PHYSICS WITH POLARIZED $\bar{P}$'s *

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Abstract

The connection between the spin observables of the nucleon-antinucleon ($N\bar{N}$) system and the underlying dynamics of spin-dependent forces is discussed. Some suggestions for producing polarized $\bar{N}$ beams are evaluated.

Introduction

The study of spin observables for nucleon-nucleon (NN) scattering has been a long and largely successful venture. Much has been learned about the strength of the effective two-body spin-orbit and tensor interactions which are responsible for the (sometimes dramatic) spin phenomena observed at low and medium energies. A quantitative understanding of NN spin observables in terms of quark/gluon dynamics is not yet at hand. Perturbative QCD techniques have been applied to the low-medium energy/momentum transfer processes under consideration here, but may not be justified. Another approach consists of using effective Lagrangians at the hadronic level. For instance, one boson exchange potential (OBEP) models have been frequently used to quantitatively analyze NN data. Such a picture would appear to make sense for the medium and long range parts of the NN interaction, whereas the short range part is parametrized in a

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purely phenomenological way. Attempts have been made to graft an OBEP picture onto a six quark description at short distances.

Here, we discuss several models which have been introduced to describe the $N\bar{N}$ interaction. Our emphasis is on how the spin observables for elastic and charge exchange scattering may be used to distinguish between models. The field of $\bar{N}$ spin physics is in fact wide open, since only a few polarization data are available, and other spin observables, such as the Wolfenstein parameters, will only be measured in the ACOL era at LEAR. The theoretical predictions for spin observables discussed here are thus only to be taken as representative of a class of optical models, constrained mostly by differential and total cross section data. There may indeed by surprises as the experimental situation evolves.

The Two-Body $N\bar{N}$ Interaction

In the conventional picture of the NN interaction, the potential V is generated by meson exchange (t-channel). Such a picture is appropriate for the medium and long range parts of V. In phenomenological one boson exchange (OBE) models, contributions to V arise from exchanges of nonets of scalar, pseudoscalar and vector mesons. In the work of the Paris[1] group, the σ and ρ exchange contributions of the OBE approach are replaced by isoscalar and isovector two pion exchange contributions evaluated by dispersion relation techniques. In either approach, a potential of the form $V_{NN} = \sum_i V_i$ arises, where i refers to the quantum numbers of the various t-channel exchanges. If G_i is defined as the G-parity of the exchanged meson i, then the corresponding part of the $N\bar{N}$ potential is just $V_{N\bar{N}} = \sum_i G_i V_i$; note that $G = (-1)^n$ for a system of n pions. This is the "G-parity transformation", which leads to a very close connection between the t-channel NN and $N\bar{N}$ potentials, and fostered hopes that an analysis of the $N\bar{N}$ observables would provide additional constraints on the meson exchange picture of the NN force.

In practice, the usefulness of the G-parity transformation is limited to the medium and long range part of V. The short range part of the NN force is generally treated phenomenologically (by hard cores or other parametrized cutoffs), and it is not clear how to transform these prescriptions into the $N\bar{N}$ sector. For $r < 0.8 - 1$ fm, the representation of V as a local meson exchange potential breaks down, since the quark bags making up the N and $\bar{N}$ start to overlap appreciably. The short range aspects of the NN and $N\bar{N}$ systems demand a description in terms of quark dynamics. In addition, the $N\bar{N}$ system, having baryon number $B = 0$, easily annihilates into mesons (the $N\bar{N}$ absorption cross section is about twice that for elastic scattering at low energies). The annihilation mechanism has no counterpart in the low energy NN system (here pions are only appreciably produced above 400 MeV kinetic energy). Thus the NN phenomenology provides no guidance as to how to construct the effective $N\bar{N}$ annihilation potential $V_{ann} + iW$. The presence of strong absorption masks the sensitivity of the $N\bar{N}$ observables to the short range real potential. Note also that the annihilation process (through dispersive corrections) generates a real potential V_{ann} as well as an imaginary part W. The magnitude of V_{ann} could be comparable in size to the t-channel meson exchange potential at critical distances of order $r \approx 1$ fm, although it is intrinsically of shorter range.

Is it possible to isolate the longer range effects of the t-channel meson exchange potential from an analysis of $N\bar{N}$ observables? So far this has not been accomplished, since the available $N\bar{N}$ data consist mostly of total cross sections (elastic, charge exchange and annihilation) and some angular distributions, which reflect mainly the strong absorption (geometric) aspects of the problem. Except for some data on $p\bar{p}$ elastic polarization, no spin observables have been measured. These spin quantities hold the key to seeing the characteristic effects of t-channel exchanges in $N\bar{N}$, and hence establishing some connection to the NN problem.

We now indicate that the coherences present in the $N\bar{N}$ potential provide signatures in the $N\bar{N}$ spin observables even in the presence of strong absorption.

Let us first review the coherence properties[2] of the NN system, and their effect on the observables. The most dramatic effect of coherence in the NN system is seen in the ${}^{2I+1,2S+1}L_J = {}^{33}P_0$ phase shift. Here, the one pion exchange potential (OPEP), dominated by its tensor component, is strongly attractive. On the other hand, the short range spin-spin, spin-orbit and vector meson exchange forces are all coherently repulsive. The competition between strong long range attraction and coherent short range repulsion leads to a sign change in the ${}^{33}P_0$ phase shift near 200 MeV. The same mechanism holds also for other triplet-odd NN waves with $J = L - 1$. Partial waves for which an attractive OPEP is balanced against non-coherent short range repulsion do not display a zero of the phase shift; an example is the ${}^{13}D_2$ channel, where the phase shift remains close to the OPEP value and there is no zero. Deviations from OPEP predictions for peripheral NN partial waves are particularly interesting, since they register the coherent summed strength of $\underset{\sim}{\sigma}_1 \cdot \underset{\sim}{\sigma}_2$, $\underset{\sim}{L} \cdot \underset{\sim}{S}$ and vector exchange potentials.

