Spin Dependence of NN and $NN\pi$ Reactions and the Question of Dibaryon Resonances

Recent experiments on the spin dependence of the coupled NN and $NN\pi$ systems are reviewed and compared with theory. Conventional models involving the usual interactions of mesons and nucleons appear capable of explaining the rich spin dependence observed.

INTRODUCTION

The experimental information on spin dependence in the coupled NN and $NN\pi$ systems for medium energies has mushroomed in the past few years. The energies involved run from pion production threshold (around 300 MeV incident nucleon laboratory energy) to about 1500 MeV (where two-pion production begins to become important). At the same time theoretical models for the coupled NN and $NN\pi$ systems have undergone vigorous development. Both experiment and theory have been much stimulated by the observation of relatively sharp energy-dependent structures.[1] It was quickly suggested that these might be manifestations of new degrees of freedom, such as the dibaryon resonances suggested by the quark bag model.[2]

This Comment summarizes recent experimental progress in this field[3] and discusses to what extent the new data require an interpretation in terms of new quark substructures.

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WHAT IS A DIBARYON RESONANCE?

A resonance is more than just a bump in a cross section. The classic example of an elastic resonance is provided by a Breit–Wigner amplitude, $T_J = \frac{1}{2}\,\Gamma/[E_R - E - i\Gamma/2]$, where J denotes the partial wave amplitude which is resonating. Such a structure has a pole in the complex energy plane at $E = E_R - i\Gamma/2$, i.e., "on the second sheet." As the energy increases through E_R the complex amplitude T_J traces out a counterclockwise path along a circle of radius one-half centered at $+\frac{i}{2}$, the so-called "unitarity circle." In this example without any background, the partial wave amplitude reaches the top of the circle $(+i)$ at the resonance energy E_R and moves around into the left half plane for energies above E_R. This counterclockwise motion on an Argand diagram is typical of a resonance. However, a *warning* is definitely in order: Such motions can arise from other kinds of analytical structures as well as from resonance poles.

In the presence of inelasticity (i.e., coupling to other open channels) the scattering amplitude becomes a matrix, and a resonance shows up as a pole in each matrix element. As the energy increases the path traced out by the elastic amplitude T_J is still counterclockwise, but the conservation of probability (unitarity) constrains it only to be somewhere within the unitarity circle.

At least two such counterclockwise looping behaviors deep inside the unitarity circle have been found in phase shift analyses for NN elastic scattering.[4] These occur in the $^1D_2$ and $^3F_3$ partial waves, the two prime candidates for dibaryon resonances. One needs a model to extrapolate the physical amplitude into the complex energy plane and search for resonance poles. There is an extensive theoretical literature that deals with the question of whether the looping behavior is due to resonance poles (i.e., dibaryons).[5] The issue is not settled, but it is clear from simple models that coupled-channel resonance poles can certainly be present. On the other hand, the cut from the $NN \rightarrow N\Delta$ threshold also produces a resonancelike behavior, and it could be the combined effect of poles and $N\Delta$ cut that causes the structures seen in the observables.

The existence of dibaryons was first suggested in 1977 by the energy-dependent structures found in spin-dependent total cross section differences.[6] These and other structures go hand in hand with inelasticity, which in this energy region means single-pion production, $NN \longrightarrow NN\pi$. If they are actually given by resonance poles, then the next questions are: What is their origin? Can they be explained by conventional models of mesons interacting with nucleons? Or does their existence imply a new underlying hadronic structure, such as that associated with quarks and color degrees of freedom?

THEORETICAL FRAMEWORK

In the energy region under discussion the standard description of the $NN \to NN\pi$ or $\pi d \to \pi d$ scattering amplitudes uses the isobar model, [7] as illustrated by the graphs in Figures 1a and 1b. Originally, the isobar amplitudes (the "blobs" in the figure) were simply fit to the available data or calculated in the Born approximation. Today, however, these amplitudes are calculated in a unified and unitary way. There are two approaches.

