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THE NUCLEON-ANTINUCLEON INTERACTION

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THE NUCLEON-ANTINUCLEON INTERACTION

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The current status of our understanding of the low energy nucleon-antinucleon ($N\bar{N}$) interaction is reviewed. We compare several phenomenological models which fit the available $N\bar{N}$ cross section data. The more realistic of these models employ an annihilation potential W(r) which is spin, isospin and energy dependent. The microscopic origins for these dependences are discussed in terms of quark rearrangement and annihilation processes. It is argued that the study of $N\bar{N}$ annihilation offers a powerful means of studying quark dynamics at short distances. We also discuss how one may try to isolate coherent meson exchange contributions to the medium and long range part of the $N\bar{N}$ potential. These pieces of the $N\bar{N}$ interaction are calculable via the G-parity transformation from a model for the NN potential; their effects are predicted to be seen in $N\bar{N}$ spin observables, to be measured at LEAR. The possible existence of quasi-stable bound states or resonances of an $\bar{N}$ plus one or more nucleons is discussed, with emphasis on few-body systems.

1. INTRODUCTION

In contrast to the situation for the nucleon-nucleon (NN) system, relatively little high precision data is available for the $N\bar{N}$ system. This situation should change dramatically in the next few years, as the LEAR (Low-Energy-Antiproton Ring) facility comes on line at CERN. The present review may be considered as a "pre-LEAR perspective." My object is to critically appraise the current theories of the low energy $N\bar{N}$ interaction, and point to some of the avenues of research which are likely to further enhance our understanding of the $N\bar{N}$ problem.

Why is the $N\bar{N}$ system so interesting? There are numerous reasons, some of which are discussed here. One tantalizing possibility is that one may be able to exploit the intimate relation (via the G-parity transformation) between the longer range (nominally $r \geq 0.8 - 1$ fm, a typical "bag" radius) part of the $N\bar{N}$ potential and that for the NN system. Repulsive coherences in the NN spin-orbit forces due to meson exchange, for instance, become attractive coherences of $N\bar{N}$ tensor forces as a result of the G-parity transformation. The strong predicted spin and isospin dependence of the meson exchange (t-channel) part of the $N\bar{N}$ potential should show up more readily in a comparison of spin observables in channels with different isospin structure ($\bar{p}p \to \bar{p}p$ vs $\bar{p}p \to \bar{n}n$, for instance) than in total cross sections.

The extraction of useful constraints on the NN interaction from a study of the "crossed" $N\bar{N}$ channel is hampered considerably by the presence of annihilation processes in the latter. Since the $N\bar{N}$ system has baryon number $B = 0$, it can dissolve into a spray of mesons (the mean multiplicity of pions is about 5 at low energies), a mode of decay unavailable to the NN system with $B = 2$. For distances $r < 1$ fm or so, the annihilation mechanism dominates, and one can obtain very little information on the structure of the real potential. In any case, a meson exchange description breaks down inside of 1 fm, since in this region the "bags" containing the N and $\bar{N}$ overlap, and one probes the dynamics of internal quark degrees of freedom. The microscopic description of $N\bar{N}$ annihilation at the quark level is a problem of high importance; we review several attempts to formulate a quark rearrangement model to account for the observed $N\bar{N}$ branching ratios into various mesonic channels. In principle, detailed two meson interferometry studies should provide signatures of differing quark mechanisms operating in $N\bar{N}$ annihilation.

The $N\bar{N}$ system is an ideal entrance channel for accessing narrow "baryonium" states, if they exist. These could be either of "quasi-nuclear" type or $(Q^2\bar{Q}^2)$ composites. An abundant spectrum of such states is predicted theoretically, but the estimates for their width are unreliable. Since the experimental situation is murky, we do not enumerate the detailed properties of predicted baryonium spectra here. We content ourselves with the remark that the "color chemistry" of multiquark systems ($n \geq 4$ quarks) is of fundamental interest in nuclear and particle physics, and that the $N\bar{N}$ channel offers the best window for studying the $Q^2\bar{Q}^2$ sector.

In addition to questions relating to the $N\bar{N}$ problem itself, we also consider how the characteristic signatures of the two-body problem (spin, isospin and energy dependences, ranges of real and imaginary potential, etc.) are transmitted to the many-body scenario. For instance, the marked spin dependence of the $N\bar{N}$ annihilation potential $W(r)$ which occurs in several models leads to strong excitation of isoscalar spin-flip ($\Delta T=0$, $\Delta S=1$) modes of nuclei in $\bar{N}$ inelastic scattering. These are only weakly excited by the nucleon probe. We also investigate the possibility that relatively long-lived nuclear systems containing an $\bar{N}$ may exist. Certain few-body systems are the most likely candidates, since one may take maximum advantage of spin-isospin selectivity in the absorptive potential and the influence of the long-range one pion exchange potential in systems where the nuclear core is not spin-isospin saturated.

2. BRIEF REVIEW OF $N\bar{N}$ DATA

The experimental situation in low energy $N\bar{N}$ physics has been recently reviewed by Tripp[1] and Smith[2]. The emphasis of these reviews is on the evidence (for and against) pertaining to the existence of narrow "baryonium" states in $N\bar{N}$ scattering. At the time of the Bressanone meeting[1], earlier evidence for the S(1940) and other resonances in the $N\bar{N}$ system was placed in question by a spate of negative results.

In the past year, the CERN-Heidelberg-Saclay group presented new results[3] on $\bar{p}p$ elastic scattering and annihilation. This experiment had better mass resolution (0.4 MeV) than earlier attempts (typically about 1.5 MeV). A dip-bump structure was seen near 1936 MeV, perhaps indicating the resurrection of the S meson. Other recent results, discussed by Smith[2], do not indicate a narrow structure near the S, although high mass resolution may well be critical. The S region could contain overlapping resonances (both potential and quark models give certain isospin or C-parity doublets, for instance), and high resolution studies at LEAR are necessary in order to clarify this very confused situation.

Resonant structures have also been looked for in backward ($\theta = 180°$) $\bar{p}p$ scattering. A priori, large angle scattering might appear to be quite promising for bump hunting, since cross sections are much smaller than in the forward direction, and a resonance might be expected to show up more readily. D'Andlau et al.[4] found evidence for structure in the S region, but a later higher precision experiment of Alston-Garnjost et al.[5] found only a smooth cross section at 180° as a function of momentum. The main problem is that the 180° $\bar{p}p$ cross section attains a diffraction maximum around $p_{lab} = 510$ MeV/c, i.e. just the position of the tentative S meson. Interest in the 180° data has recently been rekindled by the Nijmegen group[6], who have performed an optical model fit[7] to all the available $N\bar{N}$ data (elastic and charge exchange angular distributions, total cross sections, and polarization data). A result of this fit is a good theoretical description of the diffractive background at 180°. When this background is subtracted from the data of Alston-Garnjost et al.[5], there is still evidence for a narrow structure at 1940 MeV. This structure can be accommodated in a coupled channel framework[6] if the NN channel is coupled to a $Q^2\bar{Q}^2$ "baryonium" channel. In ref. 6, this coupling is taken in the $^{11}P_1$ $N\bar{N}$ wave as an example, but the data are not sufficient to actually determine the quantum numbers of the proposed resonance.

