Polarization phenomena in the reaction $NN \to NN\pi$ near threshold

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First calculations for spin-dependent observables of the reactions $pp \to pp\pi^0$, $pp \to pn\pi^+$, and $pp \to d\pi^+$ near threshold are presented, employing the Jülich model for pion production. The influence of resonant [via the excitation of the $\Delta(1232)$] and nonresonant *p*-wave pion production mechanisms on these observables is examined. For the reactions $pp \to pn\pi^+$ and $pp \to d\pi^+$ nice agreement of our predictions with the presently available data on spin correlation coefficents is observed whereas for $pp \to pp\pi^0$ the description of the data is less satisfying.

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The last few years have witnessed a rather rapid growth of the data set on the various charge channels of the reaction $NN \to NN\pi$ near threshold [1]. Naturally the first observables that became available were total cross sections. But soon they were supplemented with data on differential cross sections as well as analyzing powers. At present a third stage has been reached where results from measurements involving polarized beams as well as polarized targets are becoming available [2–6].

As far as microscopic model calculations of the reaction $NN \to NN\pi$ are concerned one has to concede that theory is definitely lagging behind the development of the experimental sector. Many works [1] deal only with the reaction $pp \to pp\pi^0$. Furthermore, they take into account only the lowest partial wave(s). Therefore it is not possible to confront those models with the wealth of experimental information available nowadays, specifically with differential cross sections and with spin-dependent observables. In fact, to the best of our knowledge so far there are only two model calculations where all relevant pion production channels are considered and, in addition, higher partial waves are included as well, namely, the ones of the Osaka [7,8] and the Jülich [9,10] groups.

The forthcoming data on spin-dependent cross sections and spin correlation coefficients are very welcome since it is expected that they might play an important role in deepening our theoretical understanding of pion production near threshold. Thus, in order to keep up with the development of the experimental side we want to present here corresponding predictions of the Jülich model in order to facilitate a comparison with the new measurements. Furthermore, we investigate the sensitivity of these observables to specific production mechanisms. Such information will be useful for a future, more detailed analysis. Note that this is the first time that model calculations of these observables have been made available for the reactions $pp \to pp\pi^0$, $pp \to pn\pi^+$, and $pp \to d\pi^+$ near threshold.

Let us first describe shortly the Jülich model for pion production. In this model all standard pion-production mechanisms (direct production [Fig. 1(a)], pion rescattering [Fig. 1(b)], contributions from pair diagrams [Fig. 1(c)]) are considered. In addition, production mechanisms involving the excitation of the $\Delta(1232)$ resonance [cf. Figs. 1(d) and 1(e)] are taken into account explicitly. All NN partial waves up to orbital angular momenta $L_{NN} = 2$ and all states with relative orbital angular momentum $l \leqslant 2$ between the NN system and the pion are considered in the final state. Furthermore, all πN partial waves up to orbital angular momenta $L_{\pi N} = 1$ are included in calculating the rescattering diagrams in Figs. 1(b) and 1(e). Thus, our model includes not only *s*-wave pion rescattering but also contributions from *p*-wave rescattering.

The reaction $NN \to NN\pi$ is treated in a distorted-wave Born approximation, in the standard fashion. The actual calculations are carried out in momentum space. For the distortions in the initial and final NN states we employ the model CCF of Ref. [11]. This potential has been derived from the full Bonn model [12] by means of the folded-diagram expansion. It is a coupled-channel (NN, $N\Delta$, $\Delta\Delta$) model that treats the nucleon and the Δ degrees of freedom on equal footing. Thus, the $NN \leftrightarrow N\Delta$ transition amplitudes and the NN T matrices that enter in the evaluation of the pion production diagrams in Fig. 1 are consistent solutions of the same (coupled-channel) Lippmann-Schwinger-like equation.