Coupled two-body channels. This involves solving coupled scattering equations with transition potentials between the NN, $N\Delta$ and πd two-body channels. This method has been applied to calculate inelasticity parameters and phase shifts for NN scattering above the pion production threshold[8-10] and spin observables for the $pp \to d\pi$ reaction.[11]

Three-body equations. This has been the most realistic approach to the elastic scattering of pions by deuterons, with important work being done by Rinat and Thomas,[12] Garcilazo[13] and the Lyon group.[14] Garcilazo has extended his calculations to the breakup process $\pi d \to \pi NN$ with good success.[15] The other two groups have emphasized the treatment of NN intermediate states, which is closely connected to an alternative approach. This involves the truncation of an underlying field theory to consider at any given time only two nucleons or two nucleons and a pion. The original work was that of Afnan and Thomas.[16] Later developments[17-20] vary in their details and philosophical basis. The major emphasis of Refs.18–20 has so far been on the $pp \to d\pi$ reaction, while the authors of Ref.17 have concentrated on calculating spin observables for the three-body final state, $NN \to NN\pi$.[21]

All these models, two-body as well as three-body, are conventional in that they involve only the known mesons and nucleons interacting in the usual way. If there are "explicit" dibaryon resonances, i.e., resonances *not* generated by the conventional meson–nucleon dynamics, then these models must be supplemented by contributions

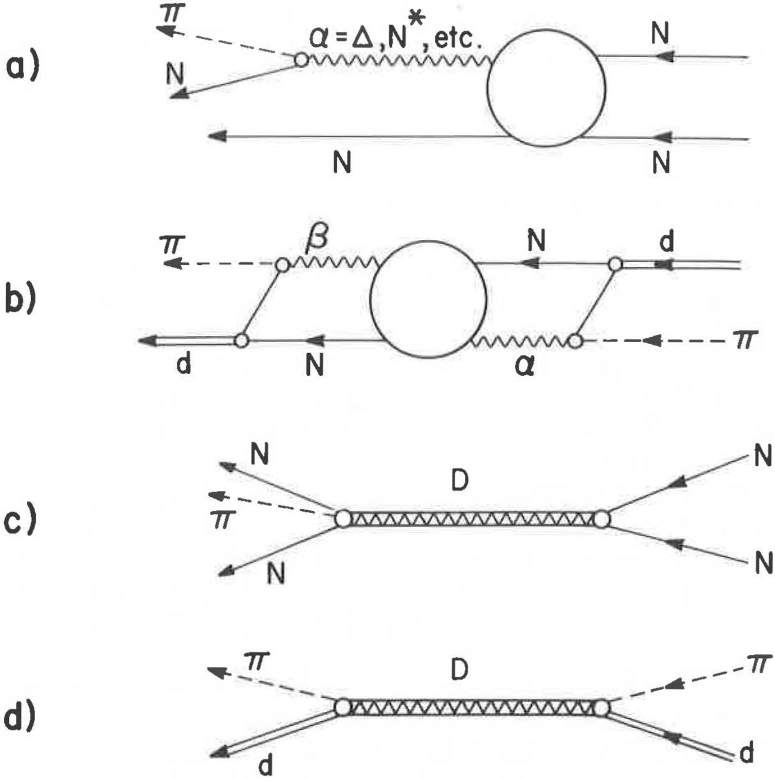

FIGURE 1. Four Feynman graphs. (a) and (b) show graphs for the isobar model treatment of the $NN \rightarrow NN\pi$ and $\pi d \rightarrow \pi d$ reactions, respectively, while (c) and (d) indicate explicit dibaryon resonance graphs.

that look like Figures 1c and 1d. "Adding in" such graphs without destroying the unitarity of the conventional models is slightly problematic. One way of doing this has been discussed by Locher and co-workers.[22]

