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The Antibaryon-Baryon Interactions*

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Abstract

An overview is given of the various $\bar{p}p$-scattering reactions (elastic, charge exchange, and strangeness exchange). The (partial wave) analyses of these scattering data are discussed in more detail. One of the main conclusions is that meson exchange models can in principle describe the data very well. However, many models, presented as realistic meson exchange models, are too simple, have too few free parameters, and therefore cannot fit at all the entire data set.

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I. INTRODUCTION

The antiproton beam at LEAR has been used to study a variety of reactions. In this talk we will consider the following reactions:

elastic scattering	$\bar{p}p \rightarrow \bar{p}p$,
charge-exchange (CEX)	$\bar{p}p \rightarrow \bar{n}n$,
strangeness-exchange (SEX)	$\bar{p}p \rightarrow \overline{\Lambda}\Lambda; \overline{\Lambda}\Sigma + \overline{\Sigma}\Lambda; \overline{\Sigma}\Sigma$.

When we forget for a moment about the accompagning annihilation, these $\overline{B}B$-reactions are quite similar to the NN-reactions $pp \rightarrow pp$ and $np \rightarrow pn$, and the YN-reactions $\Lambda p \rightarrow p\Lambda$, $N\Sigma$ and $\Sigma^{\pm}p \rightarrow N\Sigma$, $n\Lambda$.

II. C-CONJUGATION VERSUS G-CONJUGATION

It has already been pointed out by us before [1], and we would like to stress it here again, charge conjugation (C) is **the** operation that brings us from the NN- or YN-potentials to the $\bar{p}p$, $\bar{n}n$, $\overline{\Lambda}\Lambda$, etc. potentials and **not** G.

The G-operation is commonly defined as $G = C\exp(i\pi I_2)$. It is an operator that contains charge conjugation C and assumes charge independence or $\mathrm{SU}(2,I)$. It has been impossible to extend the definition of G to $\mathrm{SU}(3,F)$. This implies that G can never be used for going from the YN-reactions to the SEX-reactions. But even in the transition from the NN-potentials to the potentials in the elastic- and CEX-reactions it is much handier to use C and not G. It is much more natural and direct to use charge conjugation C and the broken flavor symmetry groups $\mathrm{SU}(2,I)$ and $\mathrm{SU}(3,F)$ separately.

Using charge conjugation symmetry it is obvious that the ppm^0-coupling constant g is equal to the $\bar{p}\bar{p}\overline{m^0}$-coupling constant. The meson m^0 is an eigenstate of the C-operator, with eigenvalue η_c (the charge-parity of the meson m^0), because $Cm^0 = \overline{m^0} = \eta_c m^0$. This implies that the $\bar{p}\bar{p}m^0$-coupling constant $\bar{g}$ and the ppm^0-coupling constant g are related by

$$\bar{g} = \eta_c g \ ,$$

This has very important consequences for the potentials.

Because the vector mesons have negative charge-parity, the vector meson exchange potentials change sign, when going from BB potentials to $\overline{B}B$ potentials. The scalar and pseudoscalar mesons have positive charge-parity and the π-exchange potential and the ϵ-exchange potential are therefore the same in pp and $\bar{p}p$. The combined efforts of ϵ- and ω-exchange give rise to a very strong, central attraction, which lead to the speculations of the presence of important $\overline{N}N$-bound states [2].

The tensor forces due to π- and ρ-exchange, which partially cancel each other in the pp-potential, do add coherently in the $\bar{p}p$-potential. They are important in the CEX-reaction. Similarly the combined effort of K- and K^*-exchange gives rise to strong tensor forces in the strangeness exchange (SEX) reactions.

III. THE SIMILARITY BETWEEN $\overline{N}N$ AND NN

It is not for us to discuss the question if experimental techniques applied in NN-scattering also apply in $\overline{N}N$-scattering. That the experimentalists must do. In both cases we have spin$\frac{1}{2}$-spin$\frac{1}{2}$ scattering and the various observables defined in one reaction can be defined in exactly the same way for the other reactions.

It is clear that in $\overline{N}N$-**data analyses**, the same techniques apply as in NN data analyses. Both are spin$\frac{1}{2}$-spin$\frac{1}{2}$ scattering. Because there is no Pauli principle operating in the $\overline{N}N$-reactions, these reactions have twice as many partial-wave amplitudes as the NN-reactions. In $\overline{N}N$-scattering there are, due to the large annihilation, inelasticities present. We would like to remind you that inelasticities are also present in NN-scattering above the pion production threshold. These inelasticities can be handled in exactly the same way. An important feature of both reactions is that the longest-range, strong interaction is the one-pion-exchange (OPE). It turns out that in $\overline{N}N$-data analyses exactly the same, standard, multienergy, partial-wave analyses (PWAs) are possible as in NN. The large expertise obtained in the many years of doing PWAs or the NN-scattering data was a big help in setting up the $\overline{N}N$-PWA.

In the theoretical models for describing the interaction the techniques applied in NN can also be used in $\overline{N}N$. For example the meson-exchange model for the potentials works excellently in either case. It is really too early for quark-gluon exchange models, which are at present still too primitive. These models should become a lot more sophisticated and should first be applied to the much better known case of NN-scattering. Our knowledge of the $\overline{N}N$-data is still too sparse, so that it is impossible to recognize the quality, or the lack of quality of such quark-gluon exchange models.