The $\pi N \to \pi N$ T matrix needed for the rescattering process is taken from a microscopic meson-exchange model developed by the Jülich group [13]. This interaction model is based on the conventional (direct and crossed) pole diagrams involving the nucleon and Δ isobar as well as *t*-channel meson exchanges in the scalar (σ) and vector (ρ) channel derived from correlated 2π exchange. Note that in our model of the reaction $NN \to NN\pi$ contributions where the pions are

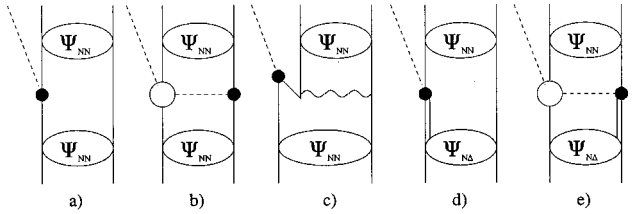

FIG. 1. Pion production mechanisms taken into account in our model: (a) direct production, (b) pion rescattering, (c) contributions from pair diagrams, and (d) and (e) production involving the excitation of the $\Delta(1232)$ resonance. Note that diagrams where the Δ is excited after pion emission are also included.

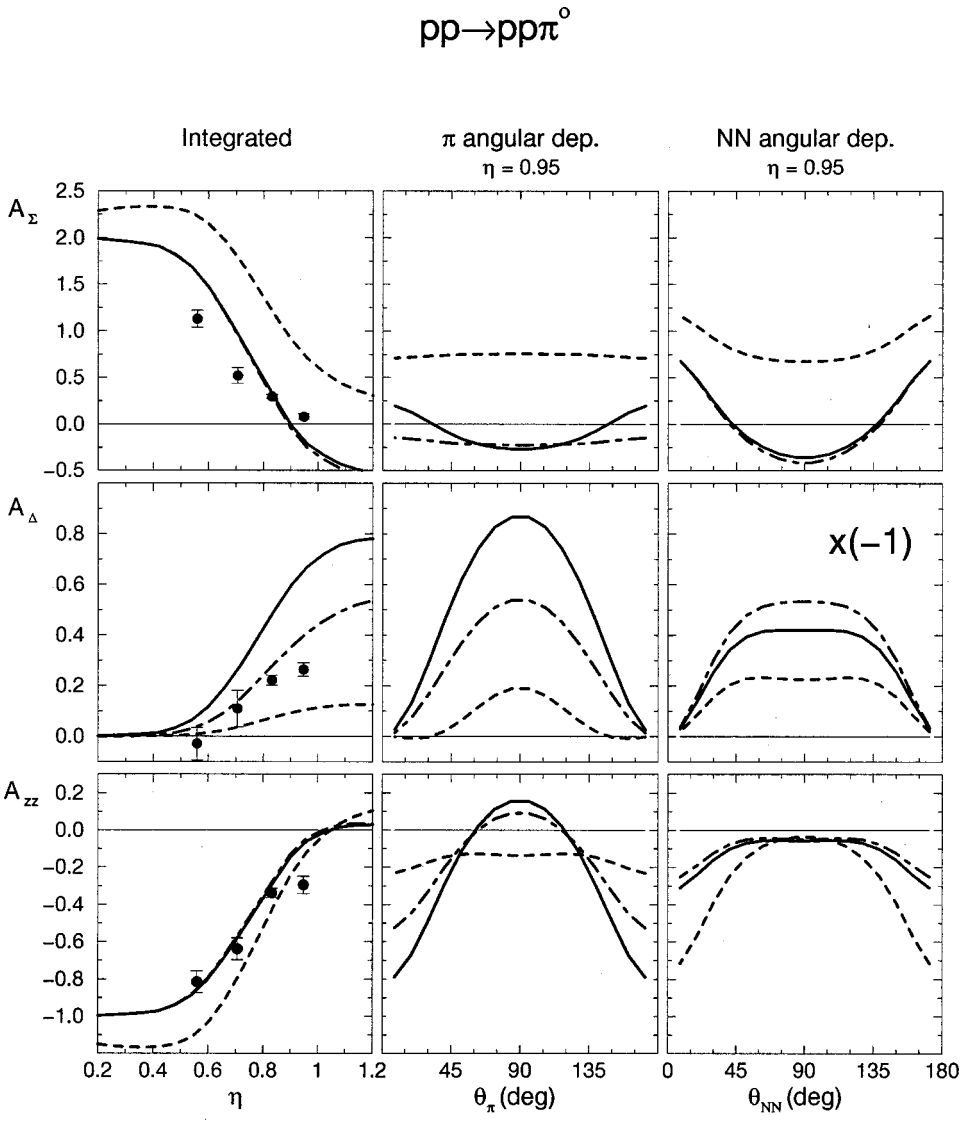

FIG. 2. Spin correlation parameters for the reaction $pp \rightarrow pp\pi^0$, where $A_\Sigma = A_{xx} + A_{yy}$ and $A_\Delta = A_{xx} - A_{yy}$. The solid line represents the result of our full model. The dash-dotted curves are obtained when the contributions of nonresonant *p*-wave pion rescattering are omitted. The dashed curves show results where the contributions to pion production via the $\Delta(1232)$ resonance are switched off as well. The experimental results are taken from Ref. [2].

produced directly from the nucleon or Δ [cf. Figs. 1(a) and 1(d)] are taken into account explicitly. Therefore, the corresponding nucleon and Δ pole terms have to be taken out of the πN T matrix in order to avoid double counting.

The contributions of the pair diagrams [Fig. 1(c)] are viewed as an effective parametrization of short range production mechanisms that are not explicitly included in the model. Their strength, the only free parameter in the Jülich model, was adjusted to reproduce the total $pp\pi^0$ production cross section at low energies. Note that, due to their vertex structure, those pair diagrams contribute only to *s*-wave pion production.