RECENT EXPERIMENTS

It is convenient to discuss separately five kinds of spin-observable experiments: πd elastic scattering, $pp \rightarrow d\pi$ (and its inverse), spin-dependent total cross sections and inclusive and exclusive experiments

TABLE I
Definitions of spin observables

$\pi d \rightarrow \pi d^{a}$
$iT_{11}(\theta) = (\sqrt{3/2})\,[\,\sigma(M_d=+1) - \sigma(M_d=-1)\,] \,/ \left[\sum_{M_d=-1,0,1} \sigma(M_d)\right]$
$T_{20}(\theta) = (1/\sqrt{2})\,[\,\sigma(+1) - 2\sigma(0) + \sigma(-1)\,] \,/ \left[\sum_{M_d=-1,0,1} \sigma(M_d)\right]$
Total Cross Section Differences[b]
$\Delta\sigma_T = \sigma(\uparrow\downarrow) - \sigma(\uparrow\uparrow)$
$NN \rightarrow NN\pi$ (or $d\pi$)[c]
$A_N(\theta,...) = [\,\sigma(\uparrow) - \sigma(\downarrow)\,] \,/\, [\,\sigma(\uparrow) + \sigma(\downarrow)\,]$
$A^{(tgt)}_N(\theta,...) \neq A^{(beam)}_N(\theta,...)$
$A_{NN} = [\,\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow) + \sigma(\downarrow\downarrow)\,] \,/\, \text{sum}$

[a]The deuteron spin is quantized normal to the scattering plane.
[b]Initial nucleon spins are quantized in a direction transverse to the beam direction. $\Delta\sigma_L$ is defined likewise, but with spins quantized along the beam direction (longitudinal).
[c]Initial nucleon spins are quantized normal to the reaction plane. Similar formulas define A_{LL}, A_{SS}, A_{LS} and $A_{SL} \neq A_{LS}$, but with longitudinal and sideways quantization axes. Likewise for spin transfer observables D_{NN}, K_{LL}, etc., except one spin is for an initial nucleon, and the other for a final nucleon.

on the $NN \rightarrow NN\pi$ reaction. Table I gives definitions for these different spin observables.

Elastic pion-deuteron scattering. There are two different spin observables measured for this reaction. The sharp angular oscillations in the vector polarization (iT_{11}) found[23] at $T_{\pi,\text{Lab}} = 256$ MeV have been particularly suggestive of a $^1G_4$ dibaryon resonance. The extant (conventional) three-body calculations (e.g., Ref.14) gave rather smooth angular variations for iT_{11}. By incorporating explicit dibaryon resonance graphs, as in Figure 1d, Locher *et al.*[22] were able to predict oscillatory behavior very much like that observed.

Recently, however, Gibbs[24] noticed that the three-body calculations are quite sensitive to the "small" πN interactions which enter as input. The vector polarization is basically an interference effect between the dominant P_{33} πN interaction and the smaller contributions. In particular, the earlier three-body calculations used input πN potentials which were in fact unsupported by the πN experimental data. Gibbs and Gibson[24] have shown that a single-scattering approximation calculation with πN input directly related to the πN phase shifts can do a reasonable job of reproducing the 256 MeV iT_{11} angular distribution, with the exception of a singularly negative datum at 135°. That datum, in the meantime, has been remeasured and found to be positive.[25] Thus, the experimental data set on iT_{11} over the whole energy range measured, now seems not to require (explicit) dibaryon resonances.

The other spin observable of current interest in πd scattering is the tensor polarization T_{20} of the recoil deuteron. Two groups have obtained very different experimental results. The Argonne group[26] finds T_{20}s in agreement with conventional expectations, i.e., predictions of the three-body models. In contrast, the ETH group's data[27] are sufficiently oscillatory that if correct may demand an interpretation involving explicit dibaryon resonances. In view of the present discrepancy in the T_{20} data it is difficult at this time to draw any conclusions about the existence of dibaryon resonances.