In passing from the NN to the $N\bar{N}$ system, the G-parity transformation leads to a dramatic change in the pattern of coherence. For $N\bar{N}$, the central, tensor and quadratic spin-orbit forces are fully coherent and attractive for isospin $I = 0$ states with spin $S = 1$ and $L = J \pm 1$. For fixed J, the channels of maximum attraction are ${}^{13}P_0$, ${}^{13}S_1 - {}^{13}D_1$, ${}^{13}P_2 - {}^{13}F_2$, etc. These channels form a natural parity band with $J^{\pi C} = 0^{++}$, 1^{--}, 2^{++}. etc.

The $\bar{N}N$ and NN systems are thus primarily sensitive to different components of the underlying potential. Our hope is that the $\bar{N}N$ spin observables will enable us to determine the summed strength of the tensor interaction. Clearly, the pion tensor force has the most important influence on spin properties, because of its long range. It will be interesting to see to what extent one can extract the coherent vector meson contribution, in the presence of a rather strong absorptive potential. We are also interested in isolating dramatic spin effects which are relatively model independent, i.e., driven essentially by pion exchange alone. That is, we look for situations where one obtains large polarizations, spin rotations, spin transfers, etc. These are of direct interest for the question of how to produce polarized $\bar{p}$ or $\bar{n}$ beams.

The real meson exchange potentials considered above must be supplemented by a description of the annihilation process. Although there have been interesting attempts to construct a complex annihilation potential $V_{ann} + iW$ in terms of a microscopic quark model[3], an adequate fit to the $\bar{N}N$ data has so far only been obtained with purely phenomenological forms. For illustration, we present predictions for spin observables obtained with two different forms, the simplest being a local Woods-Saxon form

$$V_{ann}(r) + iW(r) = -(V_0 + iW_0)/\left(1 + \exp((r-R)/a)\right) . \tag{1}$$

Choosing $V_0 = 21$ GeV, $W_0 = 20$ GeV, $R = 0$, $a = 1/5$ fm or $V_0 = W_0 = 500$ MeV, $R = 0.8$ fm, $a = 1/5$ fm, we arrive at models DRI and DRII, respectively, of Dover and Richard[4], which were fitted to elastic, annihilation and charge exchange total cross sections. A more general form was employed by the Paris group[5], namely

$$W(r) = \Big\{ g_C(1 + f_C E) + g_{SS}\,(1 + f_{SS}E)\,\underset{\sim}{\sigma}_1\cdot\underset{\sim}{\sigma}_2 + g_T S_{12} + \frac{g_{LS}}{4m^2}\,\underset{\sim}{L}\cdot\underset{\sim}{S}\,\frac{1}{r}\,\frac{d}{dr}\Big\}\,\frac{K_0(2mr)}{r} \tag{2}$$

The coefficients g_C, g_{SS}, g_T, g_{LS} are adjusted separately for isospins I = 0, 1. The radial dependence is given in terms of the modified Bessel function K_0 of range 1/2m ≈ 0.1 fm (held fixed), which reduces to a Yukawa form for large r. The form (2) incorporates arbitrary spin, isospin and energy (E) dependence, as well as L and J dependence through the spin-orbit ($\underset{\sim}{L}\cdot\underset{\sim}{S}$) and tensor ($S_{12}$) terms. No real annihilation potential was considered. Further free parameters are required to specify the short range cutoff. We refer to Eq. (2) as the PARIS model[5] in the following.

Since numerous free parameters are involved in these fits, it is clear that they cannot all be uniquely determined from the limited data. In particular, since the only spin observable that has been measured is P(θ), it is difficult to disentangle the effects of $\underset{\sim}{\sigma}_1\cdot\underset{\sim}{\sigma}_2$, $\underset{\sim}{L}\cdot\underset{\sim}{S}$ and S_{12} terms. Note that the spin and isospin dependence of W(r) in the PARIS model is very strong. For s-waves, the values of W^{IS} stand in the ratio

$$W^{00} : W^{10} : W^{01} : W^{11} = \begin{cases} 1:0.81:0.11:0.073, & E = 0 \\ 0.92:1:0.15:0.035, & E = 100\ \text{MeV} \end{cases} \qquad (3)$$

From Eq. (3), we see that W is an order of magnitude or so more absorptive in S = 0 than in S = 1 channels, whereas the isospin dependence is significant but not as strong as the spin dependence. Further, we note that W is strongly energy dependent. For instance, as E changes from 100 to 200 MeV, W^{00} increases by a factor 1.6.

The strong spin dependence of W(r) characteristic of the PARIS model is to be contrasted with the results of the Nijmegen group[6], who solve a multichannel Schrödinger equation with an interaction coupling the $N\bar{N}$ system to a set of two body annihilation channels which is dependent on I but independent of S, L, and J. Unfortunately, the predictions of the Nijmegen model[6] for $N\bar{N}$ spin observables are not yet available. The question of the spin-isospin dependence of W(r) must be regarded as an open one. More theoretical input constraining the form of W(r) is needed, which can only be obtained from microscopic models of the annihilation process.

Spin Observables

Since $N\bar{N}$ forces depend strongly on spin and isospin in a complicated way, they cannot be deduced uniquely from a few measurements such as the differential cross section and polarization. In general, difficult experiments involving polarized beams and/or polarized targets are required. This places a premium on obtaining high intensity $\bar{N}$ beams. Some of the relevant experiments will be possible in the ACOL era of LEAR. Note that the determination of the isospin dependence of the $N\bar{N}$ force involves a study of charge exchange ($p\bar{p} \to n\bar{n}$) and $\bar{n}p$ (or equivalently $\bar{p}n$) elastic scattering in addition to the $p\bar{p} \to p\bar{p}$