Results of this model for total cross sections and analyzing powers for the reactions channels $pp \rightarrow pp\pi^0$, $pp \rightarrow pn\pi^+$, $pn \rightarrow pp\pi^-$, and $pp \rightarrow d\pi^+$ were presented in Refs. [9,10]. It was found that the model yields a very good overall description of the data from the threshold up to the Δ resonance region. In fact, a nice quantitative agreement with basically all experimental information (then available) was observed over a wide energy range. Thus, this model is very well suited as a starting point for a detailed analysis of the forthcoming spin-dependent observables of the reaction $NN \rightarrow NN\pi$.

Predictions for the spin correlation coefficient combinations $A_\Sigma = A_{xx} + A_{yy}$, $A_\Delta = A_{xx} - A_{yy}$, and A_{zz} are shown in Figs. 2 (for $pp \rightarrow pp\pi^0$), 3 (for $pp \rightarrow pn\pi^+$), and 4 (for $pp \rightarrow d\pi^+$). The polar integrals of these observables are displayed in the left panels as a function of η, the maximum momentum of the produced pion in units of the pion mass. [Note that the polar integral of $-(A_{xx} + A_{yy})$ and A_{zz} yield the spin-dependent total cross section $\Delta\sigma_T/\sigma_{tot}$ and $\Delta\sigma_L/\sigma_{tot}$, respectively; cf. Refs. [2,14] for definitions.] The other two panels contain the results at $T_{lab} = 400$ MeV as a function of the pion angle (middle panel) and of the angle between the nucleons (right panel).

One of the specific features of the Jülich model is that contributions from *p*-wave pion rescattering are fully taken into account. Their resonant part is, of course, given by the pion production via the Δ excitation as depicted in Fig. 1(d). However, our model includes nonresonant contributions from *p*-wave pion rescattering as well. Thus, we can study the influence of the latter on those spin observables. Results