The reaction $pp \rightarrow d\pi$ and its inverse. Because the two-body final state is easier to deal with experimentally than the three-body state, there is already an extensive data set for this reaction from threshold to above 1000 MeV. Three kinds of spin observables have been measured—polarization asymmetries, spin-spin correlations, and polarization transfers.[28]

The data, especially for the asymmetries A_N, are smoothly varying with energy and generally have very small error bars. At the moment no conventional theoretical model[11,18,20] does a very good job. However, the models do reproduce the general trends of the data. To judge from the differences among the various models, which are big compared with the experimental errors, it is reasonable to presume that a conventional model can someday fit this data set.

Incidentally, the spin-spin correlations A_{NN} for $pp \rightarrow d\pi$ are large and negative, $A_{NN} \simeq -0.8$. This result comes out of conventional models quite easily, since the reaction is dominated by $N\Delta$ intermediate states with orbital angular momenta $L' = 0$. These are produced in the initial NN state from the $^1D_2$ partial wave. Thus, the basic negativeness of A_{NN} is largely determined by nearly model-independent considerations (see definition, Table I).

Spin-dependent total cross sections. It was the Argonne ZGS measurements of the cross section differences $\Delta\sigma_L$ and $\Delta\sigma_T$ that created the great interest in dibaryons.[1] These quantities have since been remeasured at all the meson factories. The sharp energy-dependent structures seen in $\Delta\sigma_L$ and $\Delta\sigma_T$ have been confirmed, though there is not yet complete agreement as to what the magnitudes of the cross section differences are.

The peak in $\Delta\sigma_T$ and $\Delta\sigma_L$ at 550 MeV is related to the resonancelike structure of the $^1D_2$ amplitude, while the dip in $\Delta\sigma_L$ near 750 MeV is related to the $^3F_3$ amplitude. ($\Delta\sigma_L$ contains contributions from the $L=J$ triplet partial waves but $\Delta\sigma_T$ does not.) From the point of view of conventional models, these structures are to a large extent due to the onset of the $NN \rightarrow N\Delta$ reaction as it opens up in the *s*- and *p*-waves of the $N\Delta$ state, respectively. However, none of the conventional models has as yet reproduced the details of the experimentally observed structures. As an example, Figure 2 compares the predictions of Ref. 29 with the data.

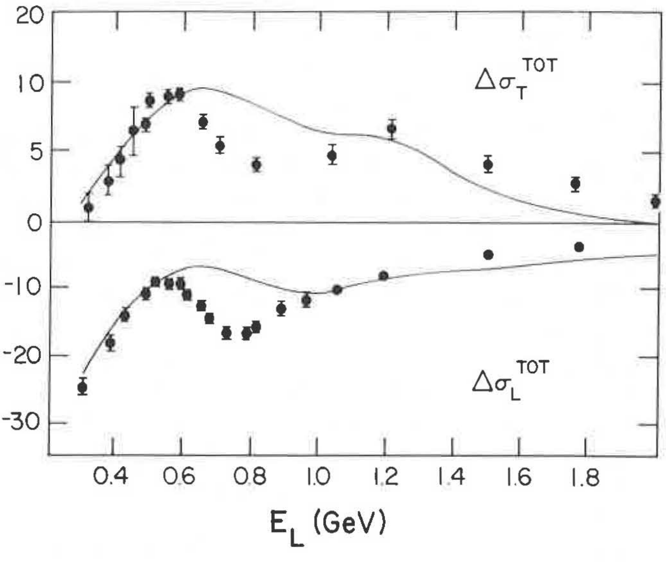

FIGURE 2. Experimental data for $\Delta\sigma_T$ and $\Delta\sigma_L$ (in mb) compared with the conventional model prediction of Ref. 29 (from which this figure was taken).

