity, and the recent debate stimulated by the Nijmegen group [23], which challenged the generally accepted value of $f_c^2 = 0.079$, we consider this result of the utmost importance.

4.3 The Paris optical potential

Already in 1982 the Paris group proposed an optical potential to describe the low energy N$\bar{\text{N}}$ interaction [24]. The real part of this potential is obtained by G-parity transformation of the long- and medium-range parts of the Paris NN potential, supplemented with a phenomenological short-range part. Its imaginary part has a form which is suggested by explicit calculations of the N$\bar{\text{N}}$ annihilation diagrams into two mesons or resonances, and it is of short range, and energy and state dependent. The parameters of the short-range potentials were determined on the data set existing in 1982, which turned out to be adequately described by the model (χ^2/ndf=2.80 for 915 data points). But since that time many more new measurements have been performed, mostly at LEAR, and that original parametrization is no longer adequate to describe the entire data set [20, 25]. The Paris group has consequently redetermined on the presently existing data base the short-range part of their potential ($r \leq 1$ fm) [26]. In each isospin state 9 parameters are needed for the real potential, and 6 for the absorptive part, thus a total of 30 parameters have been fitted on the data. Much in the same way as for the Nijmegen group, 168 data from the total existing data set used by the group (3800 data) were rejected because of internal inconsistencies, thus the fit was performed on the 3632 remaining data. The goodness of the fit is indicated by the χ^2/ndf value, which is 3.87, and decreases to 2.46 if more dubious data (337) are dropped. This result is quite good, in particular because the new parametrization differs from the old one essentially for $r < 0.7$ fm, which means that the new precise data allow to pin down the short-range part of the potential. Some comparison between data and model calculations are given in fig. 7, which shows some measured and computed values of $d\sigma/d\Omega$, A_{0n}, and D_{0n0n}. The improvement in the agreement between the Paris calculation and the data when using the new core parametrization as compared to the old parametrization is remarkable.

4.4 Coupled-channels models

A theoretically more appealing approach to the N$\bar{\text{N}}$ interaction than the optical potential is offered by the coupled-channel model calculations. In these models the minimal number of channels is two, the N$\bar{\text{N}}$ channel, interacting with a meson-exchange potential, and the annihilation channel, which for simplicity is usually taken to be two effective mesons. Annihilation is simulated by coupling the N$\bar{\text{N}}$ system to the two meson channels. In contrast to the optical model, the interaction Hamiltonian is hermitian, and therefore the coupled-channel model is a unitary theory with a complete set of orthogonal eigenfunctions [27].

Several groups have undertaken coupled-channel model calculations. The Nijmegen group has recently updated their coupled-channel model [28] by fitting to the same 1993 N$\bar{\text{N}}$ scattering data base they have used for their phase-shift analysis, obtaining an overall χ^2/ndf of 1.6. In their model the N$\bar{\text{N}}$ interaction is again computed from the charge-conjugated Nijmegen one-boson-exchange potential and the low χ^2 value indicates that also in this case they obtain excellent fits to the data.

An impressive effort has been devoted by the Bonn group to improving their model [29], which uses the G-parity transform of the Bonn NN potential and a number of selected two-meson annihilation diagrams, whose contribution is artificially enhanced to provide the observed total annihilation rate. The procedure of using only a few annihilation channels, accounting for only 30% of the total annihilation, led to a very strong state and energy dependence of the annihilation interaction, and the model (model C in ref. 29) failed to describe quantitatively the $\bar{\text{N}}$N → $\bar{\text{N}}$N data. Since a few years many more annihilation channels have been taken into account and a new model has been proposed (model D in ref. 30). Although the agreement with the new N$\bar{\text{N}}$ data is still modest, the model has the advantage of providing a simultaneous description of both N$\bar{\text{N}}$ scattering and annihilation into two mesons phenomena.

To conclude this section I would like also to quote the work of the Shapiro group. By now they succeed to reproduce the low-energy cross-section data [31], and are working on a relativistic formulation of their coupled-channel model, which should be adequate in the energy of the new polarization data from the LEAR experiments.

5 Results from Experiment PS206

5.1 The new $\bar{p}p \to \bar{n}n$ differential cross-section measurement

Experiment PS206 has measured at LEAR the charge-exchange $\bar{p}p \to \bar{n}n$ differential cross-section using a liquid hydrogen target. The motivation of the experiment was to measure with good precision and high statistical accuracy the shape of the differential cross-section at small values of the momentum transfer ($-t \sim m_\pi^2$), where a sharp forward peak has been observed followed by a dip-bump structure [32]. Also, by measuring the differential cross-section over the entire angular range and with a small normalization error, it aimed at providing data for a new and independent evaluation of the πNN coupling constant f_c^2.