IV. $\overline{N}N$-SCATTERING

In the study of $\overline{N}N$-scattering one can distinguish 3 different fields of expertise. First of all there are the experiments in which one measures $d\sigma/d\Omega$, $A(\theta)$, D_{nn}, etc. This part will be covered by Professor Bradamante and this is therefore not a topic for us to discuss.

Secondly one has the data analyses. The data obtained in the various experiments can be analyzed with various kinds of data analysis methods, such as (i) Amplitude Analysis, (ii) Effective Range Analysis, and (iii) Partial Wave Analysis. The discussion of data analyses will be an important part of this talk. It will turn out that an amplitude analysis is impossible. Effective range analysis is just a simplified partial-wave analysis.

Finally there are the theoretical models which are used to explain the data. The very first (1967) model was the boundary condition model [3, 4], next came in 1968 the optical potential model [5, 6], and finally in 1984 the coupled channels model [7, 8, 9]. The first two types of models are now already more than a quarter century old.

As far as the experimental efforts are concerned, we would like to suggest to the experimentalists: "Do not try to look for experiments that will disprove certain theoretical models, but please look for experiments that will improve the PAW."

V. AMPLITUDE ANALYSIS

We consider the scattering of an incoming antiproton with relative momentum $\mathbf{p}_i$ and spin-wavefunction χ_{i_1}, colliding with the target nucleon with spin-wavefunction χ_{i_2}. In elastic scattering the outgoing antiproton will have the relative momentum $\mathbf{p}_f$ and spin-wavefunction χ_{f_1} and the recoil nucleon the spin-wavefunction χ_{f_2}. The wavefunction ψ in the elastic channel reads asymptotically

$$\psi \sim e^{ik_i z}\chi_{i_1}\chi_{i_2} + \frac{e^{ik_i r}}{r}\sum_f \chi_{f_1}\chi_{f_2} M_{fi}(\theta,\phi) \ ,$$

where $M_{fi}(\theta,\phi)$ is the scattering amplitude. In charge exchange (CEX) or strangeness exchange (SEX) scattering the wavefunction in the outgoing channel looks asymptotically like

$$\psi \sim \frac{e^{ik_f r}}{r}\sum_f \chi_{f_1}\chi_{f_2} M_{fi}(\theta,\phi) \ .$$

When we know the scattering amplitude $M(\theta,\phi)$ then it is easy to calculate cross sections, asymmetries, polarizations, spin transfers, etc. In the cm-frame it is customary to introduce the vectors

$$\mathbf{q} = \frac{1}{2}(\mathbf{p}_i + \mathbf{p}_f) \ , \quad \mathbf{k} = \mathbf{p}_f - \mathbf{p}_i \ , \quad \mathbf{n} = \mathbf{p}_i \times \mathbf{p}_f = \mathbf{q} \times \mathbf{k} \ .$$

The scattering amplitude M is generally written [10] in terms of 5 complex functions a, b, c, d, and e, which are often called Wolfenstein parameters

$$\begin{aligned} M = \frac{1}{2}[&(a+b) + (a-b)\boldsymbol{\sigma}_1\cdot\mathbf{n}\boldsymbol{\sigma}_2\cdot\mathbf{n} + (c+d)\boldsymbol{\sigma}_1\cdot\mathbf{k}\boldsymbol{\sigma}_2\cdot\mathbf{k} + \\ &(c-d)\boldsymbol{\sigma}_1\cdot\mathbf{q}\boldsymbol{\sigma}_2\cdot\mathbf{q} + ie(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\mathbf{n}] \end{aligned}$$

The experimental observables can now be expressed in terms of these 5 Wolfenstein parameters, which are functions of θ. For example one finds for the differential cross section

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

The polarization P of the outgoing $\bar{p}$ is given by

$$\sigma(\theta)P(\theta) = -\mathrm{Im}\ a^* e \ .$$

The depolarization parameter D is given by

$$\sigma(\theta)D(\theta) = \frac{1}{2}(|a|^2 + |b|^2 - |c|^2 - |d|^2 + |e|^2) \ .$$

In an amplitude analysis one tries to determine at each angle θ the 5 complex Wolfenstein parameters a, b, c, d, and e. For this we need at least 9 independent observables measured at each angle. The overal phase of these amplitudes is free.

When we look at NN, then we note that for low energies, say $T_{\rm lab} < 350$ MeV, we have never seen an amplitude analysis performed. The reason is simple. So many independent observables have never been measured. Amplitude analyses fo r low-energy NN-scattering is therefore impossible. This means, that also for $\overline{N}N$-scattering amplitude analyses are equally impossible . Therefore it does not make any sense to use arguments related specifically to amplitude analyses in trying to push for new experiments. Such arguments sound OK, but one should recognize that they are false.

VI. EFFECTIVE RANGE EXPANSION

Analyses of the NN-data and $\overline{N}N$-data using effective range expansions are in effect partial-wave analyses in which the various partial-wave amplitudes are parametrized by effective range expansions [11]. In practice these are often zero-range (one, for $\overline{N}N$ complex, parameter) expansions, because otherwise one has too many parameters. These effective range expansions have an unknown, but probably very limited range of validity. For example, in the very accurately known pp-scattering one finds that a two parameter effective range expansion is already at $T_{\rm L} = 385$ keV 1 *sd* away from the experimental value. However, when one does not worry about accuracy, then the expansion is not unreasonable up to about 30 MeV. However, this is not true for zero-range, or 1-parameter expansions. These are much worse.

We have not tried yet to make a study of the standard effective range expansions for $\overline{N}N$, therefore we cannot say much about it.