Conventional models might also be running into trouble with the inelastic part of the longitudinal cross section difference, $\Delta\sigma^{in}{}_{L}$. This has been found to be negative (-3.5 ± 1 mb) at 800 MeV.[30] Three different conventional models[17,31,32] give positive ($\simeq$7 mb) predictions for this quantity at that energy. Even the *shape* of the energy dependence differs markedly between the models and data. It should be pointed out that extracting $\Delta\sigma^{in}{}_{L}$ is difficult, involving the difference of two large numbers obtained from two different experiments. The results of Ref. 30 should be checked.

The above remarks all refer to $I = 1$ cross sections. Rather little is known about the $I = 0$ cross section differences, although a flat $\Delta\sigma_L$ observed in *pd* interactions has been interpreted as requiring a $^1F_3$ "antidip" to compensate the $^3F_3$ dip at 750 MeV.[33] Such a structure, if it exists, would be very difficult to interpret in terms of conventional models.

Inclusive NN → NNπ reactions. These are reactions in which typically only one particle in the three-body final state is detected. Such experiments are more easily performed and more precise than exclusive experiments, which use detectors in coincidence to determine the momentum and direction of every final state particle. The results of inclusive experiments measuring spin observables are just now beginning to appear in the literature.

One such experiment measures the analyzing power A_N in the reaction $\mathbf{p}p \rightarrow pX$ ($X = n\pi^+$ or $p\pi^0$), at 800 MeV.[34] The prominent feature in the data is a sharp rise to a value of 0.3 at the upper end of the outgoing proton momentum spectrum (Figure 3). This feature can be reproduced in a unitary model[35] (the solid line in Figure 3) but appears difficult to explain using a Born approximation approach[36] (dashed line). Spin observables like A_N result from interference between different complex amplitudes and thus are sensitive to unitarization.

Another group has measured the polarization transfers K_{NN} and K_{LL} in the $\mathbf{p}p \rightarrow \mathbf{n}X$ reaction, $X = p\pi^+$, again at 800 MeV.[37] There are as yet no unitary model predictions for these quantities, but a Born approximation calculation[36] fails to reproduce the features of the data entirely. It will be interesting to see if unitarity alone can cure the disagreement.

Exclusive NN → NNπ reactions. Until recently kinematically complete information about this fundamental pion production process came mostly from a small number of bubble chamber experiments