In addition to the S region, there has been recent evidence for an $N\bar{N}$ resonance at 2.02 GeV/c^2 in production experiments[16,17]. In ref. (16), an I = 1 state was observed in the reactions $\bar{p}p \to p_{fast}\ \bar{n}\pi^+\pi^-\pi^-$ and

$\bar{p}p \to \pi^{r}_{fast}\ \bar{p}n\pi^+\pi^-$ at 6 and 9 GeV/c. The mass spectra showing the 2.02 GeV/c^2 peak are shown in Fig. 1. The structure at 2.02 GeV/c^2, as well as one in the S region, was also seen by Bodenkamp et al.[9] in the $\gamma p \to p\bar{p}p$ photoproduction reaction from 4.7 - 6.6 GeV, shown in Fig. 2. On the other hand, numerous attempts[10] to produce these states via baryon-exchange mechanisms have led to negative results. The experimental situation for $N\bar{N}$ resonances thus remains unclear.

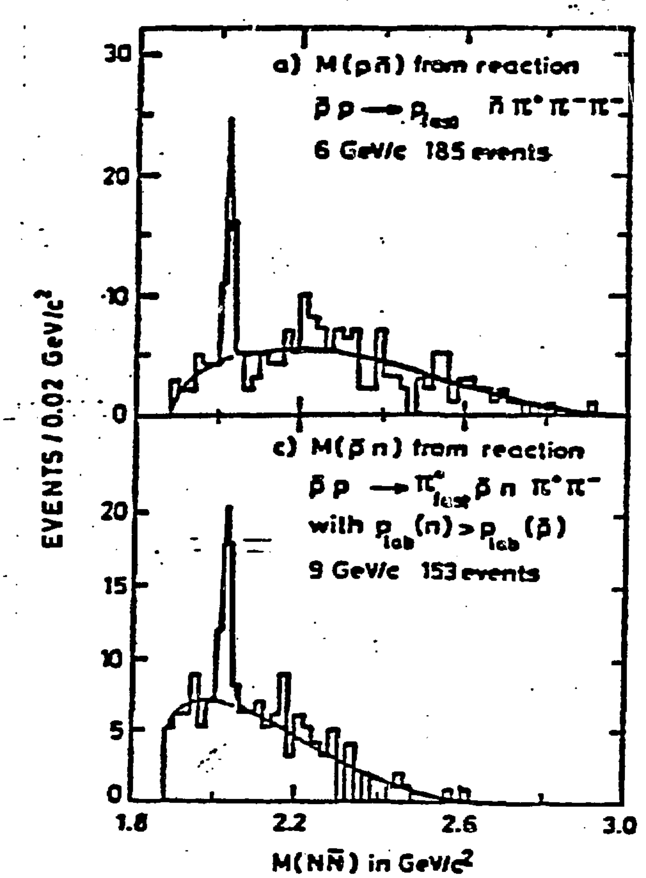

FIGURE 1

$N\bar{N}$ mass spectra from Azooz et al[8].

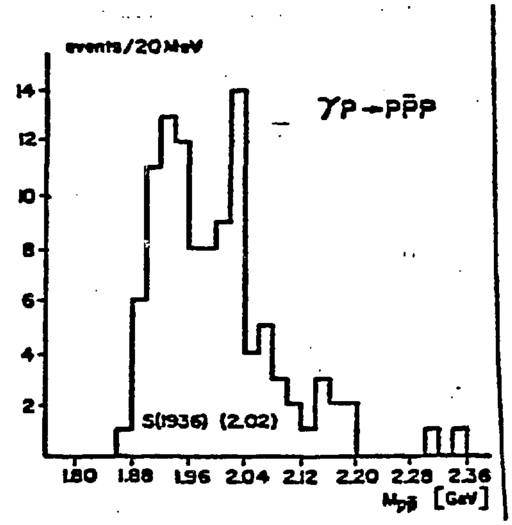

FIGURE 2

$N\bar{N}$ mass spectrum in photoproduction, from Bodenkamp et al[9].

There has been persistent evidence[11,12] for the emission of energetic γ rays (E > 100 MeV) from $\bar{p}p$ atoms. These transitions lead to the population of narrow (Γ < 20-30 MeV) $N\bar{N}$ levels at masses of about 1210, 1638, 1694 and 1771 MeV, according to the group[11] at CERN. The statistical significance of these lines is at the 3σ level. In an experiment[12] at the Brookhaven AGS, evidence at about the 3σ level was obtained for the 1771 MeV state, but the statistics were insufficient to confirm or deny the other levels seen by the CERN group.

Numerous theoretical predictions exist for the spectrum of "baryonium" states coupled to the $N\bar{N}$ channel. The quark model aspects have been reviewed in ref. (13), while considerations based on $N\bar{N}$ potential models are treated in refs. (14) and (15). In the quark model, composites of type $Q^2\bar{Q}^2$ are coupled to the $N\bar{N}$ channel via the quark-antiquark annihilation mechanism depicted in Fig. 3(a). The spectrum of $Q^2\bar{Q}^2$ states in the MIT bag model, as well as their relative couplings to $N\bar{N}$, have been worked out by Jaffe[16]. The spectrum of $Q^2\bar{Q}^2$ bag states is shown in Fig. 4; the levels are grouped into trajectories A, B and C as defined by Jaffe[16]. Trajectory A is most strongly coupled to $N\bar{N}$, followed by B and C. Several candidates for the levels seen in the γ ray experiment are evident. One of the mechanisms for populating these levels by γ or π emission is shown in fig. 3(b). The branching ratios for γ emission to $Q^2\bar{Q}^2$ states (relative to annihilation) have been evaluated by Aúer et al.[17]. The dominant mechanism was found to be γ emission from a quark or antiquark

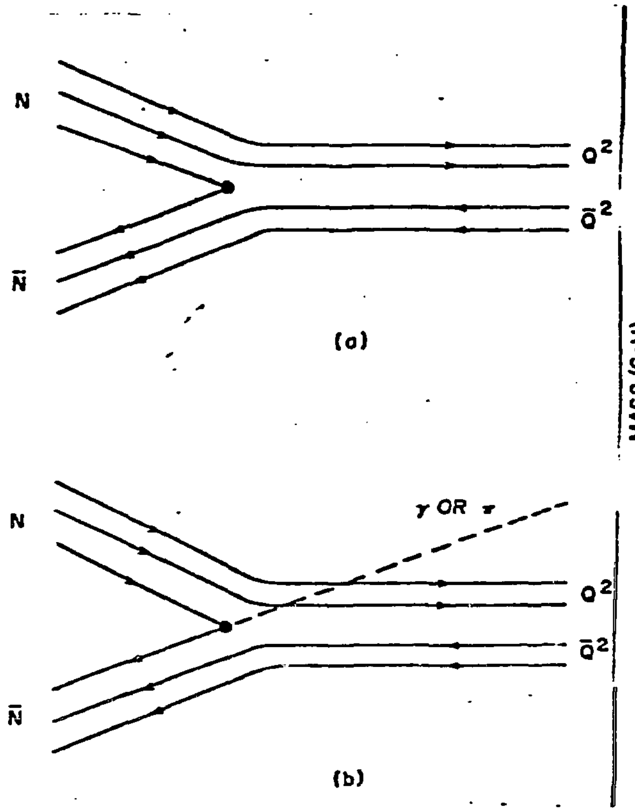

FIGURE 3

Mechanism for direct $N\bar{N}$ coupling to $Q^2\bar{Q}^2$ bag states ($^3P_0$ model) is shown in (a); one of the processes for populating $Q^2\bar{Q}^2$ states via γ or π emission is shown in (b).