The experiment was run in a parasitic way and could be performed only at two incoming $\bar{p}$ momenta, 601 and 1202 MeV/c. First results have been submitted for publication just before the conference [33], and I will refer to this paper for all the details about the apparatus and the data analysis. The results are shown in fig. 8. The forward peak and the energy dependence of the dip-bump structure show up very clearly.

The forward peak has been observed over a wide range of incident momenta [34]. A similar peak has been known since long time in the line-reversed reaction np → pn, again both at low and high momenta, and in the past it has been the object of considerable theoretical activity. For both reactions the peak can be explained in terms of the pion-exchange amplitude, interfering destructively with some 'background' amplitude [35, 36].

Since this is the first time that the structure is unambiguously observed and well measured, it is interesting to zoom the low-t data. This is done in fig. 9a, where the plotted quantity is the ratio of the differential cross-section to its best fitted value at $t = 0$ (the details of the fit are given in section 5.2). The data have comparable quality and remarkable similarities with the line-reversed reaction np → pn data, two examples of which can also be seen in fig. 9b for two similar energies [37].

5.2 Extrapolation to the pion pole

Although the very narrow width of the forward peak in fig. 8 immediately suggests a pionic phenomenon, it is not straightforward to explain the exact shape of the differential cross-section in terms of the pion propagator. To me, the cleanest way to show up the presence of the pion pole in the scattering amplitude is the extrapolation procedure which was suggested already in 1958 by G. F. Chew [38] as a way for determining the pion-nucleon coupling constant and which has been successfully applied to the np → pn reaction by several authors [39, 40, 41]. If in the t-interval under consideration the pion propagator is the only singularity of the scattering amplitude, by multiplying the differential cross-section by the square of the denominator of the pole term $x = m_\pi^2 - t$ one expects to obtain a smooth function of x

$$\left(m_\pi^2 - t\right)^2 \cdot \frac{d\sigma}{d\Omega} = \frac{\left(g_c^2 \cdot m_\pi^2\right)^2}{s} \cdot F(x) = \frac{\left(g_c^2 \cdot m_\pi^2\right)^2}{s} \cdot \left[a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \ldots\right]$$

which, when extrapolated in the unphysical region to the pole position $t = m_\pi^2$, should provide the value of the coupling constant. In the above formula s and t are the Mandelstam variables, and

$$g_c^2 = \frac{4M^2}{m_\pi^2} \cdot f_c^2 \approx 14.$$

is the charged pion-nucleon coupling constant (m_π and M are the pion and proton masses).

The quantities

$$y = \frac{s \cdot x^2}{m_\pi^4 \cdot g_c^4} \cdot \frac{d\sigma}{d\Omega}$$

are plotted as a function of x in fig. 10 for the p̄p → n̄n measured data at 601 MeV/c. For comparison, the same figure shows the corresponding quantity for the line-reversed reaction np → pn, using precise data recently measured at 435 MeV/c incident neutron momentum [42]. Also shown in the figure are the lower order polynomial fits which best reproduce the data. To evaluate the quantities y we have assumed $f_c^2 = 0.075$, a presently agreed upon value, so that the fitted functions should extrapolate to one at the position of the pole.

It is a most remarkable fact that within errors the p̄p → n̄n data nicely extrapolate to the same value as the np → pn data. This means that pion exchange is a real dynamical mechanism in NN̄ physics much in the same way as it dominates the NN interaction, and it is not masked by the annihilation process[43]. In this sense the use of π -exchange as a tool to probe the NN̄ force seems quite plausible, and the perspectives for measuring the long- and medium-distance behavior of the $N\bar{N}$ meson exchange potential, and testing its physical interpretation and the G-parity rule, look promising.

The use of the Chew extrapolation procedure to measure the πNNcoupling constant using accurate differential cross-section data for the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction was suggested almost thirty years ago [44]. Clearly LEAR was necessary to realize this program and set-up a new standard for the measurement of this constant. The most accurate determination will always be provided by fitting the whole $N\bar{N}$ scattering database, as done by the Nijmegen group, still I believe that it is useful to dispose of determinations which rely on a single experimental result, and we plan to pursue further the Chew procedure on the PS206 data [45].