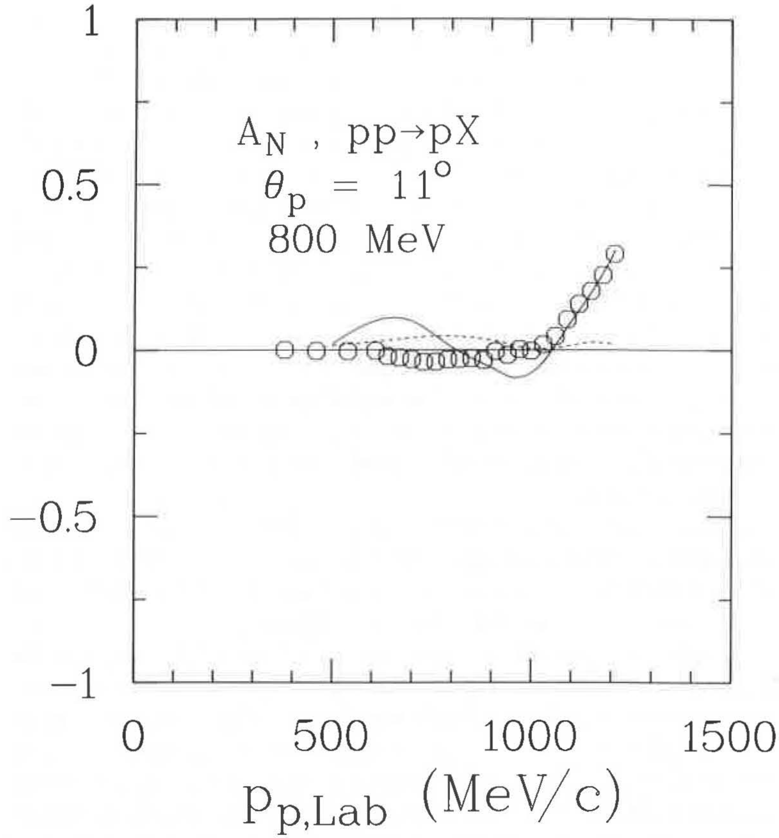

FIGURE 3. Asymmetry for the inclusive reaction $\mathbf{p}p \rightarrow pX$, $X = n\pi^+$ or $p\pi^0$. Data come from Ref. 34 and the curves are the unitary (solid) and Born approximation (dashed) predictions from Ref. 35.

performed in the 1960s. The data base was therefore embarrassingly small. With the advent of meson factories, however, there are now counter experiments which measure complete kinematics for the reaction (usually only for inplane geometry, however). Two particles (at least) must be measured in coincidence to determine five kinematic quantities: p_p, θ_p, ϕ_p, θ_π and ϕ_π.

The first such experiment[38] measured the polarization asymmetry in $\mathbf{p}p \rightarrow p\pi^+n$ at 800 MeV and established the crucial importance of dealing with unitarity properly. As the first data were being processed, Umland *et al.*[39] made Born approximation predictions of A_N

as a function of the outgoing proton momentum for the various angle pairs measured. Not surprisingly, since A_N depends on the relative phases between complex amplitudes, the agreement with the data was quite poor. They then tried including explicit dibaryon resonance graphs (Figure 1c), fitting a free phase between those graphs and the usual isobar graphs (Figure 1a). The agreement with the experimental A_N was much improved but still not remarkably good. Soon after this Dubach *et al.*[21] applied the unitary model of Ref. 17 to this problem, using the no free parameter version of the model based solely on one-pion exchange (OPE). These predictions, while still not agreeing very well with the data of Ref. 38, were qualitatively much more like the data than the Born approximation results. Considering the simple nature of the model (only OPE forces between the nucleons and isobars, only P_{33} and P_{11} πN input forces, etc.) one can be optimistic that a more complete model might eventually be able to explain these data.

The asymmetry experiment[38] was also able to record data at the same time for the reaction $\mathbf{p}p \rightarrow pp\pi^0$. It is curious that the predictions of the unitary model[21] seem to fit these data much better than in the $np\pi^+$ case.[40] It is not clear why this happens.

Another set of exclusive experiments measures spin-spin correlations A_{NN}, A_{LL}, etc. for the reaction $\mathbf{pp} \rightarrow np\pi^+$ at three energies near 500 MeV[41] and at 650 and 800 MeV.[42] The no free parameter OPE predictions of Ref. 21 are compared with preliminary data at 500 MeV in Figure 4. The agreement is quite good, i.e., these data provide no surprises in their comparison with a conventional model. All the spin-spin correlation coefficients in Figure 4 are large and negative, again reflecting the dominance of the $NN(^1D_2) \rightarrow N\Delta$ $(^5S_2)$ partial wave amplitude.

The experiment on A_{NN} and A_{LL} at 650 and 800 MeV[42] has rather fewer data points (but smaller errors). These data also are in agreement with the predictions of Ref. 21. At 800 MeV A_{LL} has become slightly positive, indicating a cancellation between the $^1D_2$ and $^3F_3$ partial waves for this quantity (see definition in Table I).

It is curious that in both experiments (and in the calculations) the beam and target particle asymmetries for a given angle pair are approximately equal and opposite in sign. There is no evident simple reason for this. (Identical particles symmetry gives exact equalities between *different* angle pairs.)