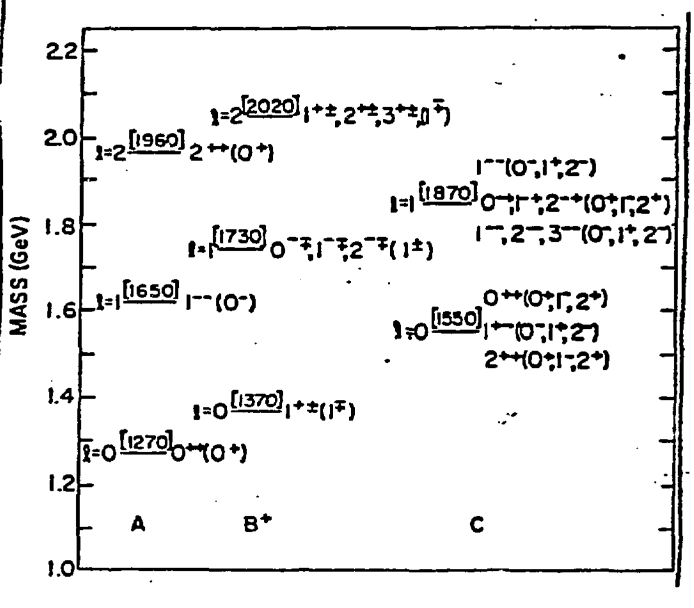

FIGURE 4

Spectrum of $Q^2\bar{Q}^2$ states (labeled by $J^{PC}(I^G)$) in the MIT bag model, after Jaffe[16].

line, followed by $Q\bar{Q}$ annihilation into the vacuum, rather than that shown in Fig. 3(b). Branching ratios of the order of a few times 10^{-4} were obtained in the quark model, about an order of magnitude smaller than the results[11] from CERN. In the $N\bar{N}$ potential model[14], the channels of maximum attraction for each L correspond to the same quantum numbers as trajectory A in Fig. 4. The branching ratios for γ or π emission to $N\bar{N}$ quasi-bound states were evaluated in ref. (17) in the context of the potential model; agreement with the experimental values is obtained, in contrast to the evaluation in the quark model. The significance of this fact is not clear at this point.

One of the first tasks at LEAR will be to confirm (or deny) the existence of narrow $N\bar{N}$ bound states or resonances. If narrow states indeed exist, detailed information on decay branching ratios would greatly facilitate quantum number assignments. If narrow states are not found, much interesting physics could still emerge from the spectroscopy of broad mesons coupling strongly to the $N\bar{N}$ channel. Firm evidence exists for broad structures in $N\bar{N}$ total cross sections (T and U mesons) and high spin states[18] in the $\bar{p}p \to \pi^+\pi^-$ reaction.

3. THE REAL (NON-ANNIHILATION) PART OF THE $N\bar{N}$ 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, for example ref. (19), contributions to V arise from exchanges of nonets of scalar, pseudoscalar and vector mesons. In the work of the Stony Brook[20] and Paris[21] groups, 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 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 early 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[19] or other parametrized cutoffs[21], for instance), and it is not clear how to transform these prescriptions into the NN 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, as we discuss in Sects. 4 and 5, 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} has not been reliably estimated theoretically; in principle, it 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 crude data on $\bar{p}p$ 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[14] 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 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 $\sigma_1 \cdot \sigma_2$, L·S and vector exchange potentials.

In passing from the $N\bar{N}$ to the NN 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. As mentioned earlier, these channels form a natural parity band with $J^{\pi C} = 0^{++}, 1^{--}, 2^{++}$, etc., which share the same quantum numbers as the "leading trajectory" of $Q^2\bar{Q}^2$ states in the bag model.

The coherence of $N\bar{N}$ tensor forces for $I = 0$ is most readily seen in spin observables. Some sample predictions from ref. (22) are shown in Figs. 5 and 6. In Fig. 5, we show an angular distribution for the $\bar{p}p$ elastic polarization P(θ) at 130 MeV. If the spin-spin and spin-orbit parts of the $N\bar{N}$ potential are set to zero, P(θ) remains essentially unchanged, while if tensor forces are neglected, P(θ) almost vanishes. In contrast to the NN system, where P(θ) arises predominantly from the spin-orbit potential, the polarization in $N\bar{N}$ is largely an effect of the coherent tensor force from meson exchange. The quantitative aspects of P(θ) (and other spin observables) are influenced, however, by a possible strong spin-spin and tensor component in W(r), which can cloud the simple and elegant interpretation based on meson exchange. In Fig. 6, we display predictions[14] for

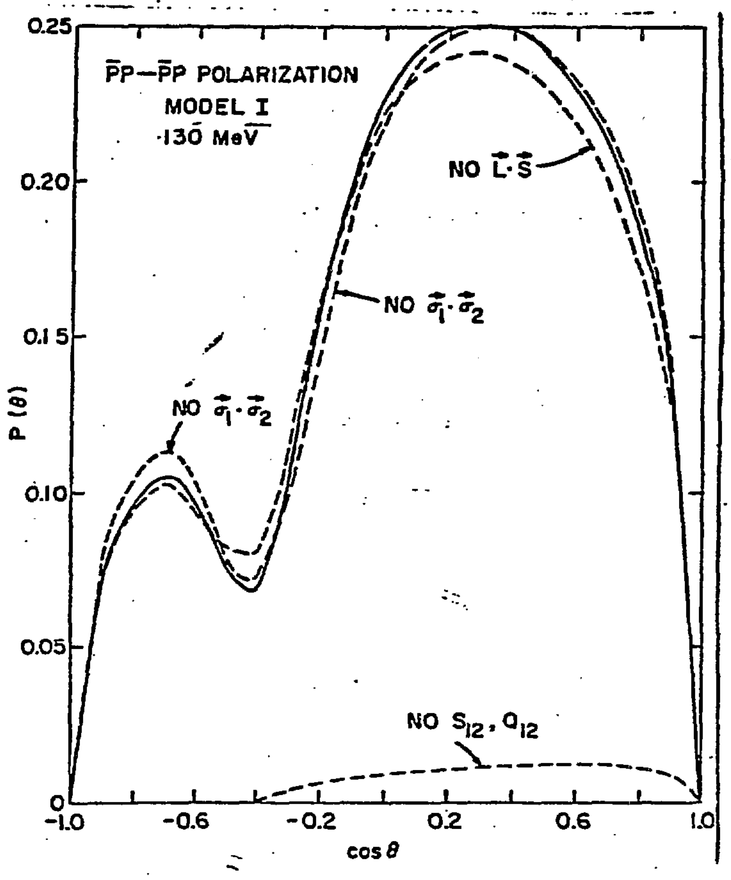

FIGURE 5

Elastic $\bar{p}p$ polarization at 130 MeV, from ref. (14).