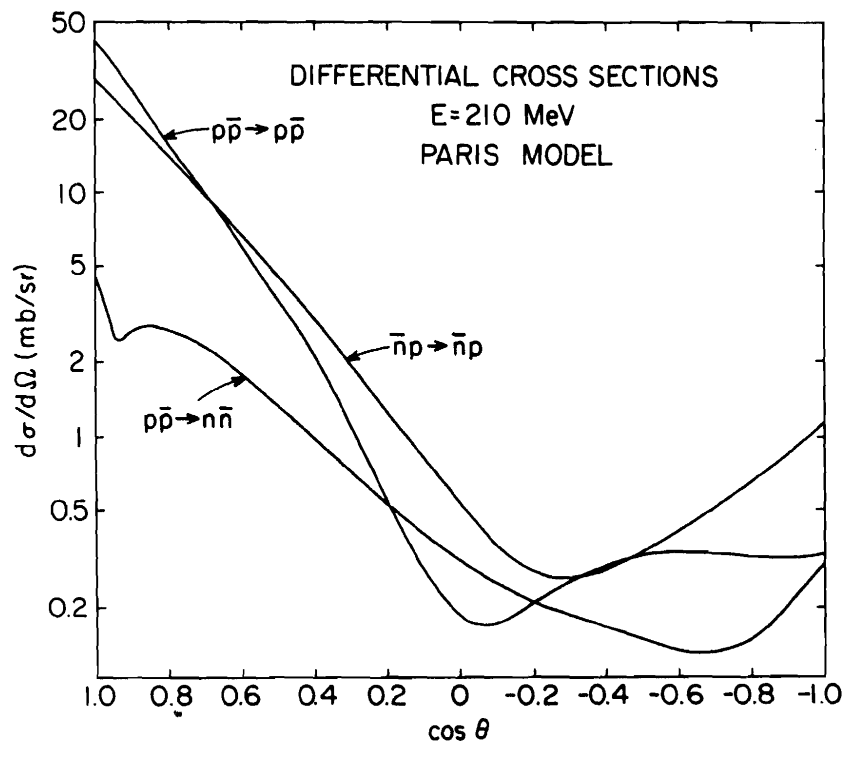

Figure 1. Predicted differential cross sections at E = 210 MeV in the PARIS model, illustrating the anticipated degree of isospin dependence of the $N\bar{N}$ potential.

channel. Some predictions[7] for the elastic $p\bar{p}$, $p\bar{n}$ and charge exchange differential cross sections are shown in Figure 1. Recent LEAR measurements[8] of the $p\bar{p} \rightarrow n\bar{n}$ cross section do not show the dip structure predicted at small angles in the PARIS model.

Since charge exchange cross sections are small, the measurement of spin quantities will be even more demanding than for $p\bar{p} \rightarrow p\bar{p}$. However, the most dramatic spin effects are expected in $p\bar{p} \rightarrow n\bar{n}$, as we see later. One might try to obtain information on $\bar{p}n$ scattering by studying $\bar{p}d$ in the spectator regime, or by using charge exchange to produce a polarized $\bar{n}$ beam and then scattering it from a hydrogen target.

In this section, we present a variety of predictions for spin observables in $N\bar{N}$ scattering, using the models DRI, DRII, and PARIS developed earlier. We emphasize the interplay between the coherent tensor force and the spin-isospin dependence of the annihilation potential. The results displayed here supplement those given in Refs. 7 and 9. We use the notation of Hoshizaki[10], who discussed the formalism for the case of NN scattering. The structure of the formulae is essentially the same for NN and $N\bar{N}$, except that the symmetries due to the Pauli principle are absent for $N\bar{N}$ ($\Theta \rightarrow \pi - \Theta$ relations, restrictions of I and S).

Tensor forces play a dominant role in $N\bar{N}$ spin physics, but their effect is already evident in total cross sections, particularly that for charge exchange. If we start with the exact PARIS model, and turn off various spin dependent components of the $N\bar{N}$ interaction (both real and imaginary parts) in turn, we see that the tensor (S_{12}) component is most important. The $p\bar{p} \rightarrow n\bar{n}$ cross section σ_{CE} drops by a factor of three if tensor forces are set to zero! In σ_{CE} the coherent contribution of $\pi + \rho$ exchange enters, although the pion plays the most important role because of its long range.

The strong tensor force effect is visible in many of the spin observables. For example, the depolarization D as a function of cosΘ (Θ = lab scattering angle) is shown in Figure 2 at a lab kinetic energy E = 130 MeV. If tensor (S_{12}) and quadratic spin-orbit (Q_{12}) terms are turned off, D is practically unity, its value in the absence of any spin dependence. With tensor forces, D differs dramatically from 1 in the backward hemisphere. The angular dependence of D is very different for elastic scattering and charge exchange. The sharp structure in D for small angles in $p\bar{p} \to n\bar{n}$ is almost model independent, and reflects the dominant one pion exchange contribution.