6 Conclusions

I have had the pleasure to illustrate the most relevant results from experiment PS199 and the brand new results from experiment PS206. I believe that these data are very interesting, and allow for the first time to pin down the isospin dependence of the $N\bar{N}$ interaction. The analysis I have illustrated in section 5 indicates that good data allow unambiguous separation of the meson-exchange dynamics from the short-range annihilation process. Also, in a simple and model-independent way one can determine a fundamental parameter of the low-energy hadronic interactions, namely the πNN coupling constant, with a precision which is comparable to that of other more standard procedures. And which could be improved, of course.

A lot of progress has been accomplished on the theoretical side. The bulk of the $N\bar{N}$ scattering data can be reproduced with a reasonable number of free parameters, which describe the characteristics of the unknown and yet incalculable short-range dynamics. In the case of the Nijmegen group the agreement between data and model calculations is impressive and testifies the goodness of the $N\bar{N}$ long- and intermediate range meson-exchange potential. In the case of the Paris group, after a re-evaluation of the core parameters the agreement is definitely good, and they clearly demonstrate that the new data pin down the short-range potential. The Bonn group still cannot produce good fits to the data, but is steadily progressing in building up a realistic model for the annihilation, by taking more and more two effective mesons channels into account.

To conclude my talk, I would like to remind that the knowledge of the $N\bar{N}$ potential allows to calculate the spectrum of resonances and bound states. This work has been done and is being done by many groups, and as an example I would like to quote just the most recent result from the Paris group [26], which finds a bound state having the AX(1565) quantum numbers and the right mass. In the past this complementarity between reaction dynamics and spectroscopy was always kept in mind, but for some reasons it was forgotten by the CERN Committee which met in Cogne in 1990. A new Committee will meet again in a few month, with a more difficult task, in a more difficult moment, to make recommendation about the future of LEAR. My only wish is that they read this report before making the decision.

7 Acknowledgements

The material for this talk is the outcome of the coherent effort of the entire PS199 and PS206 Collaborations, and I would like to take this opportunity to thank all of my colleagues. Although both experiments are finished and have been dismantled, a lot of analysis work is still going on, and it is a great pleasure for me to explicitly mention

the invaluable contributions of the Ph.D. students (mostly ex-, by now) Abdellah Ahmidouch, Andrea Bressan, Massimo Lamanna, and Christian Mascarini, and of the analysis coordinator Anna Martin.

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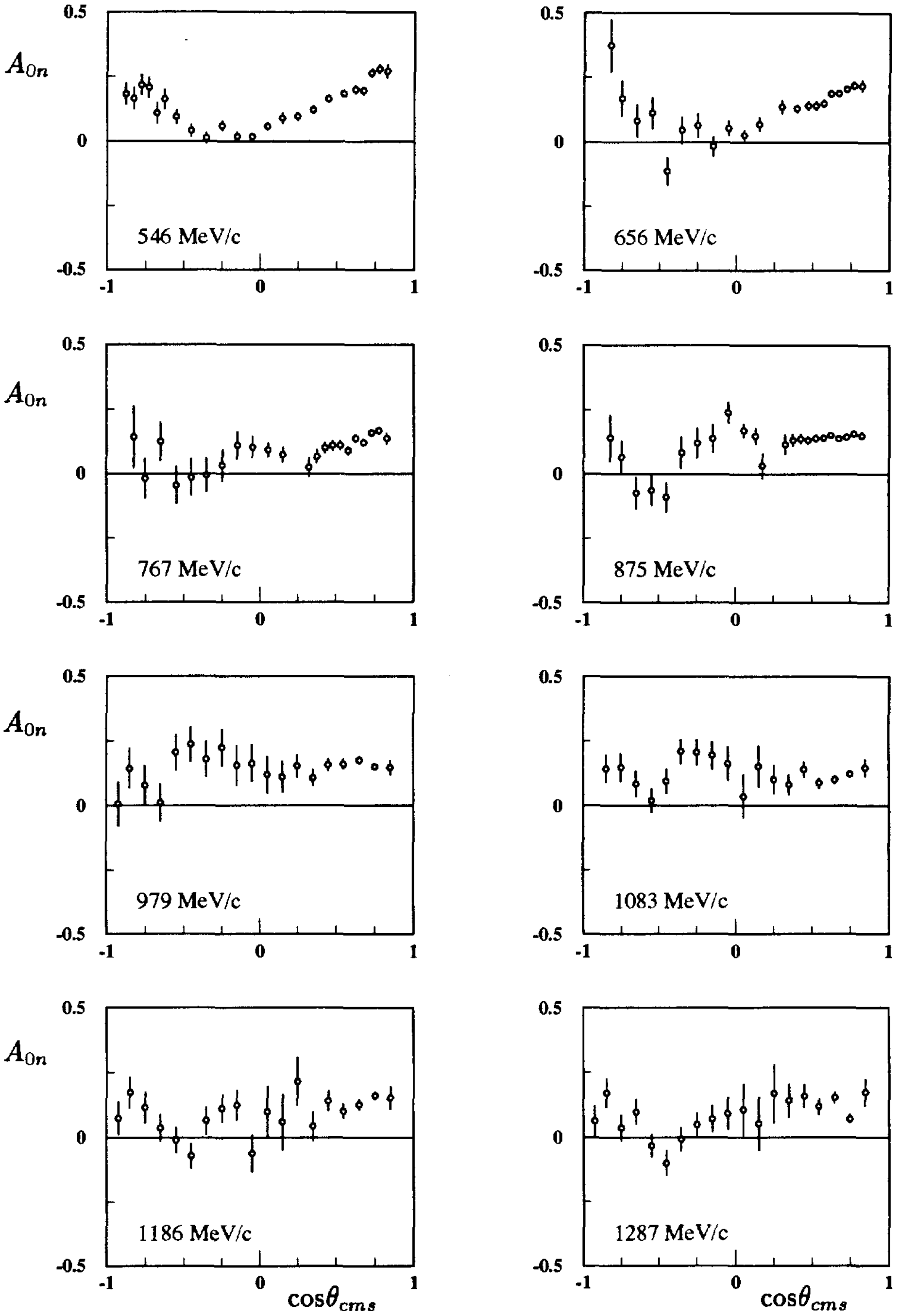