A_t, which may be measurable in future experiments at LEAR. Fig. 6 shows that the polarization transfer A_t is considerably enhanced if the coherent vector meson contribution is added to one pion exchange.

To summarize, a careful measurement of $N\bar{N}$ spin observables could provide an important constraint on the summed strength of the π, ω and ρ tensor potentials (and also the coherent quadratic spin-orbit potentials). This information would be complementary to that obtained from a study of the spin dependence in NN scattering.

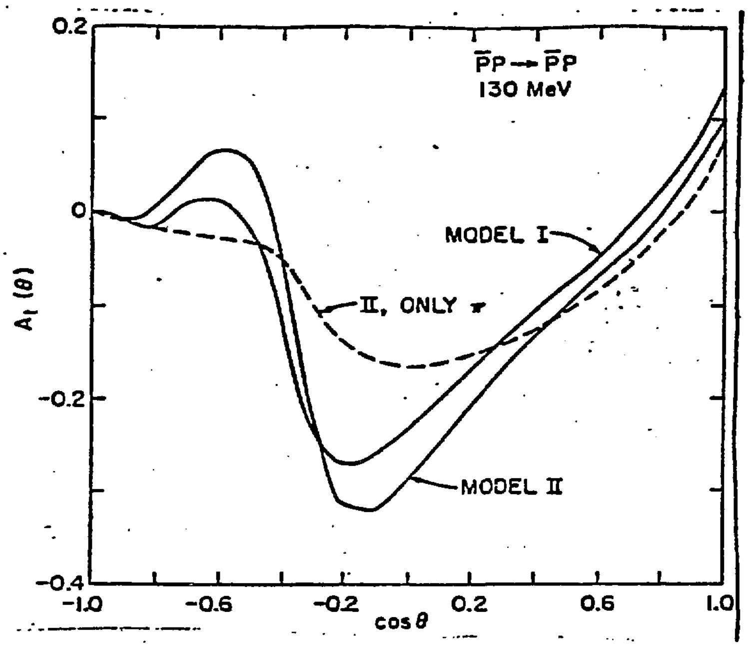

FIGURE 6
Polarization transfer A_t at 130 MeV, from ref. (14).

4. GEOMETRIC AND PHENOMENOLOGICAL MODELS OF $N\bar{N}$ ANNIHILATION

The G-parity transformation provides a means of obtaining the medium and long range parts of the $N\bar{N}$ meson exchange potential from a model for the NN interaction. This is only part of the story, since annihilation processes in $N\bar{N}$ are very strong. This is strikingly illustrated by considering the total $\bar{p}p$ elastic and annihilation cross sections σ_E and σ_A, which can be represented[23] phenomenologically as

$$\begin{aligned} \sigma_E &= 28 + 17/p_{lab} \ (\text{mb}) \\ \sigma_A &= 38 + 35/p_{lab} \ (\text{mb}) \end{aligned} \tag{1}$$

for p_{lab} in the range 0.5 – 2 GeV/c. We see that σ_A is very large (far exceeding the s-wave unitarity bound even at the lowest measured momenta) and that $\sigma_E/\sigma_A \approx 1/2$ at low energies, unlike the result $\sigma_E \approx \sigma_A$ which one might expect in the most naive geometric limit.

The qualitative features of σ_E and σ_A can already be understood[14] in the simplest sort of absorbing sphere model, based on the old continuum theory of nuclear reactions, as described by Blatt and Weisskopf[24], for instance. In this model, the annihilation potential $W(r)$ is replaced by an incoming wave boundary condition at a strong absorption radius $r = R$:

$$\left[u'_\ell(r)/u_\ell(r)\right]_{r=R} = -iK \ , \ K = \left(M(E-V_o)\right)^{1/2} \tag{2}$$

Here, V_o is the depth of the real potential at $r = R$ and M is the nucleon mass. In ref. (14), this model was used, with $R = 1$ fm, to fit σ_E and σ_A. The model reproduces the monotone-decreasing cross sections rather well, in particular the ratio σ_A/σ_{EL}. The boundary condition model was one of the earliest approaches[25] to understanding the size of $N\bar{N}$ cross sections. A recent application is due to Myhrer and Dalkarov[26].

Higher partial waves play an important role, even at very low momenta. The s-wave region, which lies below 150 - 200 MeV/c, has not yet been explored experimentally; this is an important task for LEAR. The representation (1) of σ_A is reminiscent[24] of the "1/v law", but in fact has nothing to do with s-wave dominance. The signal that we are getting into the s-wave region is that σ_A drops significantly below the value obtained by simply extrapolating Eq. (1) to low momentum. An interesting quantity is $\beta\sigma_A$, where $\beta = v/c$; as $\beta \to 0$, $\beta\sigma_A$ must approach a constant. From two recent optical models for fitting the $N\bar{N}$ cross section data, we find[27]

$$\beta\sigma_A = \begin{cases} 28.21 + 0.192E + 0.0128E^2 & \text{(ref. 28)} \\ 32.83 + 0.096E & \text{(ref. 29)} \end{cases} \tag{3}$$

where $\beta\sigma_A$ is in mb and E (lab kinetic energy) is in MeV. Eq. (3) holds for $E < 10$ MeV. The average threshold value is about $(\beta\sigma_A)_{\beta\to 0} = 30$ mb. This value could change significantly if narrow bound s-states exist close to the $N\bar{N}$ threshold. These do not occur in refs. (28) and (29); there are instead deeply bound and very broad $N\bar{N}$ s-states in these models.

The simple black disk or boundary condition models are sufficient for a semi-quantitative understanding of total cross sections, but provide no useful account of spin observables, isospin dependence, or large angle elastic or charge exchange scattering. For these quantities, which contain most of the interesting physics, the full optical model treatment is necessary.

An early optical model fit to the $N\bar{N}$ data was carried out by Bryan and Phillips[30]. They used an OBE model for the t-channel meson exchange potential, and a local Woods-Saxon form

$$V_{ann}(r) + iW(r) = -(V_o + iW_o)/(1 + \exp\left[(r-R)/a\right]) \tag{4}$$

for the complex annihilation potential. They used $V_o = 0$, $W_o = 62$ GeV, $R = 0$ and $a = 1/6$ fm. This type of analysis was later redone by Dover and Richard[28], who used the Paris potential[21] for the t-channel part, and also included a real annihilation potential. They fit the high precision $\bar{p}p \to \bar{n}n$

charge exchange data[31] which had become available. A family of annihilation potentials was found which fit the data (Model I with $V_o = 21$ GeV, $W_o = 20$ GeV, $R = 0$, $a = 1/5$ fm and Model II with $V_o = W_o = 500$ MeV. $R = 0.8$ fm, $a = 1/5$ fm are two examples; see Fig. 6). This family has the characteristic that the absorptive parts are comparable at around 1 fm. The enormous values (many GeV) attained by the annihilation potential at short distances are of no physical significance. The cross sections are insensitive to the potentials in this region, as long as absorption is sufficiently strong. A similar situation prevails in heavy ion reactions.