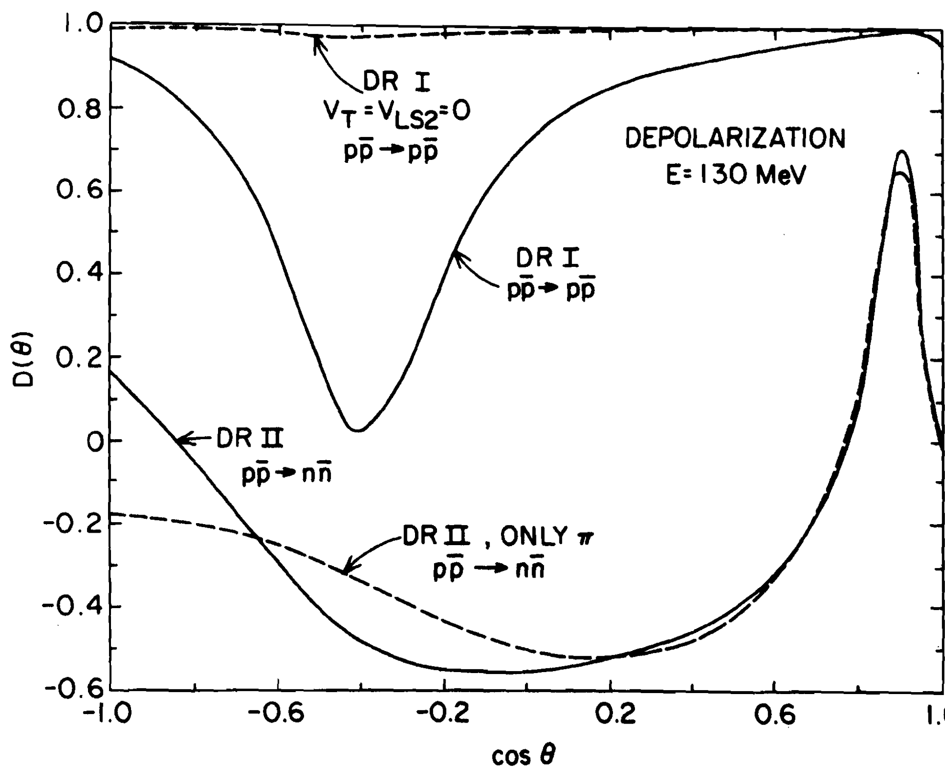

Figure 2. The depolarization D as a function of the lab scattering angle Θ, at a lab kinetic energy of E = 130 MeV, for models DRI/DRII. The dashed curve for $p\bar{p} \to n\bar{n}$ shows the effect of turning of all tensor (V_T) and quadratic spin-orbit (V_{LS2}) terms in the $N\bar{N}$ potential. The dashed curve for $p\bar{p} \to n\bar{n}$ corresponds to a calculation in which the full annihilation potential is retained, but only π exchange is included in the real part due to meson exchange.

The dominant effect of the pion tensor force is also seen in other spin observables for charge exchange. For instance, in Figure 3, we display the angular dependence predicted for the spin rotation R in $p\bar{p} \rightarrow n\bar{n}$ at E=130 MeV.

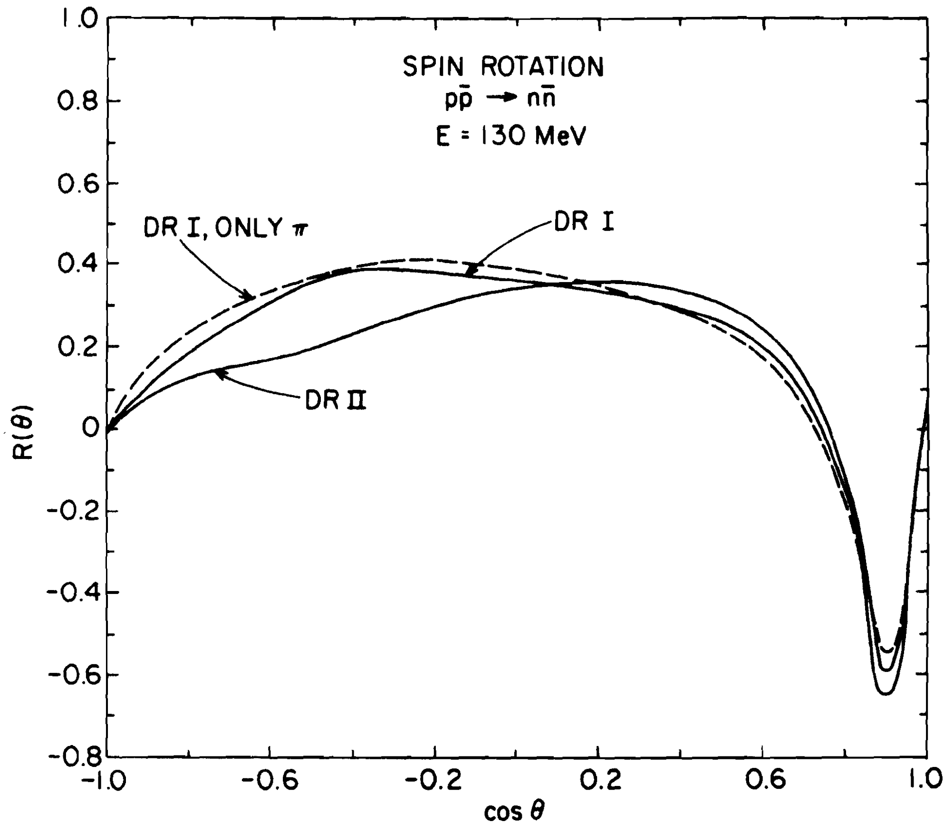

Figure 3. Spin rotation R for charge exchange at 130 MeV.

Here we see that the role of vector meson exchange is rather small in the forward hemisphere, the large excursion of R away from 0 near 0° being almost exclusively due to one pion exchange. In general, the pion is less dominant in $p\bar{p} \rightarrow p\bar{p}$ and $p\bar{n} \rightarrow p\bar{n}$ than for $p\bar{p} \rightarrow n\bar{n}$, since here isoscalar meson exchanges are allowed. Coherent spin effects due to $\rho + \omega$ exchange show up in elastic scattering, whereas ω exchange does not contribute to $p\bar{p} \rightarrow n\bar{n}$.

The tensor (S_{12}) interaction also has a significant influence on the cross section differences

$$\Delta\sigma_L = \sigma_{\substack{\rightarrow\\ \leftarrow}} - \sigma_{\substack{\rightarrow\\ \rightarrow}}$$
$$\Delta\sigma_T = \sigma_{\downarrow\uparrow} - \sigma_{\uparrow\uparrow} \qquad (4)$$

In Figs. 4 and 5, we show the changes in $\Delta\sigma_L/\sigma$ and $\Delta\sigma_T/\sigma$ produced by setting various components of the $N\bar{N}$ potential to zero. The suppression of S_{12} terms has the largest effect, both in elastic scattering and charge exchange. Note that the spin effects are not negligible in $\Delta\sigma_L$ and $\Delta\sigma_T$ if tensor terms are suppressed, unlike the situation for D in model DRI (see Fig. 2). The effect of $\underset{\sim}{L} \cdot \underset{\sim}{S}$ terms is somewhat larger for the PARIS than the DR model, since the imaginary part of the PARIS $N\bar{N}$ potential contains a substantial spin-orbit component, absent in the DR model.