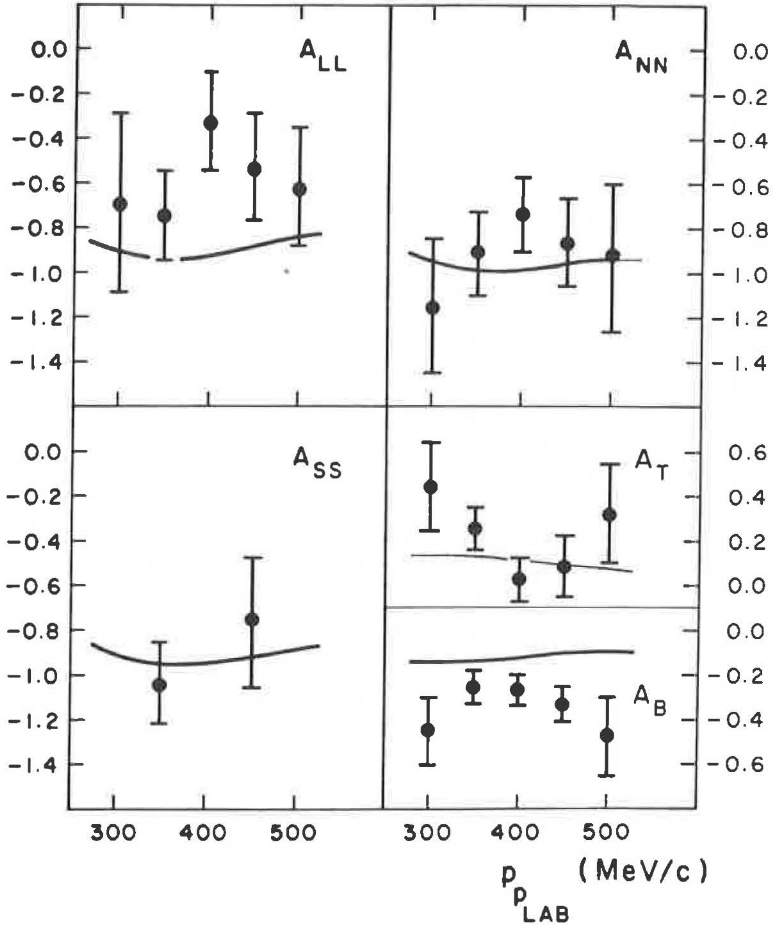

FIGURE 4. Spin-spin correlation coefficients for **pp** → $n p \pi^+$ at 500 MeV. Data are from Ref. 41 and the curves were calculated as in Ref. 21. This figure is a corrected version of one appearing in Ref. 41.

A third kind of experiment involves the measurement of the polarization transfer coefficient D_{NN} for the reaction **p**p → n**p**π^+ at 800 MeV.[43] The one data point measured (right at the peak of the Δ^{++} resonance) is also in good agreement with the prediction of Ref. 21. The differential cross section data elsewhere indicate the presence of a strong final state interaction between the outgoing nucleons. One naturally wonders how well the unitary models (which generally do not contain such interactions in their input) will compare with a more extensive D_{NN} data set.

CONCLUSIONS

In general we have seen that conventional models of mesons and nucleons are so far able to explain a substantial amount of new experimental data on the rich spin dependence of the coupled *NN* and $NN\pi$ interactions. Not all predictions agree perfectly, but that is to be expected at this stage. It seems a little peculiar that the gross quantities (total cross section differences) seem harder to understand in this picture than the detailed ones (exclusive cross sections). Nonetheless, the major point to be emphasized is that there is no *obvious* need at this time to invoke new quark substructures to explain the present data.

So where, then, are the effects of the quarks and gluons in the $A = 2$ interacting systems to be seen? It may simply be that the present round of experiments is not very sensitive to quark degrees of freedom.[44] To find out what experiments *are* sensitive, perhaps of this type or perhaps of some totally different kind, will probably require a lot more experimental and theoretical work.

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