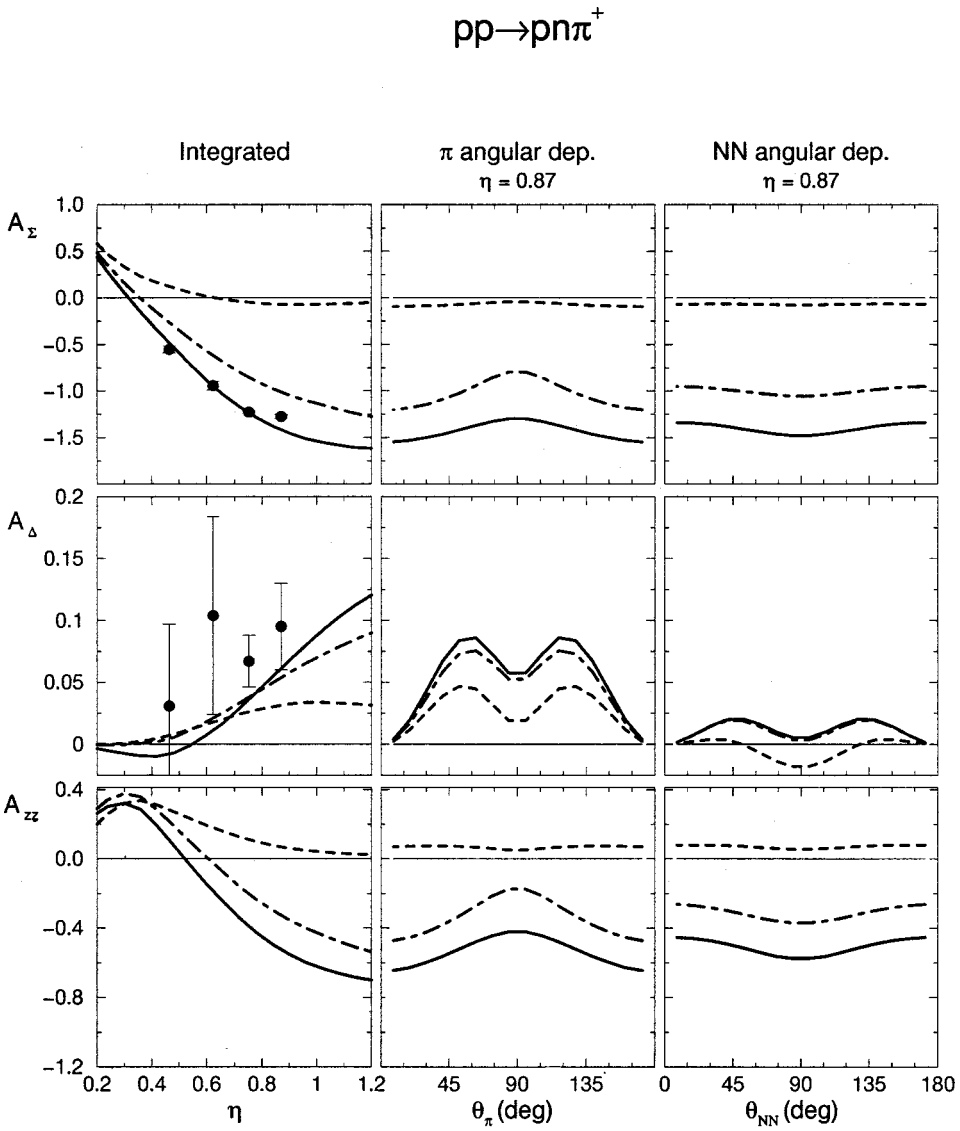

FIG. 3. Spin correlation parameters for the reaction for $pp \rightarrow pn\pi^+$. Same description of the curves as in Fig. 2. The experimental results are taken from Ref. [4].

were the contributions of nonresonant *p*-wave pion rescattering are omitted are shown by the dash-dotted curves in Figs. 2–4. One can see that the effect of these contributions is definitely not negligible, e.g., there is a strong influence on the observable A_Δ, which is visible in the angular dependence as well as in the integrated result. In the reactions $pp \rightarrow pn\pi^+$ and $pp \rightarrow d\pi^+$ nonresonant *p*-wave rescattering even yields a change in the sign for energies $\eta \leqslant 0.6$. But since in this energy range the overall magnitude of A_Δ is rather small, it will be difficult to resolve these differences experimentally. Also the other spin correlation coefficient combinations are, in general, significantly modified by the contributions from nonresonant *p*-wave rescattering, in particular at higher energies.

The dashed curves in Figs. 2–4 represent results where the contributions from pion production via Δ excitation are switched off as well. Evidently this leads to rather large changes manifesting the important role which the Δ plays for these spin correlation parameters. Thus, these observables are very well suited for testing the model treatment of the pion-production contributions involving the Δ resonance. In particular, they allow one to examine the Δ contributions at energies far below the resonance regime. As can be seen from Figs. 2–4, the effect of the Δ extends down to fairly low energies, specifically in the reaction $pp \rightarrow pp\pi^0$.

Note that all results shown in Figs. 2–4 are normalized to the same total cross section (for each reaction), namely, the one predicted by the full model. Without this renormalization dramatic but basically artificial changes in the spin correlation coefficients would appear when adding additional contributions.