Figure 1: Analysing power data for the $\bar{p}p \to \bar{n}n$ charge-exchange reaction as a function of centre-of-mass $\cos\theta$. The measurements were performed at the indicated values of the incident $\bar{p}$ momentum by the PS199 collaboration[4].

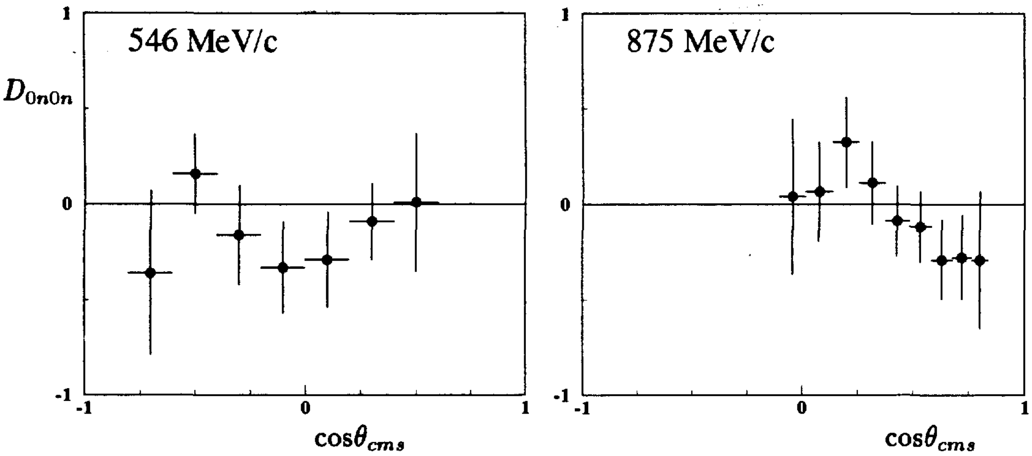

Figure 2: D_{0n0n}[6,7] data at 546 and 875 MeV/c incident p̄ momentum as a function of centre-of-mass cosθ, from the PS199 collaboration.