VII. PARTIAL WAVE ANALYSES

The Nijmegen PWA [12, 13] of the $\overline{N}N$ scattering data was set up along similar lines as the Nijmegen PWA's of the NN-data [14]. In this way use could be made of the experience, the theoretical machinery, and of the necessary hard- and software that was build during the last 16 years here in Nijmegen. People interested in the NN-results should look with mosaic, netscape, or lynx at [15].

In a partial-wave analysis one does not look directly at the 5 different amplitudes as sketched in section V. Instead one makes use of the conservation of angular momentum. This alone would not help, because there are now an infinite number of partial-wave scattering amplitudes to be determined. The thing that makes PWA possible (above amplitude analysis) is:

1. The short range of the strong interaction e^{-mr}/r (Yukawa form). This makes that for high ℓ's the repulsive centrifugal barrier $1/r^2$ and the $1/r$ Coulomb interaction dominate the strong interaction and the phases for high ℓ are therefore well known. One is thus left with a **finite** number of nuclear phases that need to be determined.

2. The longest range of the nuclear interaction is due to one-pion-exchange and is therefore also well established. The same holds more or less for the lon g range part of the exchange of heavier bosons, such as ϵ, ρ, η, ω, etc. Making explicitly use of this knowledge enabled us to do the energy-dependent PWA's of the low energy $\overline{N}N$-data.

Using our PWA we were able to determine the various phases as a function of p_{lab}. Having determined these phases we can calculate the 5 amplitudes and so the whole amplitude. The amplitude M we determine is essentially unique. Of course, the various phases will have statistical and systematic errors, where we believe that the systematic errors will probably be the largest. People [16], who claim that it is impossible for us to do a PWA of the $\overline{N}N$-data, confuse our energy dependent PWA with an amplitude analysis.

VIII. NIJMEGEN 1993 DATABASE

A lot of time was spent in setting up a reliable database of all $\overline{N}N$-data. Every piece of data was looked at and studied for its acceptability. Our 1993 database for elastic- and CEX-scattering contains all experiments published before 1 January 1993. It contains a total of $N_d = 2788$ elastic differential cross sections. Not taken into account were 514 elastic scattering data. Next to the 2788 elastic differential cross sections, there are 234 A_y data, 124 data for σ_{ann} and σ_{tot} and some (5) new data [17] on D_{nn}.

For charge exchange our 1993 database contains 245 $d\sigma/d\Omega$-data, 89 A_y-data, and 63 σ_{ce}-data. New are now 12 extra $d\sigma/d\Omega$-data [18], 32 A_y-data [18] and 16 D_{nn}-data [19], which are **not** contained in our 1993 database and so are not taken into account in our published analysis [13].

IX. DATA SELECTION

One of the most important results of our PWA of the $\overline{N}N$-data is the Nijmegen $\overline{N}N$-database. In setting up this database a judgement on the acceptability of each dataset had to be made. This was done on the basis of statistical criteria only. To demonstrate how this works in practice, let us look more in detail at some of the data on elastic scattering which we did not incorporate in our database, because of these statistical reasons.

source	ref	n	χ^2	N_d
PS172	[21]	3	504	84
PS173	[22]	4	505	173
PS198	[23]	3	1743	84
KEK	[24]	5	3096	173

TABLE I. Omitted data sets.
n is the number of momenta at which the measurements were performed, χ^2 is with respect to the Nijmegen PWA93, and N_d is the number of data.

In Table I we give the 4 main sets of data, the number of data N_d and the χ^2 with respect to the Nijmegen PWA93. We have adjusted the norm. We see that the χ^2 of all 4 datasets is much too high. Let us show here our study of the PS172 data in more detail.

PS172 has measured differential cross sections at 3 different momenta. They present a total of 90 data. On the advice of the experimentalists we omit from each set the most forward and the most backward point. This leaves us with $N_d = 90 - (3 \times 2) = 84$ data. With respect to the Nijmegen PWA93 these data have

$$\chi^2/N_d = 504/84 = 6.0 \ .$$

We will compare this set with the set of pre-LEAR data by Eisenhandler et al. [25]. These data were included in the Nijmegen database and their contribution in the Nijmegen PWA is

$$\chi^2/N_d = 277/276 = 1.00 \ .$$

When we include also these PS172 data in our database and we refit, then we fin d for PS172 that we have to discard 7 more datapoints, because each of them has a χ^2-contribution larger than 9. We are left with $N_d = 77$ data and we find

$$\text{PS172} \qquad \chi^2/N_d = 202/77 = 2.62 \ .$$

The χ^2 on the Eisenhandler data rises then with 37.

$$\text{Eisenhandler et al.} \qquad \chi^2/N_d = 314/276 = 1.14 \ .$$

Obviously the χ^2 on the PS172 data is still much too high.

We also did a fit with the PS172 data **in** and the Eisenhandler et al. dat a **out**. Then again 2 extra points needed to be discarded, so that now $N_d = 75$ and we get after fitting

$$\text{PS172} \qquad \chi^2/N_d = 139/75 = 1.85 \ .$$

The experimentalists quoted a 10% error on their norm. We find for the norm $N = 1.35$. One can study the allowable values for the χ^2-contribution to the fit for $N_d = 75$ datapoints. The expectation value $\langle\chi^2\rangle = 75$. The 3 sd value for $N_d = 75$ data is $\chi^2_{\rm max}(75) = 113.6$. A dataset with 75 data and a χ^2 larger than 113.6 must be discarded for a too large χ^2. In view of the fact that (i) we already had to remove 15 of the 90 datapoints in the original PS172 data and that (ii) we still end up with a too large χ^2 we feel that we cannot do anything else than make the following conclusion. The PS172 data are statistically **either** not good **or** not compatible with the rest of the database. Therefore we feel justified not to incorporate these data into our database.