For all three considered reactions some experimental information on spin correlation coefficients has become available very recently and thus we can already compare the predictions of our model with them. In the case of the reaction $pp \rightarrow pp\pi^0$ there will be data soon on all the observables shown in Fig. 2 [6]. So far values for the integrated spin correlation coefficients A_Σ, A_Δ, and A_{zz} have been published [2]. Evidently two of those observables are reasonably well reproduced by our model calculation (cf. Fig. 2) whereas A_Δ is overestimated by a factor of 2 or so. Since the result without nonresonant *p*-wave πN rescattering (dash-

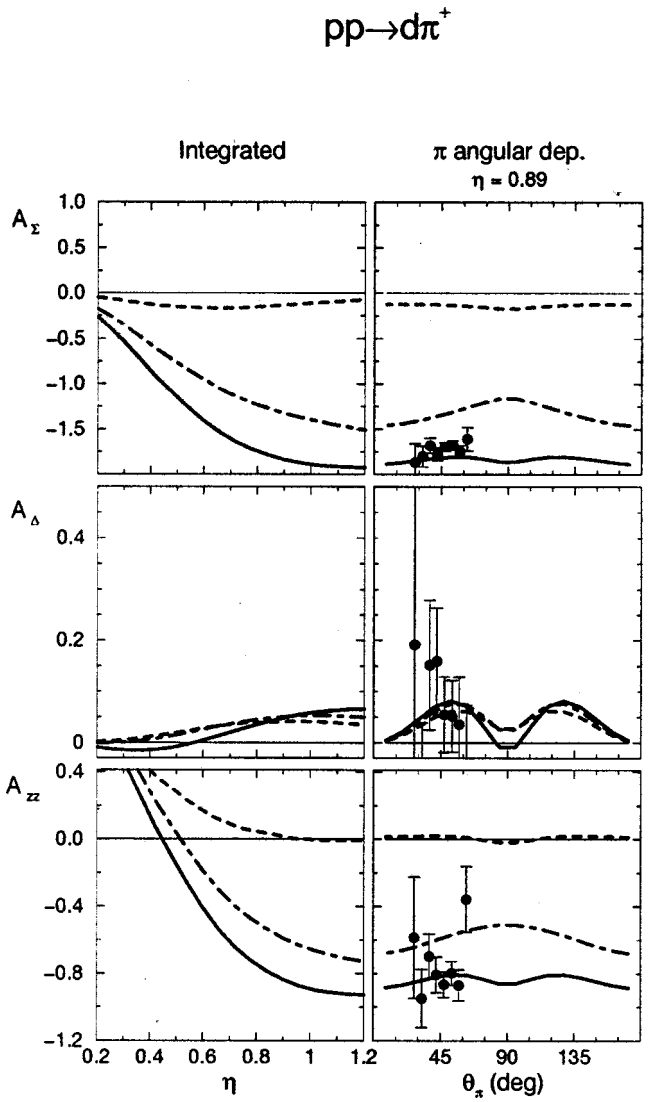

FIG. 4. Spin correlation paramaters for the reaction for $pp \rightarrow d\pi^+$. Same description of the curves as in Fig. 2. The experimental results are taken from Ref. [5].

dotted curve) goes almost through the data points, one might be inclined to conclude that their contributions are much too large in our model, as we argued in Ref. [9]. However, one has to keep in mind that for energies corresponding to $\eta \approx 1$ our model underestimates the total π^0 production cross section already by a factor of 2 or so (cf. Fig. 3 in Ref. [9]). Since the spin correlation coefficients are normalized by σ_{tot} it is conceivable that the disagreement with the data for A_Δ simply reflects the shortcoming in the total cross section. In order to understand this let us remind the reader that the numerator of A_Δ is basically determined by the Pp partial waves [14]. (We use here the standard nomenclature for labeling the amplitudes by the angular orbital momentum in the final NN system and of the pion relative to the NN system.) The deficiency in the total cross section, on the other hand, could be due to the Ss amplitude, which might be too small at larger energies in our model. Thus, an enhancement in the Ss amplitude would lead to an increase in the total cross section (as required by the data) and accordingly to an increase in the denominator of A_Δ. But it would not change the numerator of A_Δ so that one would get an overall reduction of A_Δ.