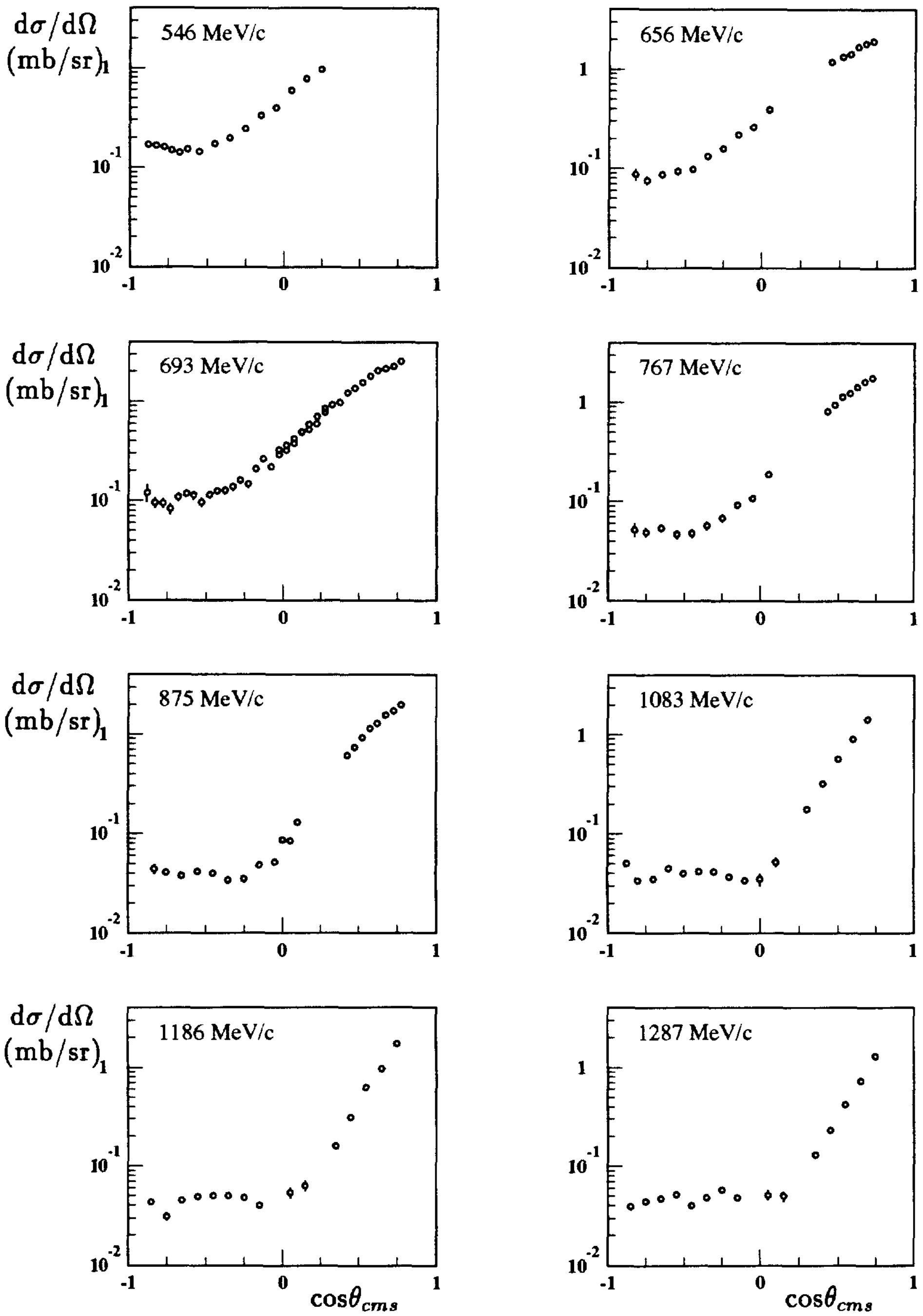

Figure 3: Differential cross-section data for the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction as a function of centre-of-mass $\cos\theta$. The measurements were performed at the indicated values of the incident $\bar{p}$ momentum by the PS199 collaboration[8].