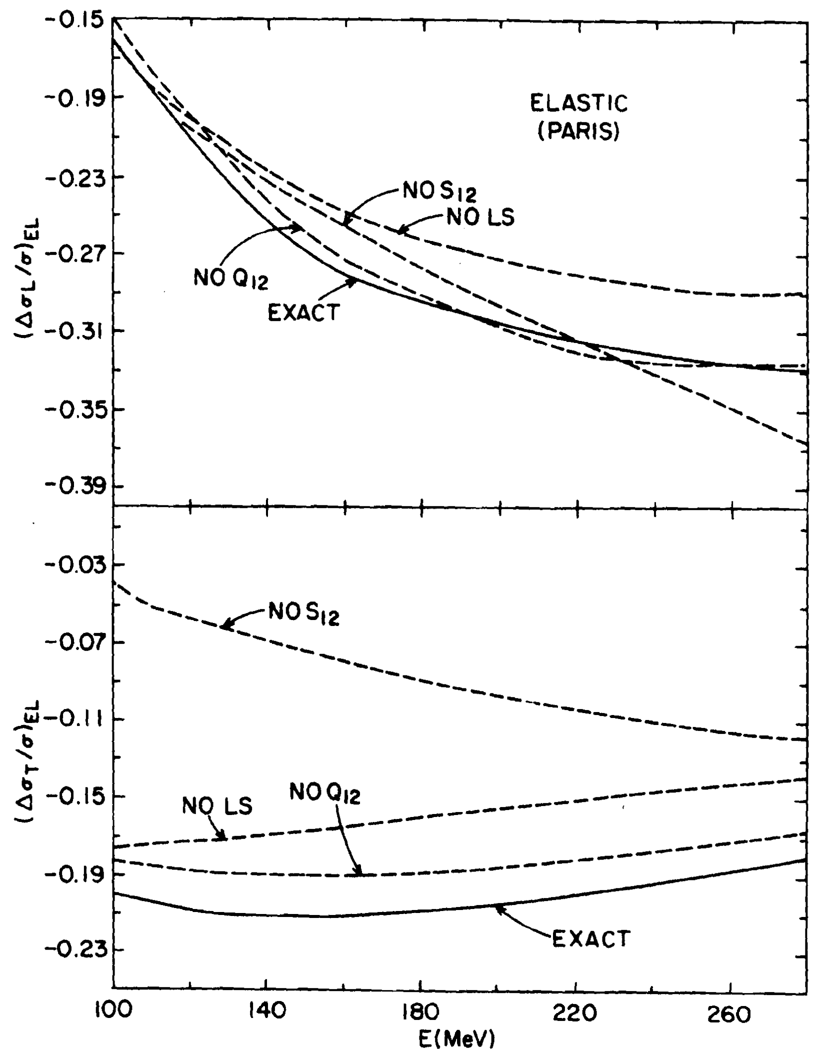

Figure 4. Cross section differences $\Delta\sigma_L$ and $\Delta\sigma_T$, defined by Eq. (4), for elastic scattering, divided by the spin averaged elastic cross section. The dashed curves show the effect of turning off one component (spin-orbit LS, tensor S_{12} or quadratic spin-orbit Q_{12}) of the $N\bar{N}$ potential at a time, both real and imaginary parts.

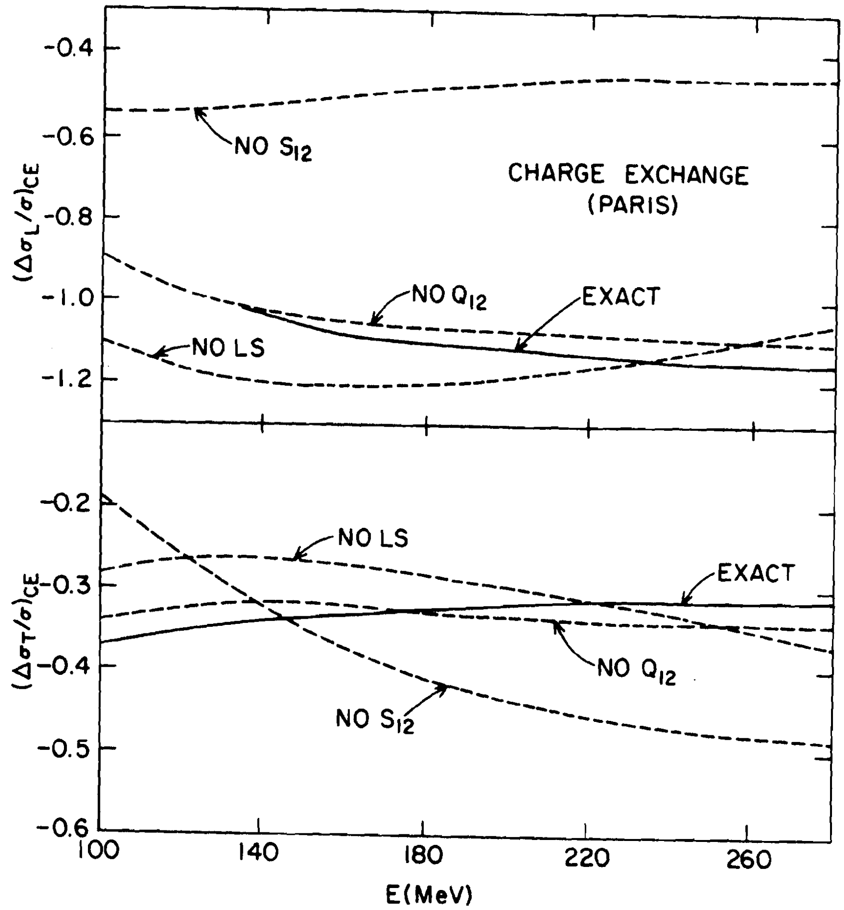

Figure 5. Same as Figure 4, but for $p\bar{p} \to n\bar{n}$ in the PARIS model

In Figure 6 we display predictions of $d\sigma/d\Omega$, P, D, R, A, R', A' for elastic $p\bar{p} \to p\bar{p}$ scattering for a lab kinetic energy of E = 160 meV. Models DRI and PARIS are seen to yield very similar predictions for the elastic scattering angular distribution, since only the spin-averaged optical potential is involved here. The spin observables show a more marked model dependence, with the PARIS results showing more dramatic angular structures. The sharpest angular variation in D, R, A, R', and A' occurs in the region of the diffraction minimum in $d\sigma/d\Omega$. Here, where we are best able to distinguish the theoretical models, the cross sections are small (typically 0.1 to 0.2 mb/sr), and the experimental measurements will be most difficult. In the forward angle region (cosθ $\geq$ 0.6), dσ/dΩ is about two orders of magnitude larger, but the model dependence of the spin observables is much more modest, so precision measurements will be needed.