After the analysis of Dover and Richard[28] appeared, $\bar{p}p$ backward ($\theta = 174°$) elastic scattering was measured with high precision by Alston-Garnjost et al[5]. Although ref. (28) was consistent with the earlier crude elastic data at backward angles, it now considerably underestimated the cross section. It proved impossible to remedy this situation by further variations of an annihilation potential of the type (4). The Paris group[29] reanalyzed the $N\bar{N}$ data, including all differential cross section and polarization information, using a more flexible phenomenological form

$$W(r) = \{g_c(1 + f_c E) + g_{SS}(1 + f_{SS}E)\underset{\sim}{\sigma}_1 \cdot \underset{\sim}{\sigma}_2 + g_T S_{12} + \frac{g_{LS}}{4m^2}\, \underset{\sim}{L}\cdot\underset{\sim}{S}\, \frac{1}{r}\frac{d}{dr}\}\, \frac{K_o(2mr)}{r} \tag{5}$$

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_o of range $1/2m = 0.1$ fm (held fixed), which reduces to a Yukawa form for large r. The form (5) is rather general, incorporating 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, and an updated version[32] of the Paris potential was used for the t-channel exchange part. Further free parameters[29] are required to specify the short range cutoff.

A sample of the good fits to the $N\bar{N}$ data obtained by the Paris group is shown in Fig. 7. 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 (crudely) is $P(\theta)$, see Fig. 7, 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. Nevertheless, some interesting conclusions can be drawn from this analysis. Firstly, the spin and isospin dependence of W(r) in ref. (29) is very strong. For s-waves, the values of W^{IS} stand in the ratio

$$W^{00}:W^{10}:W^{01}:W^{11}=\begin{cases}1:0.81:0.11:0.073, & E=0\\ 0.92:1:0.15:0.035, & E=100\text{ MeV}\end{cases} \tag{6}$$

From Eq. (6), 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) has a dramatic consequence in $\bar{N}$ inelastic scattering on nuclei[33]: isoscalar, spin-flip ($\Delta S=1$) modes of nuclei, which are excited only very weakly in nucleon inelastic scattering, become very prominent in the $\bar{N}$ inelastic response function.

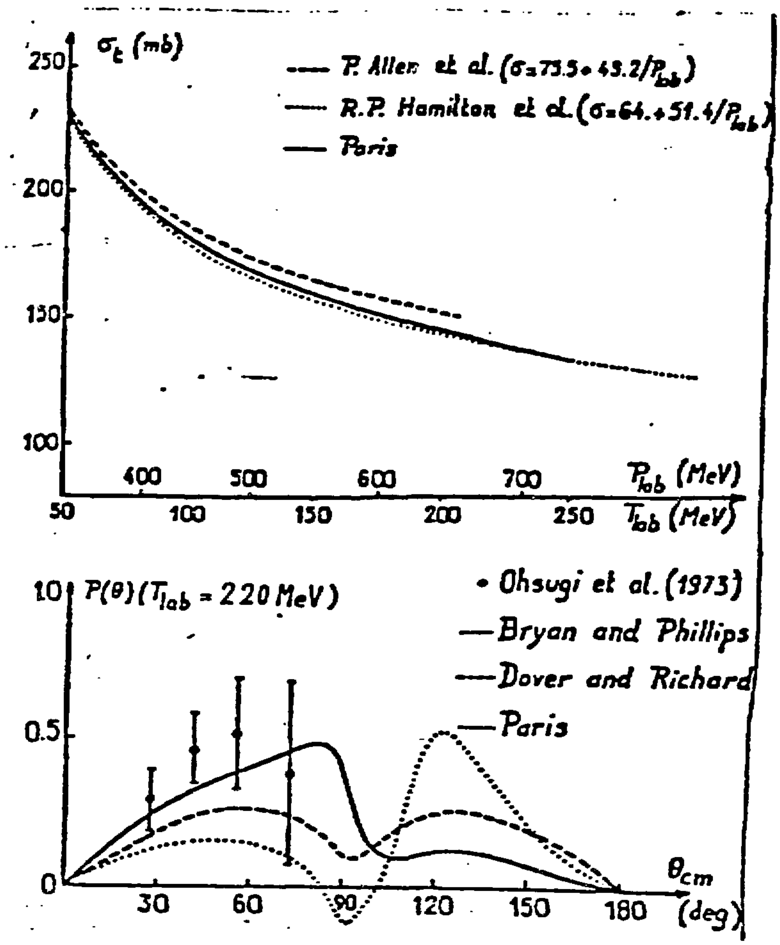

FIGURE 7

Optical model fits to $\bar{p}p$ total cross section and elastic polarization, from the Paris group[29].

Very recently, the Nijmegen group has presented a coupled model[6,7] for $N\bar{N}$ scattering. They solve the relativistic coupled channels Schrödinger equation (including the n-p mass difference and Coulomb effects) with a potential matrix of the form

$$V=\begin{pmatrix} V_{N\bar{N}} & V_A \\ \bar{V}_A & 0\end{pmatrix} \tag{7}$$

Here $V_{\bar{N}}=V_{nuc}+V_{ph}+V_{coul}$ is the diagonal $N\bar{N}$ potential, V_{nuc} is the t-channel meson exchange potential (taken as the G-parity transformed Model D potential of ref. (19)), V_{coul} is the Coulomb potential and V_{ph} is a phenomenological energy independent <u>real</u> potential of the form

$$V_{ph}(r) = \left(V_c + V_{SS}\, \underset{\sim}{\sigma}_1 \cdot \underset{\sim}{\sigma}_2 + V_T S_{12}\, m r + V_{SO}\, \underset{\sim}{L} \cdot \underset{\sim}{S} \frac{1}{m_e^2 r} \frac{d}{dr}\right) \tag{8}$$
$$\times \left(1 + \exp(m_e r)\right)^{-1}$$

with a range $1/m_e = 0.31$ fm.

The potential V_A, which couples the $N\bar{N}$ system to a set $\{i\}$ of effective two-body annihilation channels, is chosen to be

$$V_A^{(i,I)}(r) = V(i,I)\left(1 + \exp(m_a r)\right)^{-1}, \tag{9}$$

dependent on isospin, but not on L, S or J. The range of V_A is $1/m_a = 0.46$ fm. For each isospin, two annihilation channels were introduced ($i = 1,2$); the effective particles in these channels are taken to be spinless and of equal mass ($2M_1 = 1700$ MeV and $2M_2 = 420$ MeV). No interaction between these effective particles is included. All the absorptive in $N\bar{N}$ are simulated by the coupled annihilation channels, so no explicit imaginary potential is introduced.

The quality of the Nijmegen fit[7] is illustrated for the polarization in Fig. 8. The Nijmegen model has a somewhat better χ^2 (1.5 vs. 2.8 per point) than the Paris model. Again, the requirement of fitting the $\bar{p}p$ backward elastic data is very constraining. Spin orbit and tensor terms (in $W(r)$ or V_{ph}) play an important role in obtaining a good fit to the 180° data.