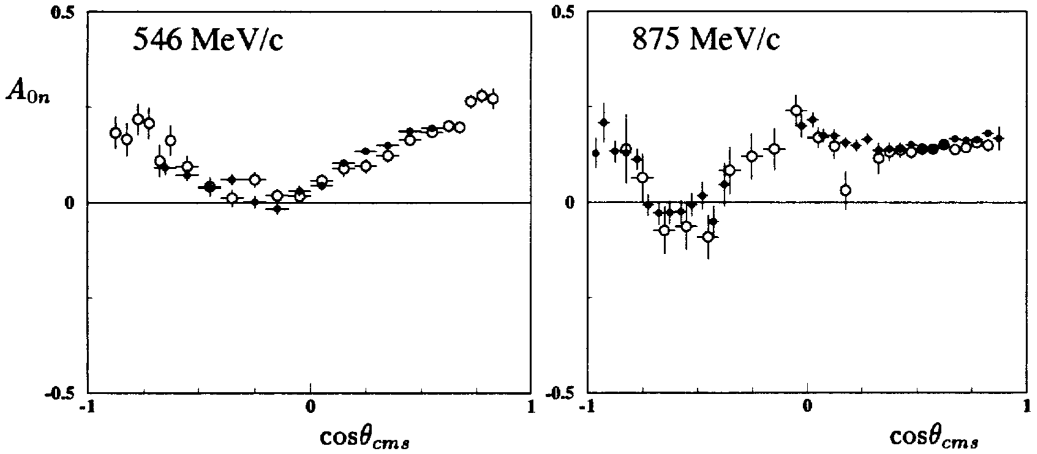

Figure 4: New A_{0n}[5,7] data (closed points) at 546 and 875 MeV/c incident p̄ momentum as a function of centre-of-mass cosθ, from the PS199 collaboration. Also shown for comparison are the previous data from the A_{0n} run (open points)[4].

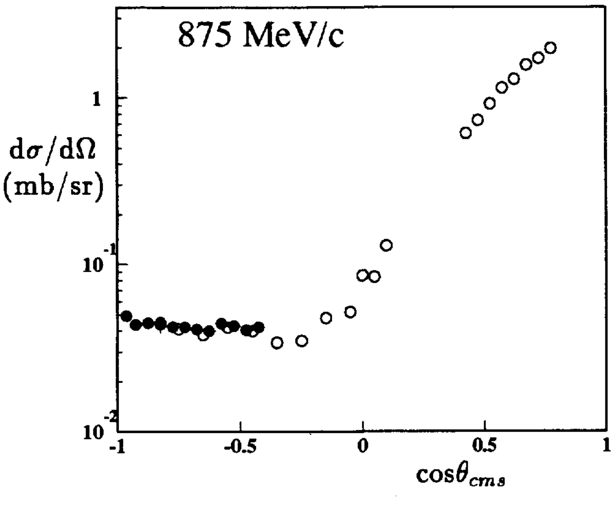

Figure 5: New $d\sigma/d\Omega$ data (closed points) from the D_{0n0n} run at 875 MeV/c from the PS199 collaboration [5]. Also shown for comparison are the previous data from the A_{0n} run (open points)[8].

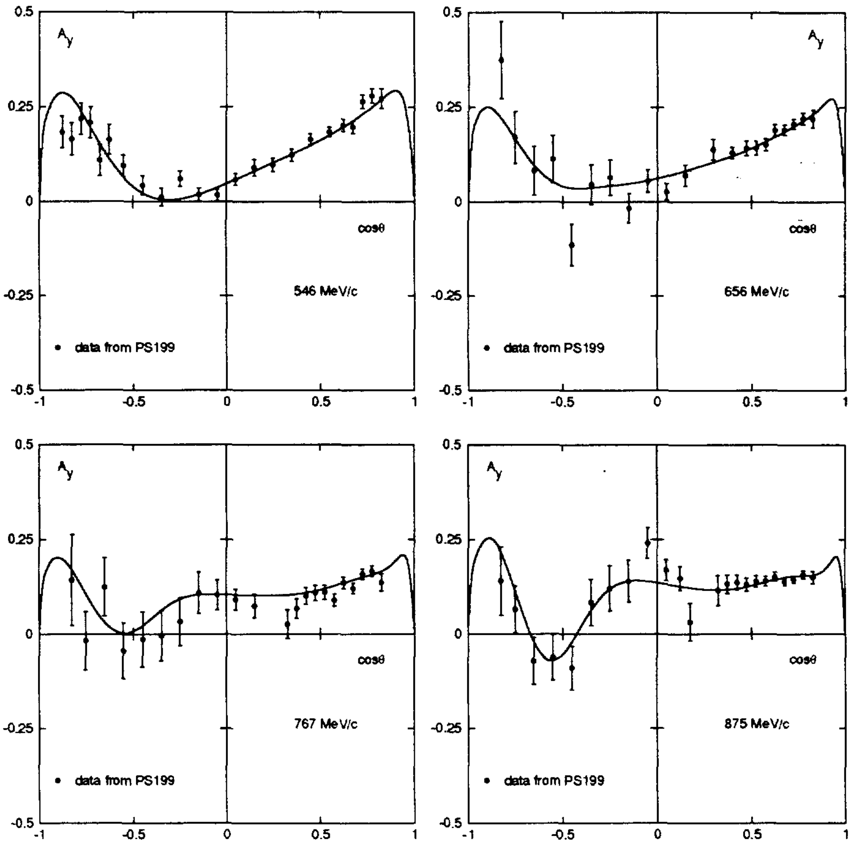

Figure 6: Comparison between A_{0n} data from the Experiment PS199[3] at the indicated incident $\bar{p}$ momenta and the results of the Nijmegen phase-shift analysis[21].