This can also be seen in Fig. 1 and 2. In Fig. 1 we show the Eisenhandler et al. data at $p_{\rm L} = 860$ MeV/c. This elastic differential cross section contains 95 data. We removed 1 datapoint for too large (> 9) single contribution to χ^2 and we found $\chi^2/N_d = 70.5/94$, which is good.

Next we look at Fig. 2, where we find the PS172 data at $p_{\rm L} = 886$ MeV/c. First of all we rejected the most forward and the most backward angle. Then from the 34 data are $N_d = 34 - 2 = 32$ left and with respect to the Nijmegen PWA93 they have $\chi^2 = 257.2$. This is obviously much too large. The Nijmegen PWA93 corresponds to the solid curve. When we include the PS172 data in our fit, we find that we have to remove 4 more datapoints, so that now $N_d = 34 - 6 = 28$. After the fit we find $\chi^2 = 138.5$ for these 28 points. The fitted norm is 1.2. Next we fit, where we do not include the Eisenhandler et al. data. The resulting fit for these 28 points is the dashed line. We get $\chi^2 = 51.5$ with the norm is 1.35.

Let us for a moment look also at the PS173 data [22] on the elastic $d\sigma/d\Omega$ at $p_{\rm L} = 287$ MeV/c. Comparing the data with the Nijmegen PWA93 we find that the 9 most forward points must be discarded, because they are obviously polluted by Molière scattering. We have then $N_d = 54 - 9 = 45$ data left, and with respect to the Nijmegen PWA93 we find $\chi^2/N_d = 188.9/45$ and the norm is 1.31. It is clear from Fig. 3 that we even do not have to try to fit these data. These data cannot be fitted properly in our PWA. These data [22] are very probably incorrect and should therefore not be included in our database.

X. RESULTS OF ANALYSIS

In our PWA we used $N_d = 3646$ data and we reached $\chi^2_{\rm min} = 3801$ which amounts to $\chi^2/N_d = 1.043$. This is a pretty good figure of merit for a PWA.

Sometimes one asks: What is the use of a PWA? What results have you obtained? Let us point out therefore that a good PWA is a powerful tool. This tool can be used to answer many silly, and some not so silly questions posed in the literature. Let us take as example the question posed [20] in 1992: "What is the evidence for one-pion-exchange?" This question was already answered [12] by us in 1991 in a preliminary version of our PWA, where we determined the mass $m(\pi^+) = 143(5)$ MeV/c^2 and the coupling constant $f_c^2 = 0.0751(17)$. The agreement with the mass and coupling constant determined from other means is such that we think that there cannot be any questions about the presence of OPE in $\overline{N}N$-scattering.

We think that the most important results of our PWA are

1. The understanding we obtained of the $\overline{N}N$-database.

We know now which data are reliable, and which data are probably not so good (see e.g. section XI). Therefore we do not have to consider anymore exotic explanations for these unreliable data.

2. The knowledge of the scattering amplitude $M(\theta, \phi)$ for all momenta below 925 MeV/c. This allows us to make **reliable** predictions for **all** new experiments done in this momentum region.

p_L (MeV/c)	$\sigma_{\rm tot}$ (mb)	$\Delta\sigma_T$ (mb)	$\Delta\sigma_L$ (mb)	$\Delta\sigma_T/\sigma_{\rm tot}$ (%)	$\Delta\sigma_L/\sigma_{\rm tot}$ (%)
200	314.8	−91.0	−19.4	−28.9	−6.2
400	194.0	−45.6	−51.8	−23.5	−26.7
600	151.8	−31.5	−58.6	−20.8	−38.6
800	128.5	−25.8	−54.1	−20.1	−42.1

TABLE II. Predictions of the Nijmegen PWA [13] for $\Delta\sigma_T/\sigma_{\rm tot}$ and for $\Delta\sigma_L/\sigma_{\rm tot}$ at several momenta.

As an example let us give (in Table II) our prediction for $\Delta\sigma_T/\sigma_{\rm tot}$ and $\Delta\sigma_L/\sigma_{\rm tot}$ as a function of energy. These numbers were important, when one considered to make polarized $\bar{p}$-beams [26]. Now they are, unfortunately, only of academic interest.

Let us look next at the new elastic scattering data not available to us when we did our PWA. That is interesting, because they could show how good our prediction in this specific case turned out to be. We compared our prediction of D_{nn} with the measurement [17] and find $\chi^2/N_d = 7.4/5$. When we refit we obtain $\chi^2/N_d = 6/5$. This shows that these 5 elastic D_{nn} data are predicted reasonable well. However, we feel that these data are too inaccurate. Therefore we unfortunately cannot boast that our prediction of D_{nn} was a big success of our PWA.

XI. THE ρ-PARAMETER

Our knowledge of the scattering amplitude allows us to calculate $\rho = \text{Re } F/\text{Im } F$, where F is the spin-averaged forward scattering amplitude.

Experimentally the values of ρ were always determined from elastic differential cross sections in the Coulomb-nuclear interference region. The theoretical methods normally used to extract ρ from such data are questionable, because the derivations of the necessary formulas contain some questionable assumptions. Moreover, the experimental data [22, 27] are contaminated by Molière scattering. In these old determinations of ρ a sharp rise was observed for low energies near the $\bar{n}n$-threshold. This rise has been puzzling many people.