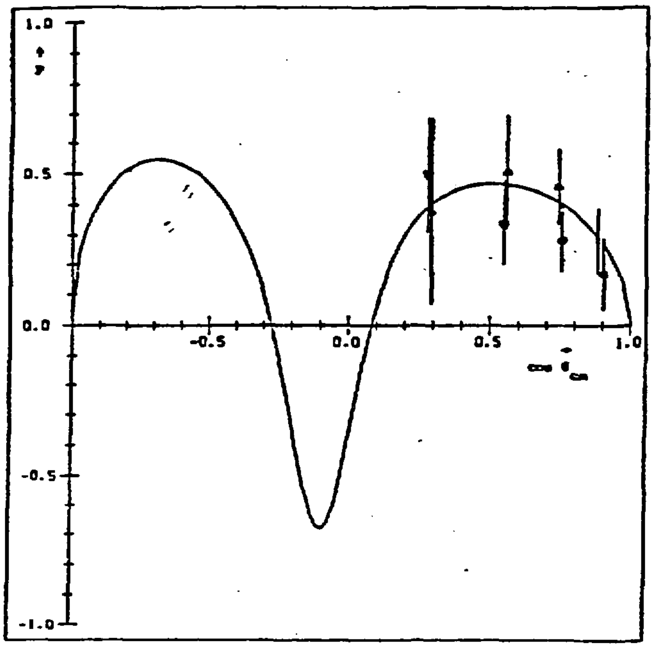

FIGURE 8

Fit to the elastic $p\bar{p}$ polarization at 230 MeV, from the Nijmegen group[7].

By comparing the predicted polarizations (at almost the same energy) in Figs. 7 and 8, one sees that although the Paris and Nijmegen models agree reasonably well in the angular region where data exist, they differ strongly in their predictions for $P(\theta)$ near $\theta \approx 90°$. The Nijmegen model leads to large negative values of $P(\theta)$ here (as large as ≈ -0.7), while $P(\theta)$ remains positive at all angles for $E \approx 220$ MeV. The situation is similar for other spin observables, but much less dramatic for total cross sections. The measurement of spin quantities at LEAR will be crucial in choosing between various theoretical models.

The importance of $N\bar{N}$ spin measurements is also emphasized by a qualitative comparison of the spin and isospin dependence of the Nijmegen and Paris models. At any r and E, the potentials V_{ph}^{IS} of Eq. (8) for s-states are in the ratio

$$V_{ph}^{00} : V_{ph}^{10} : V_{ph}^{01} : V_{ph}^{11} = 1:0.05:0.88:0.28 \tag{10}$$

Comparing to Eq. (6), we see that V_{ph} displays a strong isospin dependence and a weaker spin dependence, the reverse of the situation for W in the Paris model. The off-diagonal elements V_A, which may be more directly comparable to W, are moderately isospin dependent but are taken to be independent of S, opposite to the trend displayed by W in ref. (29). It is clear that the present $N\bar{N}$ data are insufficient to settle the fascinating question of the degree of spin and isospin dependence of $N\bar{N}$ annihilation processes. Quantitative guidance from the quark/gluon picture is needed. Various other phenomenological models have been applied to the $N\bar{N}$ system, although no fits as detailed as those of the Paris and Nijmegen groups have been done. We mention separable potential[33] models, which have some motivation in the context of quark rearrangement models. These topics are treated more extensively in the review[34] of A. M. Green.

5. MICROSCOPIC MODELS OF $N\bar{N}$ ANNIHILATION

In Chap. 4, we discussed a variety of phenomelogical models for $N\bar{N}$ annihilation. We now turn to a class of models motivated by quantum chromodynamics (QCD), in which annihilation is described in terms of confined quarks (Q) and gluons (g), either through $Q\bar{Q}$ annihilation into g, or quark rearrangement processes. In principle, $N\bar{N}$ annihilation should be a good test of quark/gluon dynamics at short distances. Our goal is to try to establish the connection between the microscopic and phenomenological forms of the annihilation potential. Aside from the geometrical aspects of the problem, which involve convolutions of bag model wave functions for quarks, we also study the spin, isospin and energy dependence predicted by various microscopic models. It is really these features which enable us to differentiate between models, since the geometrical aspects (effective size of the absorptive region) of the problem are common to all approaches.

The simplest QCD motivated approach to $N\bar{N}$ annihilation is due to the Seattle group[35], who consider quark-antiquark annihilation into one gluon. The process $Q\bar{Q} \to g$ can only occur in the overlap volume of the bags confining the quarks. The gluon is treated as a plane wave, and the bags are assumed to remain spherical as they overlap. The final state $Q^2\bar{Q}^2g$ is considered as a "doorway state" leading to many complex reaction channels. It is assumed that this $Q^2\bar{Q}^2g$ configuration never finds its way back into the elastic channel (the familiar "never come back" approximation in nuclear physics, valid when the number of compound nuclear levels is large). Thus one can simply sum over final $Q^2\bar{Q}^2g$ states in order to obtain a model for W, without worrying how this configuration hadronizes into a final state containing color singlet mesons.

In ref. (35), the spatial wave function of the quarks was taken from the MIT bag model. A similar calculation using oscillator wave functions is given in ref. (36). The resulting[35] $N\bar{N}$ absorptive potential W(r) contains central, spin-spin and tensor components, each of which has the form

$$W_i(r) = (\alpha_S^*/R)f_i(r/R)$$
$$f_i(r/R) = \sum_{n=0}^{4} a_{ni}\,[2-(r/R)]^{n+4} \text{ for } r < 2R \tag{11}$$

where α_S^* is an effective QCD coupling constant, and R is the bag radius. For $r > 2R$, W(r) vanishes, since the spherical bags do not overlap.

The explicit spin-isospin dependence of the non-tensor part of W(r) is given[36] by the factor

$$W(r) \sim \left(243 + 9\underset{\sim}{\sigma}_N \cdot \underset{\sim}{\sigma}_{\bar{N}} - 27\,\underset{\sim}{\tau}_N \cdot \underset{\sim}{\tau}_{\bar{N}} - 25\,\underset{\sim}{\sigma}_N \cdot \underset{\sim}{\sigma}_{\bar{N}}\,\underset{\sim}{\tau}_N \cdot \underset{\sim}{\tau}_{\bar{N}}\right) \tag{12}$$

This can be used to give the ratios W^{IS}:

$$W^{00} : W^{10} : W^{01} : W^{11} = 0.18 : 0.65 : 1 : 0.49\ , \tag{13}$$

valid at all r and E.

Comparing with the result (6) for the phenomenological fit of the Paris group[29], we see that the one gluon model is qualitatively different: for instance, W^{00} is now the weakest rather than the strongest component.

The one gluon model was applied[35] to total and integrated elastic and charge exchange cross sections, with good fits being obtained with

$$\alpha_S^* \approx 10, \quad R \approx 0.9 \text{ fm}\ , \tag{14}$$

although a reasonable description of the data may be obtained in the whole range $0.6 \leq R \leq 1.1$ fm. These results yield a bag radius somewhat smaller than the original MIT model[37].