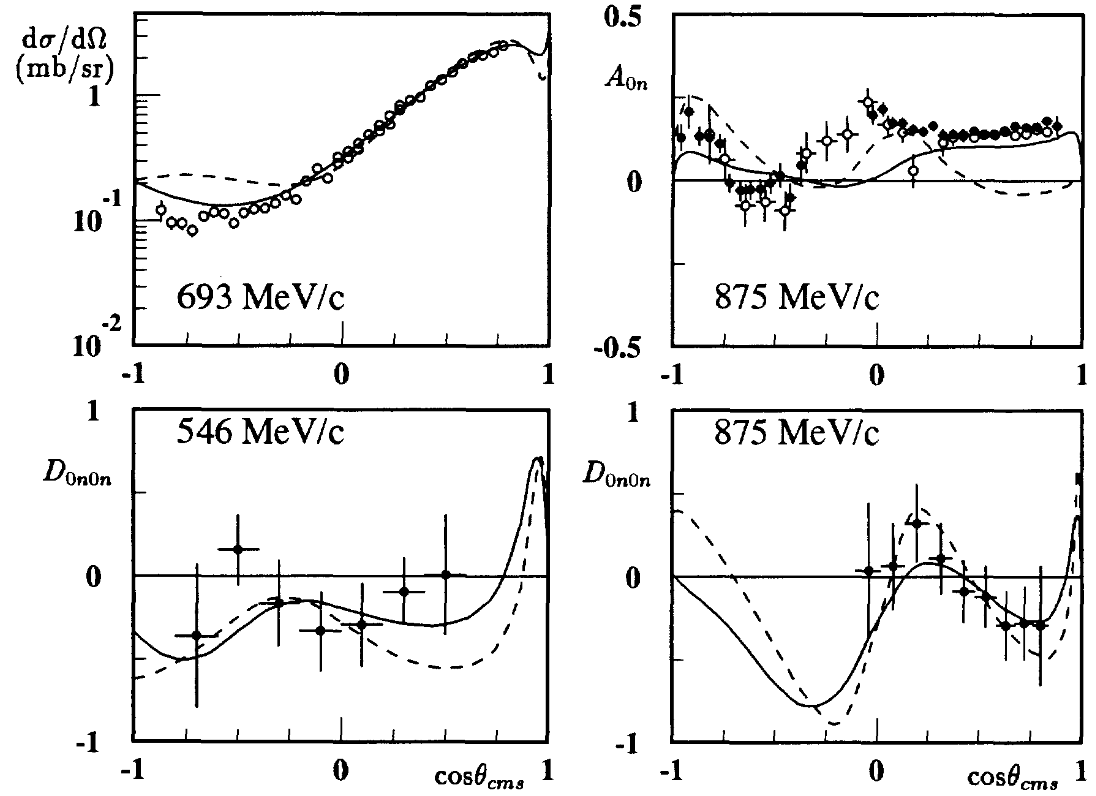

Figure 7: Comparison between some $d\sigma/d\Omega$, A_{0n}, and D_{0n0n} data at 546, 693, and 875 MeV/c from Experiment PS199 and the most recent Paris optical model calculations [26] (solid curves). Also shown (dashed curves) are the previous calculation of the Paris group [24].