After our PWA and our determination of ρ from the experimental data (see Figure 4), the behavior of this ρ-parameter at these low energies is no mystery to us anymore. Let us explain.

PS173 published values for ρ at 7 different momenta [22]. Unfortunately, they published at only 4 of these 7 momenta the corresponding differential cross sections. (See Figure 4 and the discussion in section VIII.) From these $d\sigma/d\Omega$ data we needed to discard the data at, at least, 3 of the 4 momenta. This means that we should also look very sceptically at the other momenta and reject all ρ determinations by PS173.

PS172 published at the low momenta two ρ-values [27]. The data at $p_{\text{lab}} = 233$ MeV/c are such that they should have been rejected by us. The ρ-value at the other momentum ($p_{\text{lab}} = 272$ MeV/c) is not in too violent disagreement with our determination, when we allow for a possible small pollution by Molière scattering and for the inadequacy of the theoretical methods used by PS172 in extracting the value of ρ. We would like to stress that the curve in Figure 4 is **our** determination of ρ from the experimental data. Our method to obtain ρ does not depend on the questionable theoretical assumptions used in the other method.

XII. CHARGE EXCHANGE SCATTERING (CEX)

In the Nijmegen database 93 we have included 245 data on $d\sigma/d\Omega$. There are now 12 new datapoints [18], which will be presented by Professor Bradamante. The $d\sigma/d\Omega$ data at $p_{\text{L}} = 693$ MeV/c [28] have been very constraining in our PWA and it is definitely so that these $d\sigma/d\Omega$ are important.

Then there are 89 data on A_y [29] included in our database and 32 new data [18]. In our judgement these data are also important in our PWA.

Finally there are 16 new D_{nn} data [19] not included in our database. These data are not "very constraining" for our PWA. The error bars are too large and one may even wonder if the errors are really statistical.

XIII. THEORETICAL MODELS

Let us take a very short look at the various theoretical models used to describe the elastic- and CEX-data. We are very disappointed with the quality of the majority of these models. Most models contain only very few adjustable parameters and are therefore too simple to fit the many experimental data. We think that there are really 3 exceptions.

- The optical model of the Paris group [6].
  The original model of the early 80's has been refitted in 1991. With respect to $N_d = 2714$ they find $\chi^2_{\rm min}/N_d = 6.7$. This is pretty high.
- The Nijmegen PWA93 [13].
  This, for all practical reasons, is an optical model. Only the spin-coupled partial-waves (like ${}^3P_2 - {}^3F_2$) are treated slightly differently. We find for $N_d = 3646$ data that $\chi^2_{\rm min}/N_d = 1.04$.
- The Nijmegen Coupled Channels Model [7].
  The original model stems from the early 80's and was updated in the thesis of R. Timmermans and was already presented at LEAP90. For the $N_d = 3646$ data this gives $\chi^2/N_d = 1.58$. In NN-scattering the well-known potentials like Nijmegen, Paris, and Bonn all have a $\chi^2/N_d \simeq 2$ with respect to the pp-data. Our $\chi^2/N_d \simeq 1.6$ can therefore be considered pretty good.

In Fig. 5 we compare the Nijmegen coupled channels model with the PS199 data for $d\sigma/d\Omega$ at $p_{\rm L} = 693$ MeV/c and for A_y at 656 MeV/c. We see that the curves describe the data reasonably well.

XIV. STRANGENESS EXCHANGE SCATTERING (SEX)

The database for the strangeness-exchange reactions contains at present: for $\overline{p}p \to \overline{\Lambda}\Lambda$ 270 differential cross sections, 103 polarizations, and 168 spin correlations at 10 momenta between 1.435 and 2 GeV/c; for $\overline{p}p \to \overline{\Lambda}\Sigma + \overline{\Sigma}\Lambda$ 33 cross sections, 24 polarizations, and 28 spin correlations at 2 momenta; and for $\overline{p}p \to \overline{\Sigma}\Sigma$ there are now available 8 cross sections at 1.918 GeV/c. All these data are from PS185 [30].

There are again lots of models on the market to describe these strangeness-exchange reactions: there are meson-exchange models, optical [31] and coupled-channels [32, 33], and also quark models [34]. An effective-range analysis was done by the Pittsburgh group [35]. We have performed a partial-wave analysis of these reactions [36, 37], using a coupled-channels formalism and with the Nijmegen hyperon-nucleon potential [38] as long-range interaction.

The main conclusion from this PWA is that one-kaon exchange is definitely present. From the many accurate data on $\overline{p}p \to \overline{\Lambda}\Lambda$ we can determine the ΛNK coupling constant very well. We find:

$$f^2_{\Lambda NK}/4\pi = 0.069(4) \ , \ \text{or} \ \ g^2_{\Lambda NK}/4\pi = 14.9(9) \ . \tag{1}$$

If we determine the kaon mass, we find $m(K) = 475(30)$ MeV/c^2. Assuming SU$(3, F)$ symmetry for the coupling constants, we can then calculate the $\alpha = F/(F + D)$ ratio. The result is $\alpha_{\rm PV} = 0.34(3)$ for pseudovector coupling, in nice agreement with the determination from the weak decays of the baryons: $\alpha_{\rm W} = 0.355(6)$. These results show that it is not necessary to measure D_{nn} [39] to distinguish between meson-exchange and quark models for $\overline{p}p \to \overline{\Lambda}\Lambda$.