The one gluon model of annihilation has geometrical features very similar to that of the other models we have discussed, as shown in Fig. 9. The solid curves meet in the region $r \approx 0.7 - 0.8$ fm, which appears to define an effective $N\bar{N}$ strong absorption radius. It is clear that the behavior of W(r) for $r < 0.5$ fm is largely irrelevant; the data clearly do not constrain the

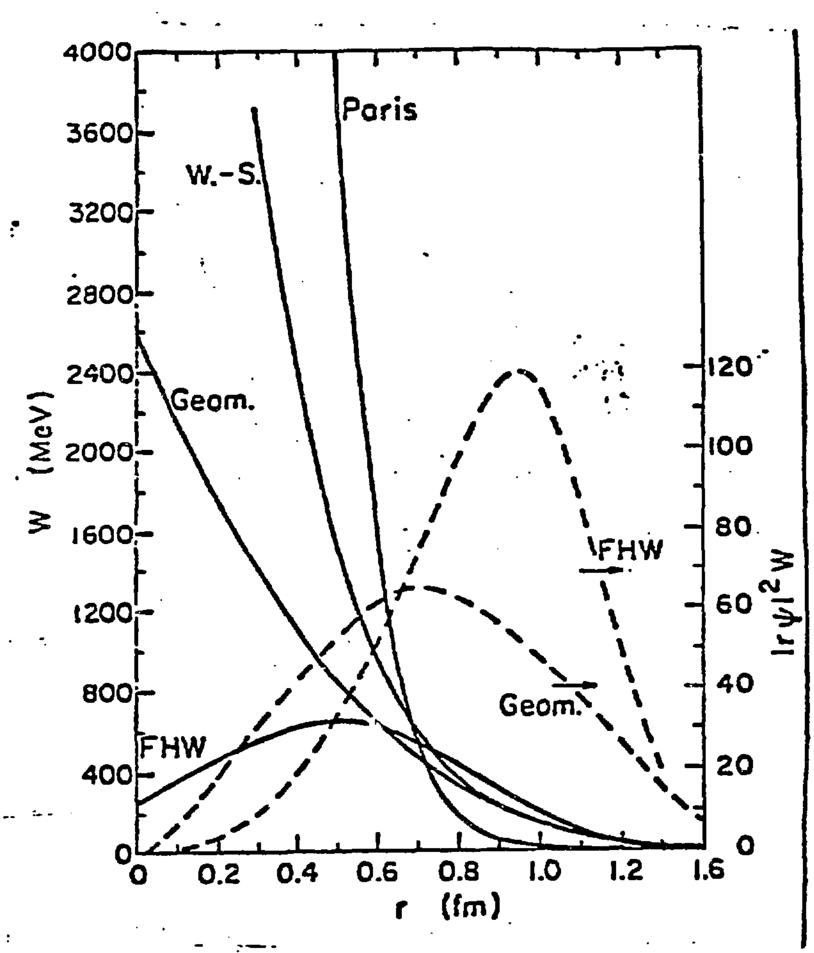

FIGURE 9

A comparison[35] of $^1S_0$ $\bar{p}p$ absorptive potentials (solid lines) for the models of Dover-Richard[28] (W.-S.), the Paris group[29], and the Seattle group[35]. For the latter, the $Q\bar{Q} \rightarrow g$ model (FHW) and a purely geometric model (Geom.) are shown. The dashed lines show the region of absorption (right-hand scale) for the atom 1s wave function.

radial shape of W(r) in this region. Note that the effective radius for the Paris analysis[29] is much the same as that for other models, although the radius parameter appearing in Eq. (5) is only 0.1 fm. In speaking of the "range" of the annihilation potential, the physically meaningful quantity is the effective range, which depends on both the well depth and the range parameter describing the radial shape.

Although the one gluon model can be arranged to give the correct $N\bar{N}$ geometrical properties by varying R and α_S^*, it has a number of faults, and is clearly not an adequate representation of the physics of $N\bar{N}$ annihilation. It is necessary to crank up α_S^* to large values in order to get the correct magnitude for the cross sections. The resulting value (Eq. (14)) is an order of magnitude larger than the perturbative value $\alpha_S \approx 1$-2. Thus α_S^* can only be considered as an effective coupling constant which simulates the summed influence of many higher order processes. Although higher order terms probably do not qualitatively alter the radial shape of W(r), there is no reason to suspect that the particular spin-isospin structure (12) obtained from the one gluon process is preserved in higher order. In fact, one expects the spin dependence to be considerably altered by multigluon and quark rearrangement graphs. A hint that the one gluon analysis provides the wrong spin-isospin mixture is seen in its very poor fits to the backward elastic data, which are sensitive to spin effects. The polarization data, which might also be illuminating, were not included[35] in the analysis. The one gluon model, through its neglect of any threshold effects relating to mesonic channels, yields an energy independent W(r). Any sensible microscopic model which takes account of specific channels will yield an energy dependence in the corresponding one channel approximation. In the Paris model[29], the fits are considerably improved by the energy dependence of W(r).

We now turn to a consideration of quark rearrangement models. In these approaches, the final state is automatically "hadronized" into physical mesons, so detailed comparisons with $N\bar{N}$ branching ratios into particular mesonic channels become feasible, as well as the description of total cross sections—possible already with far cruder models. This class of models has been reviewed by Green[34], so we will be brief.

Recent efforts by Maruyama and Ueda[38] have focused on the quark rearrangement diagram shown in Fig 10. This mechanism produces three meson states composed of π, η, ω and ρ mesons. Vector meson decay then leads to the correct pion multiplicity in the final state. The probability P for an $N\bar{N}$ system in channel $\{I,S\}$ to annihilate into mesons α, β, γ is taken to be

$$P(I,S,\alpha,\beta,\gamma) = b(I,S)C(I,S,\alpha,\beta,\gamma)g_\alpha g_\beta g_\gamma\, V(\alpha,\beta,\gamma) \qquad (15)$$

where $C(I,S,\alpha,\beta,\gamma)$ is an SU(6) overlap factor, g_α is the $q\bar{q}$ coupling strength to meson α (found to be approximately proportional to the mass m_α), V is the phase space factor (which generates an energy dependence), and b(I,S) takes account of initial state distortion effects. Eq. (15) was used[38] to fit the branching ratios for $N\bar{N}$ annihilation into three mesons; a good fit is obtained with seven free parameters. If P in