Note that in the case of the other spin correlation coefficents the Ss amplitude enters in the denominator as well as in the numerator so that they should be less affected by the aforementioned deficiency in the total cross section.

For the reaction $pp \rightarrow pn\pi^+$ there are data on the integrated spin correlation coefficients A_Σ and A_Δ [4]. The former observable is very nicely described by our model prediction (Fig. 3). It is interesting that contributions from pion production via the Δ resonance as well as from (nonresonant) p-wave rescattering are obviously required for achieving this agreement. With the Δ resonance alone the result would lie clearly below the experiment (cf. the dash-dotted curve). Our model is also in rough agreement with the data on A_Δ. Here, however, the large error bars do not really allow us to draw more quantitative conclusions.

Finally, for $pp \rightarrow d\pi^+$ there are angular distributions for the spin correlation coefficients A_Σ, A_Δ, and A_{zz} [5]. Also these data are nicely reproduced by our model; cf. Fig. 4. Note that again the contributions from (nonresonant) p-wave rescattering are crucial for getting agreement with the data on A_Σ.

In summary, we have presented first calculations of spin correlation coefficients for the reactions $pp \rightarrow pp\pi^0$, $pp \rightarrow pn\pi^+$, and $pp \rightarrow d\pi^+$ near threshold. We have also studied the influence of resonant [i.e., via the $\Delta(1232)$ excitation] and nonresonant p-wave pion production mechanisms on these observables. Our model calculation is in rather good agreement with the presently available data for the reactions $pp \rightarrow pn\pi^+$ and $pp \rightarrow d\pi^+$. This is certainly remarkable. We want to emphasize again that our results are genuine model predictions. For the reaction $pp \rightarrow pp\pi^0$, however, the description of the data is less satisfying. In particular, for the spin correlation coefficent combination $A_{xx} - A_{yy}$ there is even a serious disagreement with the experimental evidence. Here further investigations are required. Specifically it will be interesting to see whether this deficiency is connected with the still unsettled issue of the missing (s-wave) strength in the $pp \rightarrow pp\pi^0$ total cross section [1] or whether it is a sign for an additional problem concerning now the p-wave contributions to this reaction channel.

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[1] For a short review and references to experimental as well as theoretical papers see, e.g., H. Machner and J. Haidenbauer, J. Phys. G **25**, R231 (1999).

[2] H. O. Meyer *et al.*, Phys. Rev. Lett. **81**, 3096 (1998).

[3] H. O. Meyer *et al.*, Phys. Rev. Lett. **83**, 5939 (1999); P. Thörngren Engblom *et al.*, Nucl. Phys. **A663**, 447 (2000).

[4] S. K. Saha *et al.*, Phys. Lett. B **461**, 175 (1999).
[5] B. v. Przewoski *et al.*, nucl-ex/9912008.
[6] J. Balewski, Pion Production with Polarized Beam and Polarized Target at IUCF, Proceedings of the STORI99 Conference, Bloomington, Indiana, 1999, edited by H.-O. Meyer and P. Schwandt, AIP Conf. Proc. (AIP, New York, in press).
[7] Y. Maeda *et al.*, πN Newslett. **13**, 326 (1997).
[8] K. Tamura *et al.*, ''Pion production mechanism on nucleon-nucleon scattering,'' RCNP report, Osaka, 1998.
[9] C. Hanhart, J. Haidenbauer, O. Krehl, and J. Speth, Phys. Lett. B **444**, 25 (1998).
[10] C. Hanhart, J. Haidenbauer, and J. Speth, Acta Phys. Pol. B **29**, 3047 (1998).
[11] J. Haidenbauer, K. Holinde, and M. B. Johnson, Phys. Rev. C **48**, 2190 (1993).
[12] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).
[13] C. Schütz, J. W. Durso, K. Holinde, and J. Speth, Phys. Rev. C **49**, 2671 (1994).
[14] H. O. Meyer, in *Baryons '98. Proceedings of the 8th International Conference on the Structure of Baryons*, edited by D. W. Menze and B. Ch. Metsch (World Scientific, Singapore, 1999), p. 493.