In the same manner we have tried to extract the ΣNK coupling constant from the 87 data points for $\overline{p}p \to \overline{\Lambda}\Sigma + \overline{\Sigma}\Lambda$. The result was:

$$f^2_{\Sigma NK}/4\pi = 0.005(2) \ , \ \text{or} \ \ g^2_{\Sigma NK}/4\pi = 1.2(5) \ , \tag{2}$$

which is also consistent with SU$(3, F)$ symmetry. One can hope to improve on this number when more data become available.

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REFERENCES

[1] J.J. de Swart, Th.A. Rijken, and R. Timmermans, Proceedings of NAN'93, the Second Biennial Workshop on Nucleon-Antinucleon Physics, Moscow, Russia, September 1993, edited by Yu. Kalashnikova *et al.*; Yadernaya Fizika (Journal of Atomic Nuclei) **57**, 1621 (1994).

[2] I.S. Shapiro, Phys. Rep. **35C**, 129 (1978); L. Montanet, G.C. Rossi, and G. Veneziano, Phys. Rep. **63**, 153 (1980); C.B. Dover and M. Goldhaber, Phys. Rev. **15**, 1997 (1977); J. Carbonell, O.D. Dalkarov, K.V. Protasov, and I.S. Shapiro, Nucl. Phys. **A535**, 651 (1991).

[3] M.S. Spergel, Il Nuovo Cimento **47A**, 410 (1967).

[4] O.D. Dal'karov and F. Myhrer, Il Nuovo Cimento **40A**, 152 (1977).

[5] R.A. Bryan and R.J.N. Phillips, Nucl. Phys. **B5**, 201 (1968); *ibid.* **B7**, 481(E) (1968).

[6] J. Côté, M. Lacombe, B. Loiseau, B. Moussallam, and R. Vinh Mau, Phys. Rev. Lett. **48**, 1319 (1982); M. Pignone, M. Lacombe, B. Loiseau, and R. Vinh Mau, Phys. Rev. Lett. **67**, 2423 (1991).

[7] P.H. Timmers, W.A. van der Sanden, and J.J. de Swart, Phys. Rev. D **29**, 1928 (1984); R. Timmermans, Ph.D. thesis, University of Nijmegen (1991); R. Timmermans, Th. A. Rijken, and J.J. de Swart, in preparation.

[8] G.Q. Liu and F. Tabakin, Phys. Rev. C **41**, 665 (1990).

[9] O.D. Dal'karov, J. Carbonell, and K.V. Protasov, Sov. J. Nucl. Phys. **52**, 1052 (1990), (Yad. Fiz. **52**, 1670 (1990)).

[10] L. Wolfenstein and J. Ashkin, Phys. Rev. **85**, 947 (1952); N. Hoshizaki, Prog. Theor. Phys. Suppl. **42**, 107 (1968); P. LaFrance, F. Lehar, B. Loiseau, and P. Winternitz, Helv. Phys. Acta **65**, 611 (1992).

[11] I.L. Grach, B.O. Kerbikov, and Yu.A. Simonov, Phys. Lett. B **208**, 309 (1988); J. Mahalanabis, H.J. Pirner, and T.-A. Shibata, Nucl. Phys. **A485**, 546 (1988); H.J. Pirner, B. Kerbikov, and J. Mahalanabis, Zeit. Phys. **A338**, 111 (1991).

[12] R. Timmermans, Th.A. Rijken, and J.J. de Swart, Phys. Rev. Lett. **67**, 1074 (1991).

[13] R. Timmermans, Th.A. Rijken, and J.J. de Swart, Phys. Rev. C **50**, 48 (1994).

[14] J.R. Bergervoet, P.C. van Campen, W.A. van der Sanden, and J.J. de Swart, Phys. Rev. C **38**, 15 (1988); J.R. Bergervoet, P.C. van Campen, R.A.M. Klomp, J.-L. de Kok, T.A. Rijken, V.G.J. Stoks, and J.J. de Swart, Phys. Rev. C **41**, 1435 (1990); V. Stoks, R. Timmermans, and J.J. de Swart, Phys. Rev. C **47**, 512 (1993); V.G.J. Stoks, R.A.M. Klomp, M.C.M. Rentmeester, and J.J. de Swart, Phys. Rev. C **48**, 792 (1993).

[15] URL "http://NN-OnLine.sci.kun.nl"

[16] F. Bradamante, R. Hess, and J.-M. Richard, Proceedings of NAN'93, the Second Biennial Workshop on Nucleon-Antinucleon Physics, Moscow, Russia, September 1993; edited by Yu. Kalashnikova *et al.*; Yadernaya Fizika (Journal of Atomic Nuclei) **57**, 1630 (1994).

[17] R.A. Kunne *et al.*, Phys. Lett. B **261**, 191 (1991).

[18] M. Lamanna *et al.*, CERN-PPE/94-137, to be published in Nucl. Phys. B.

[19] R. Birsa *et al.*, Phys. Lett. B **302**, 517 (1993), and to be published in Nucl. Phys. B.

[20] F. Bradamante, R. Hess, and J.-M. Richard, Few-Body Systems **14**, 37 (1993).

[21] R.A. Kunne *et al.*, Phys. Lett. B **206**, 557 (1988); Nucl. Phys. **B323**, 1 (1989).

[22] W. Brückner *et al.*, Phys. Lett. B **158**, 180 (1985); Phys. Lett. B **166**, 113 (1986); Zeit. Phys. **A335**, 217 (1990).