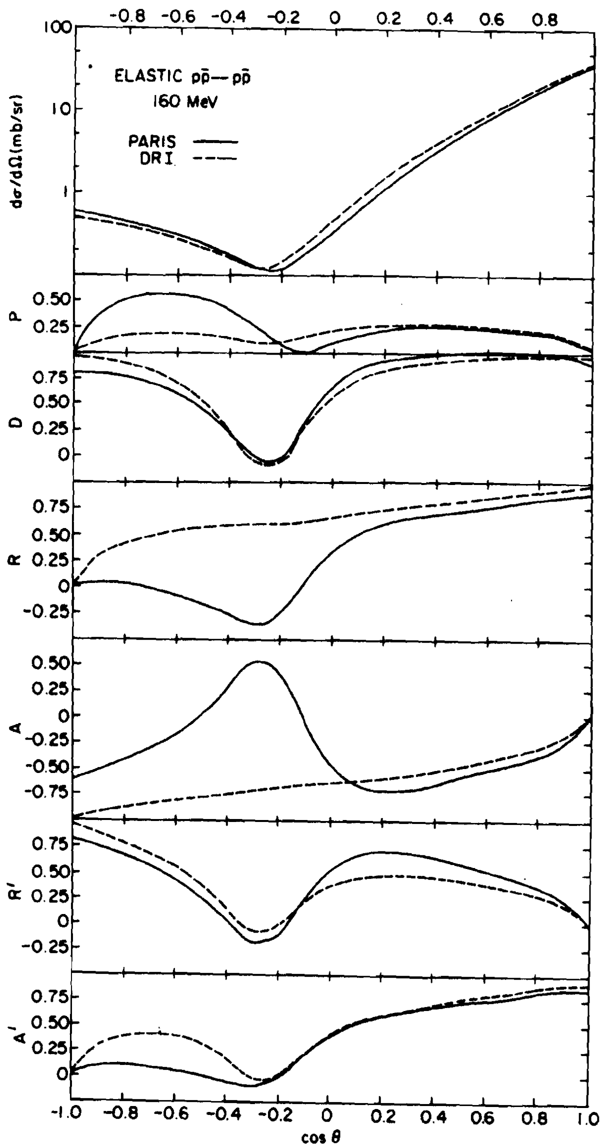

Figure 6. Differential cross section dσ/dΩ and spin observables P, D, R, A, R',A' for elastic pp̄ scattering at E = 160 MeV. The predictions for the PARIS and DRI models are shown as solid and dashed lines.

In Fig. 7, we show the energy dependence of R, A, R', and A' for model DRI. The sharp minima in D, R', and A' track the movement of the diffraction minimum in dσ/dΩ. The observables R and A are predicted to be only weakly dependent on energy in model DRI. In the PARIS model, on the other hand, the energy dependence is more pronounced.

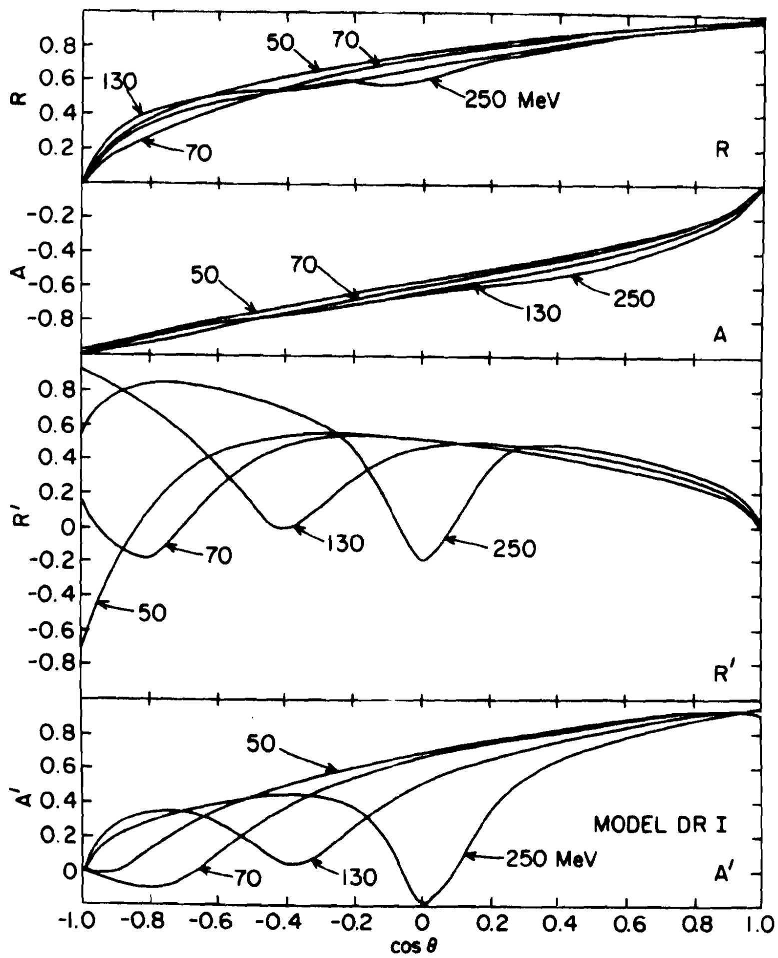

Figure 7. Angular distributions for R, A, R', and A' in model DRI for E = 50, 70, 130, and 250 MeV.

The predicted energy dependence of the polarization P(Θ) for fixed Θ in model DRI is shown in Fig. 8. The elastic polarization is not negligible, and has a rather smooth energy dependence. Some new data[11] are available from LEAR, but so far these are restricted to the small angle region, where P(Θ) is predicted (and measured) to be small.