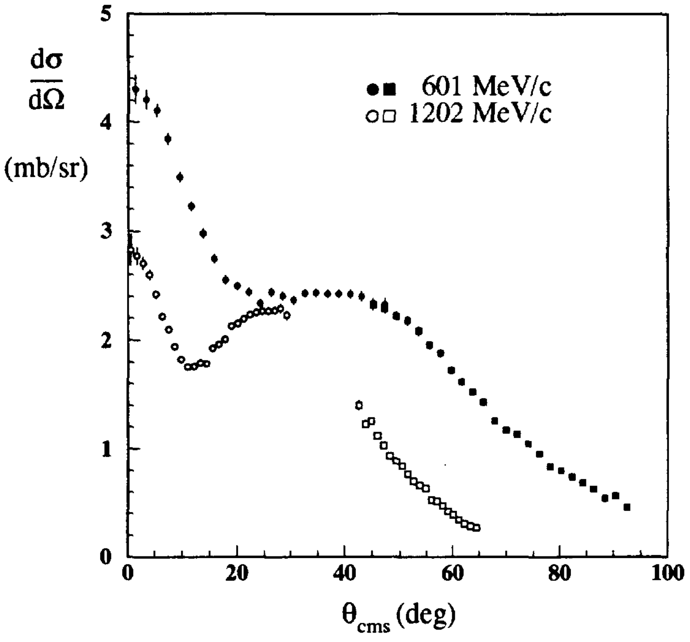

Figure 8: $d\sigma/d\Omega$ data for the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction at 601 Mev/c and 1202 Mev/c incident $\bar{p}$ momentum as a function of centre-of-mass θ from Experiment PS206[33].

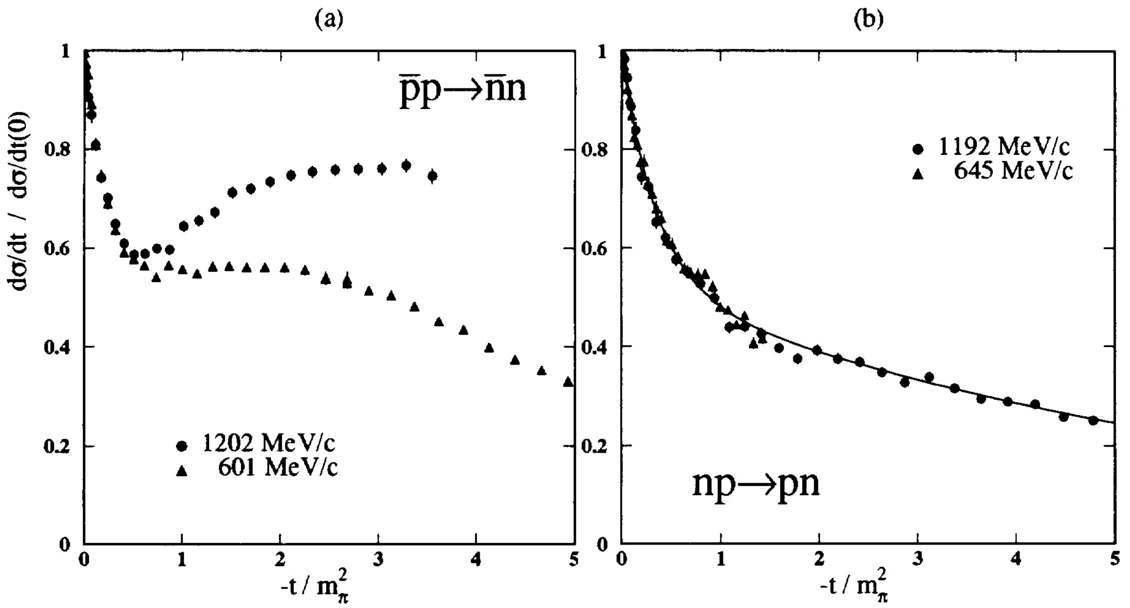

Figure 9: Ratio between the measured $\bar{p}p \rightarrow \bar{n}n$ differential cross-section data from Experiment PS206 [33] and their value at $t = 0$ (a). Ratio between the measured np → pn differential cross-section data at PSI [37] and their value at $t = 0$; the full curve is a calculation which uses the Paris potential [24] (b).

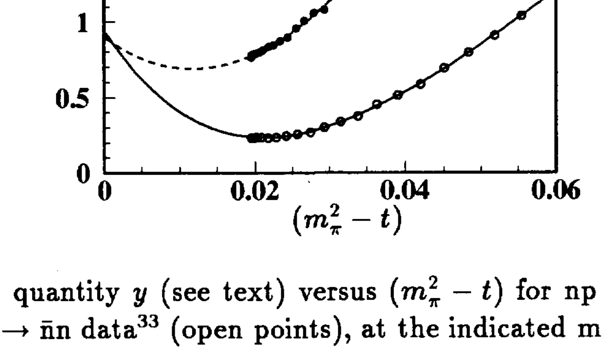

Figure 10: Plot of the quantity y (see text) versus $(m_\pi^2 - t)$ for np → pn data[41] (solid points) and PS206 $\bar{p}p \rightarrow \bar{n}n$ data[33] (open points), at the indicated momenta. Also shown are polynomial fits to the data. A value of one for the extrapolation at zero corresponds to $f_c^2 = 0.075$.