[23] R. Bertini *et al.*, Phys. Lett. B **228**, 531 (1989); F. Perrot *et al.*, *ibid.* **261**, 188 (1991).
[24] T. Kageyama *et al.*, Phys. Rev. D **35**, 2655 (1987).
[25] E. Eisenhandler *et al.*, Nucl. Phys. **B113**, 1 (1976).
[26] H. Dobbeling *et al.*, Proposal CERN-PSCC/85-80, PSCC/P92; H. Akchurin *et al.*, Proposal CERN-PSCC/89-22, PSCC/P120.
[27] L. Linssen *et al.*, Nucl. Phys. **A469**, 726 (1987).
[28] R. Birsa *et al.*, Phys. Lett. B **246**, 267 (1990).
[29] R. Birsa *et al.*, Phys. Lett. B **273**, 533 (1991).
[30] P.D. Barnes *et al.*, Phys. Lett. B **189**, 249 (1987); *ibid.* **199**, 147 (1987); **229**, 432 (1989); Nucl. Phys. **A526**, 575 (1991); P.D. Barnes *et al.*, Phys. Lett. B **246**, 273 (1990).
[31] F. Tabakin and R.A. Eisenstein, Phys. Rev. C **31**, 1857 (1985); M. Kohno and W. Weise, Phys. Lett. B **179**, 15 (1986); *ibid.* **206**, 584 (1988); P. LaFrance, B. Loiseau, and R. Vinh Mau, Phys. Lett. B **214**, 317 (1988); P. LaFrance and B. Loiseau, Nucl. Phys. **A528**, 557 (1991).
[32] P.H. Timmers, Ph.D. Thesis, Univ. of Nijmegen (1984).
[33] J. Haidenbauer, K. Holinde, and J. Speth, Nucl. Phys. **A562**, 317 (1993).
[34] S. Furui and A. Faessler, Nucl. Phys. **A468**, 669 (1987); M.A. Alberg, E.M. Henley, and L. Wilets, Z. Phys. A **331**, 207 (1988); Phys. Rev. C **38**, 1506 (1988); P. Kroll and W. Schweiger, Nucl. Phys. **A474**, 608 (1987); P. Kroll, B. Quadder, and W. Schweiger, Nucl. Phys. **B316**, 373 (1989).
[35] F. Tabakin, R.A. Eisenstein, and Y. Lu, Phys. Rev. C **44**, 1749 (1991).
[36] R. Timmermans, Th.A. Rijken, and J.J. de Swart, Phys. Lett. B **257**, 227 (1991).
[37] R. Timmermans, Th.A. Rijken, and J.J. de Swart, Phys. Rev. D **45**, 2288 (1992).
[38] P.M.M. Maessen, Th.A. Rijken, and J.J. de Swart, Phys. Rev. C. **40**, 2226 (1989).
[39] J. Haidenbauer, K. Holinde, V. Mull, and J. Speth, Phys. Lett. B **291**, 223 (1992); M.A. Alberg, E.M. Henley, L. Wilets, and P.D. Kunz, Seattle preprint DOE/ER/40427-31-N93.

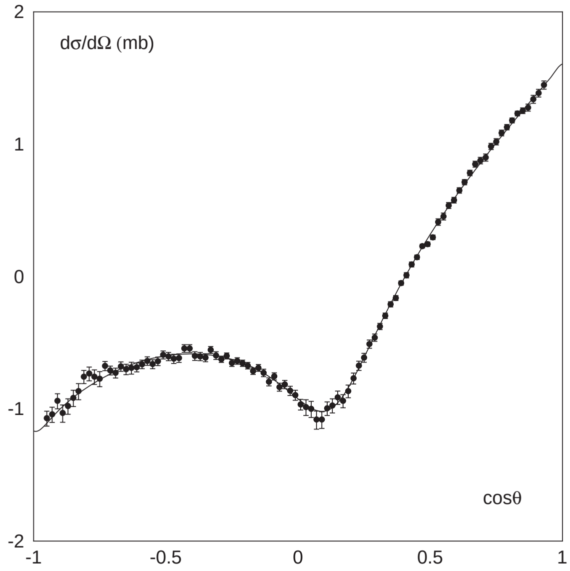

FIG. 1. Elastic differential cross section at 860 MeV/c. The data are from Eisenhandler et al. [25]. The curve is from the Nijmegen PWA [13], and has $\chi^2_{\rm min} = 70.5$ for 94 observables.

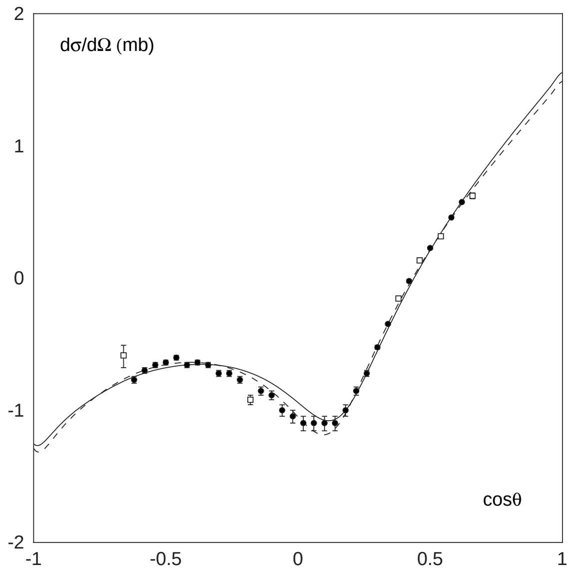

FIG. 2. Elastic differential cross section at 886 MeV/c. The data are from PS172 [21]. The most forward and backward point (open squares) are rejected (PS172, private comm.). The drawn curve is the prediction from the Nijmegen PWA [13], with $\chi^2_{\rm min} = 257.2$ for 32 points. The dashed curve is the result of the fit when we include these data. The open squares have to be rejected. For the remaining 28 points we then find $\chi^2_{\rm min} = 138.5$.