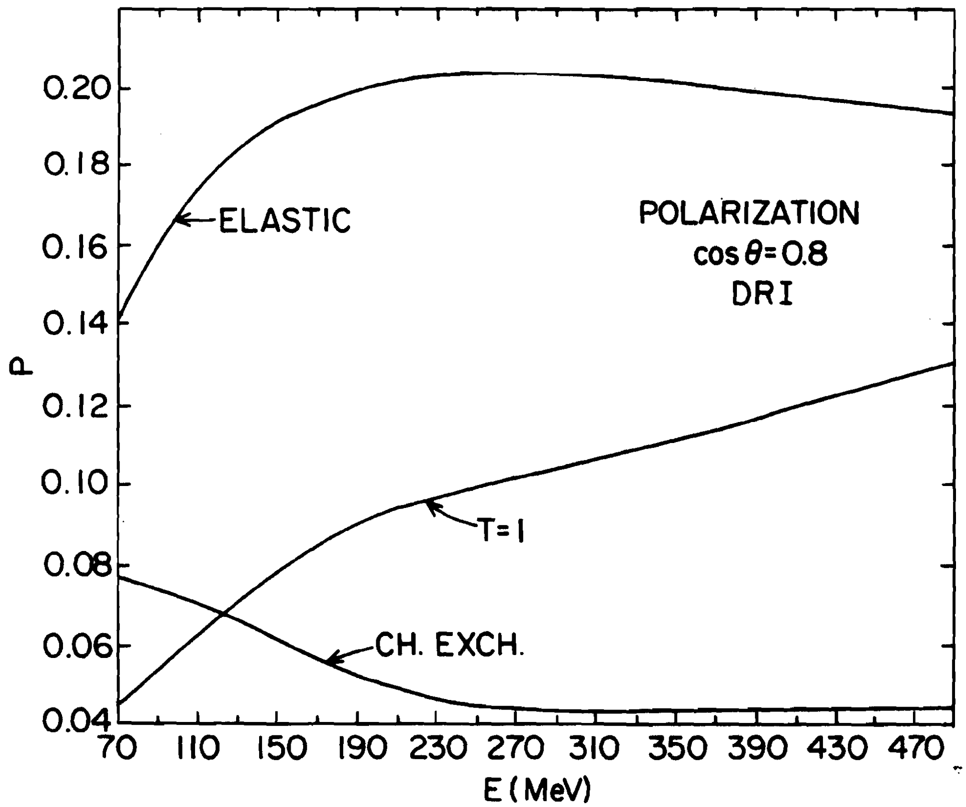

Figure 8. Energy dependence of the polarization P at fixed lab angle cosθ=0.8 for $p\bar{p} \rightarrow p\bar{p}$, $p\bar{n} \rightarrow p\bar{n}$, and $p\bar{p} \rightarrow n\bar{n}$ in model DRI.

The strong isospin dependence anticipated for P is also clear in Fig. 8. It is interesting to note that although the charge exchange polarization is predicted to be small, other spin observables for $p\bar{p} \rightarrow n\bar{n}$ show dramatic structure. This is already evident in Fig. 5, and is illustrated again in Figs. 9 and 10. The sharp variation in A_t for $p\bar{p} \rightarrow n\bar{n}$ from essentially +1 to −1 over a relatively small angular region is an effect of one pion exchange, and is thus not dependent on the details of the model, for instance the strength of the short range vector meson exchanges. These effects show up at larger angles, as seen in Fig. 9.

The energy dependence of A_t and R_t' at $\theta = 0°$ is shown in Fig. 10 for charge exchange and elastic scattering. We note that $A_t(0°)$ for $p\bar{p} \rightarrow n\bar{n}$

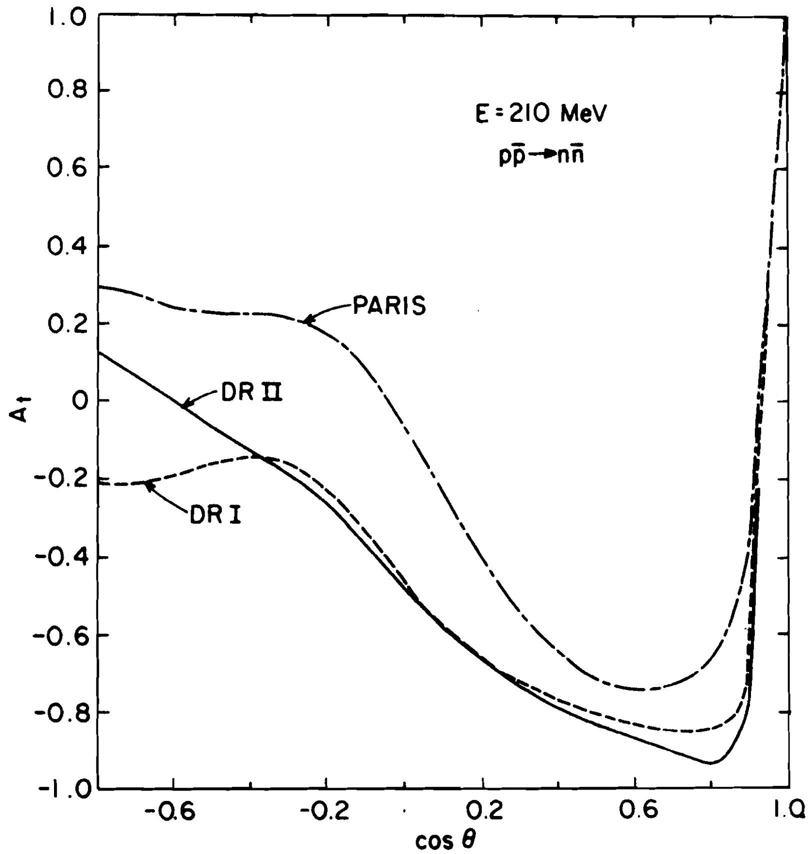

Figure 9. The predicted angular dependence of the spin transfer observable A_t for $p\bar{p} \rightarrow n\bar{n}$ charge exchange at 210 MeV.

remains > 0.9 for E > 100 MeV. This implies that with an appropriately polarized hydrogen target and an unpolarized incident $\bar{p}$ beam, the final $\bar{n}$ will enjoy almost 100% polarization. Note that A_t actually refers to the transfer of longitudinal polarization of a $\bar{p}$ beam to become transverse polarization of the recoiling neutron in $p\bar{p} \rightarrow n\bar{n}$, but is also relevant to the case of unpolarized beam and polarized target.

Other striking spin effects for $p\bar{p} \rightarrow n\bar{n}$ include the following:

$$D(180°) \approx -0.75$$
$$A'(0°) \approx -0.85 \qquad (5)$$
$$A_t(0°) \approx +0.9$$

for model DRI at E = 130 MeV. These strong effects persist at other energies in the other models. For elastic scattering, on the other hand, the spin effects are generally more modest. For instance, in Fig. 10, we note that A_t

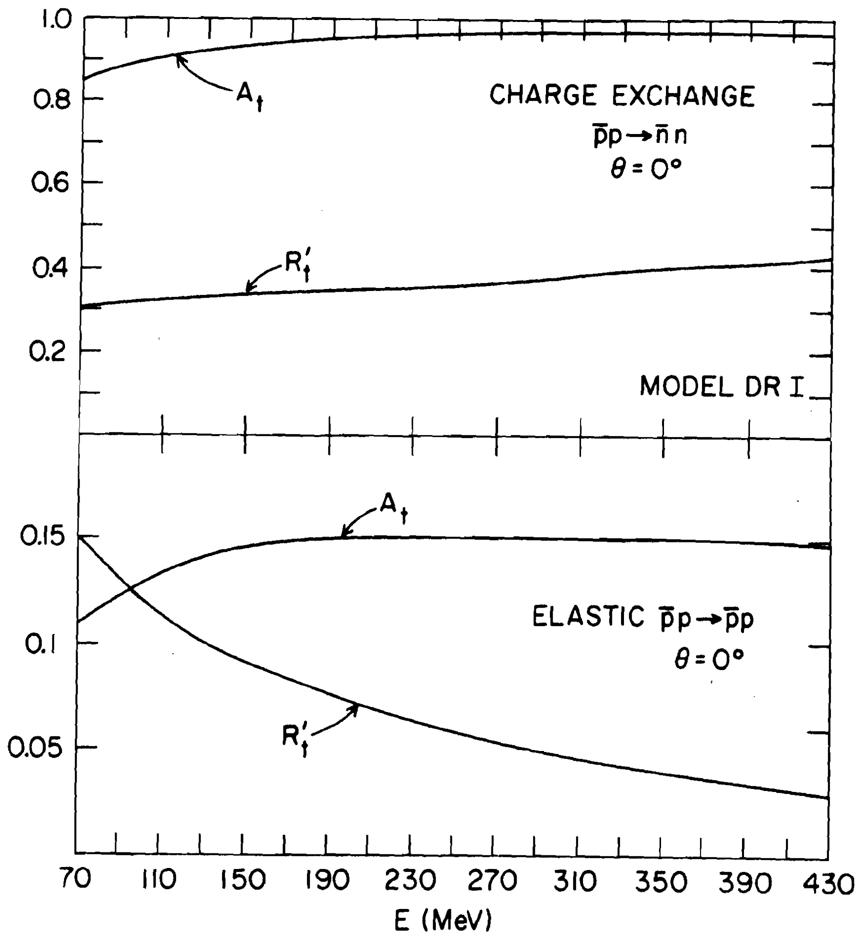

Figure 10. Spin transfer observables A_t and R_t' as a function of energy at $\theta = 0°$ for $p\bar{p} \to n\bar{n}$ and $p\bar{p} \to p\bar{p}$ scattering in model DRI.

and R_t' at 0° do not exceed 0.15 in a broad energy range. Thus, even with a polarized target, it is not easy to produce $\bar{p}$'s with appreciable polarization in elastic $p\bar{p} \to p\bar{p}$ scattering. The spin transfer observables D_t, A_t, A_t', R_t, and R_t' are all predicted to be rather small (typically $\lesssim 0.2$ in magnitude) for $p\bar{p} \to p\bar{p}$ over a range of $\{E,\theta\}$.

The spin filtering technique[12], which relies on the total cross section difference $\Delta\sigma_T$ to produce $\bar{p}$ polarization, is also not likely to produce sizable polarizations. Detailed estimates based on models DRI, DRII, and PARIS are provided in Ref. (9). It should be realized, however, that these models have not been constrained by fitting the new LEAR polarization data[11], and data on other spin observables do not exist. Since the models at hand[4-6] are essentially derived from total and differential cross section data alone, they may be unreliable in predicting spin observables. It is thus essential to proceed with the experimental program of spin measurements, not taking the theoretical predictions too seriously.

In summary, we emphasize that a substantial spin and isospin dependence is predicted for the $N\bar{N}$ interaction, but is not so readily revealed by elastic and annihilation cross sections alone. Measurements of spin observables are required, and these place a premium on obtaining the highest possible $\bar{p}$ beam intensities. Experiments with polarized beams and/or polarized targets are in general necessary to unravel the $N\bar{N}$ spin dependence, but much progress could already be made using a polarized target and an unpolarized $\bar{p}$ beam.

The spin observables for the $N\bar{N}$ system provide a signature for the strong coherences in meson exchange forces (dominantly the tensor component) predicted by theory. NN and $N\bar{N}$ scattering are sensitive to somewhat complementary aspects of the same underlying interactions. The effects of coherent tensor forces are expected to be observable in $N\bar{N}$ spin quantities in spite of the strong influence of annihilation. Note that this tensor coherence is a feature which emerges from $\pi + \rho + \omega$ exchange, after the G-parity transformation has been applied to the NN potential. If one replaces the conventional vector mesons by an effective one gluon exchange mechanism, the strong tensor coherence does not survive (i.e., single gluon exchange, treated perturbatively, does <u>not</u> change sign like the ω in passing from NN to $N\bar{N}$). Thus if we wish to treat both the real and imaginary parts of the $N\bar{N}$ interaction on the same footing within the context of QCD, surely a laudable aim, the $N\bar{N}$ spin observables will exercise a strong constraint on the form of the effective operators.

There are numerous exciting physics questions which could be addressed with a dedicated $\bar{p}$ facility of even higher intensity than LEAR. It seems naive to assume that this area of physics will be so thoroughly mined by LEAR in the 1980s that little of interest will remain. A low and medium energy $\bar{p}$ facility at Fermilab should be given serious consideration.

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