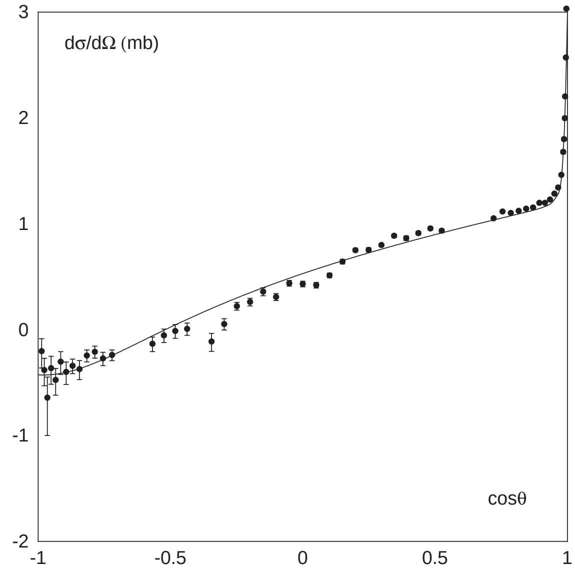

FIG. 3. Elastic differential cross section at 287 MeV/c. The data are from PS173 [22]. The curve is the prediction from the Nijmegen PWA [13]. The nine most forward points are polluted by Molière scattering. The curve has $\chi^2_{\rm min} = 188.9$ for the remaining 45 points.

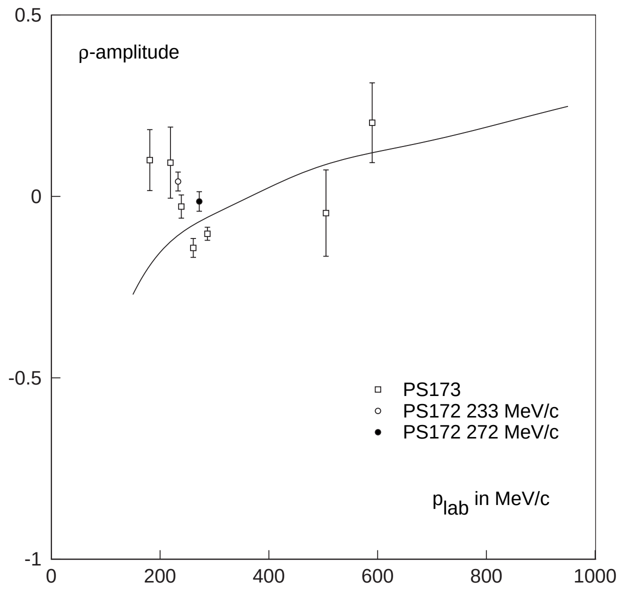

FIG. 4. The real-to-imaginary ratio ρ of the spin-averaged forward scattering amplitude as function of momentum. The data points are from PS172 [27] and from PS173 [22]. The curve is the prediction from the Nijmegen PWA [13].

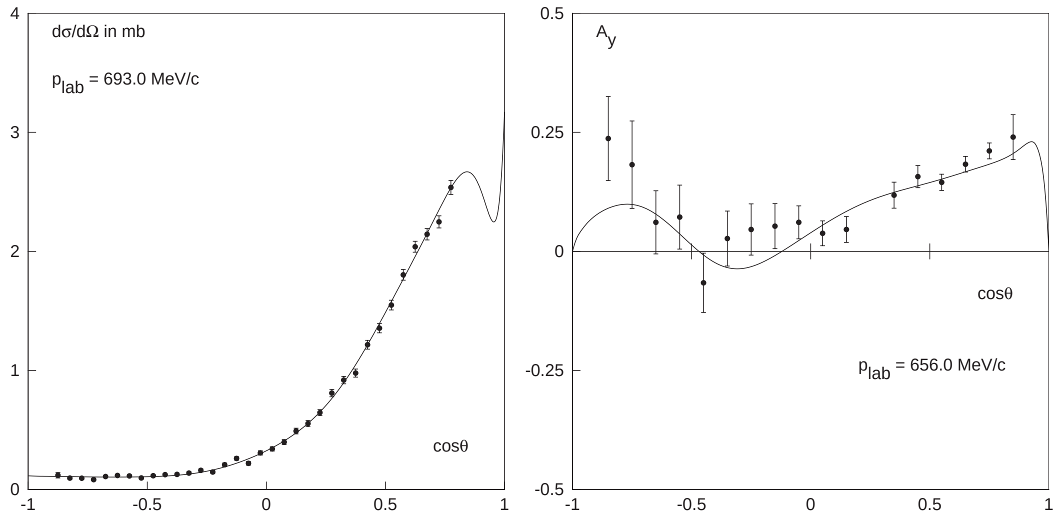

FIG. 5. Charge exchange differential cross section at 693 MeV/c and analyzing power at 656 MeV/c. The data are from PS199 [28]. The curves are from the Nijmegen coupled-channels model [7].