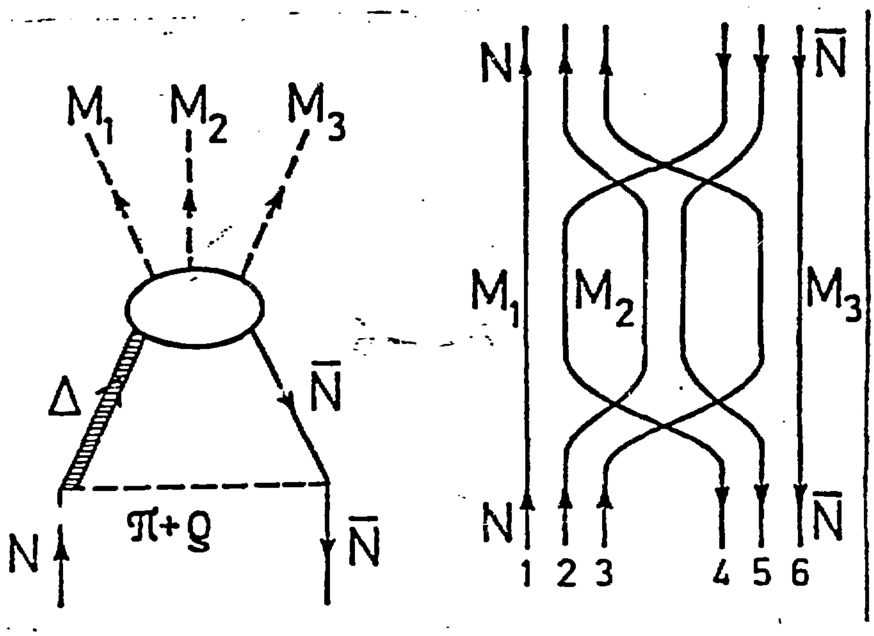

FIGURE 10
A quark rearrangement graph leading to a three meson intermediate state is shown on the right. An annihilation graph involving the Δ resonance is shown on the left (from ref. (34)).

Eq. (15) is summed over α, β, α, and identified with the absorptive strength W^{IS}, we obtain

$$W^{00} : W^{10} : W^{01} : W^{11} : = 1 : 0.57 : 0.44 : 0.36 \qquad (16)$$

Comparing with Eq. (6), we see that W^{00} is largest, as in the fit[29] to the $N\bar{N}$ scattering data, but the spin dependence is not as dramatic.

Through the phase space factor V, the effective W becomes quite energy dependent in the quark rearrangement model. Some channels involving vector mesons ($\rho^+\rho^-\pi^0$, $\rho^+\rho^-\eta$, $\omega\rho^+\rho^-$, for instance) have very large SU(6) strengths C, but do not contribute much near E = 0 due to their large mass. As E increases, these modes become dominant.

The quark rearrangement model has recently been refined by Green and his collaborators[39,40], in the form of a system of coupled equations for $N\bar{N}$ elastic and annihilation channels. The transition potential for $N\bar{N} \rightarrow M_1M_2M_3$ is non-local (and separable, if oscillator wave functions are used to calculate overlaps). In Eq. (39), a local approximation was applied to the equivalent one channel annihilation potential

$$V_{ann}^{IS}(r) + iW^{IS}(r) = \lambda e^{-\beta r^2} I(IS,E) \qquad (17)$$

The function I is rapidly increasing with energy; thus it is possible in principle to have some relatively narrow $N\bar{N}$ bound states ($E < 0$), while retaining very strong absorption at higher energies. If λ is adjusted phenomenologically, the $N\bar{N}$ data, including the backward elastic points, can be fitted well. It will be interesting to see whether or not the 180° fit can be reproduced when the full non-local coupled equations are solved. In ref. (40), the quark rearrangement model is generalized to include $N\bar{\Delta} + \bar{N}\Delta$ and $\Delta\bar{\Delta}$ intermediate states. The spin-isospin dependence of I (IS,E) is rather similar to Eq. (16), i.e. W^{00} is strongest and W^{11} is weakest at E = 0, and W^{00} generally remains the largest for E > 0. This is qualitatively similar to the Paris result[29] of Eq. (6), except that the total spread in W^{IS} values is only a factor of 2-3, rather than an order of magnitude or more.

A problem with these models is that the overall strength cannot be reliably calculated (a rough estimate is given in ref. (40)). Thus, as with the one gluon model (where $\alpha_S^* \approx 5\text{-}10\ \alpha_S$), there is the danger that the effect of higher order corrections and other mechanisms is being simulated by varying the overall strength of the annihilation potential, and that one is in fact not testing the validity of the mechanism at hand. A key point is the <u>spin-isospin dependence</u> of W: different mechanisms at the quark level lead to quite distinct predictions for W^{IS}. Presently, the data are not sufficient to obtain a sharp distinction between competing models: the measurement of spin observables in different isospin channels ($\bar{p}p \rightarrow \bar{p}p$, $\bar{n}n$ and $\bar{n}p \rightarrow \bar{n}p$) is crucial to further progress.

6. THE $\bar{N}$ AS A PROBE OF THE NUCLEUS

We mention briefly a few possibilities: i) $\bar{N}$ inelastic scattering, ii) quasi-stable few-body systems, iii) production of hypernuclei with $\bar{N}$'s.

The strong spin and isospin dependence of the $\bar{N}$ absorptive potential W^{IS} should show up as a characteristic selectivity in $\bar{N}$ inelastic scattering from nuclei. For instance, using the Paris model[29], it has been predicted[41] that the isoscalar, spin flip ($\Delta T=0$, $\Delta S=1$) modes of nuclei are strongly excited with $\bar{N}$'s. In a model where W is spin-isospin independent, these modes are only weakly excited, as is the case for nucleon inelastic scattering.

Another consequence of the spin-isospin dependence of W is that some relatively long-lived few-body systems containing an $\bar{N}$ may exist. For instance, if one believes that the two-body $N\bar{N}$ absorption is smallest for $I = S = 1$ (W^{11} in Eq. (6)), then one can try to exploit this selectivity by preparing the spin-isospin environment of an $\bar{N}$ in a nucleus so as to emphasize this channel. The prototype reaction would involve a deuteron:

$$\bar{p} + (d)_{S=1,I=0} \rightarrow p + (\bar{p}n)_{S=1,I=1}, \tag{18}$$

for instance $^6\mathrm{Li}(\bar{p},p)^6_{\bar{p}}\mathrm{H}$, where $^6_{\bar{p}}\mathrm{H}$ has the cluster structure $[\alpha \otimes (\bar{p}n)_{S=I=1}]_{1^+}$. If an $\bar{N}$ is attached to a core which is not spin-isospin saturated, the long range pion exchange term contributes to the Hartree field. In few-body systems, this effect will be relatively more important. The $\bar{N}$ wave function would be localized in this region of long-range attraction, and the resulting nucleus might be relatively long-lived. For instance, one could ask whether the addition of a $\bar{p}$ stabilizes the di-neutron: the relevant reaction would be $^3\mathrm{H}(\bar{p},p)(\bar{p}nn)_{1/2^+,I=3/2}$.

The coherent tensor forces which operate in the $N\bar{N}$ system also crop up in the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ reaction. Here the coherence is due to (K,K^*) rather than (π,ρ) exchanges. The observed $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ amplitudes display a marked spin dependence; large Λ and $\bar{\Lambda}$ polarizations are seen. This leads to the possibility[42] that the $(\bar{p},\bar{\Lambda})$ reaction on nuclear targets may be used to directly populate <u>unnatural</u> <u>parity</u> states of Λ hypernuclei, for example the 2^- member of the ground state doublet in $^{12}_{\Lambda}\mathrm{C}$. These are not seen in the (K^-,π^-) reaction, since spin-flip is absent at 0°, and small at non-zero angles. Via the $(\bar{p},\bar{\Lambda}\gamma)$ reaction, one could observe the M1 γ rays connecting Λ hypernuclear doublets, and thus obtain a handle on the spin dependence of the ΛN interaction. Note that $\bar{\Lambda}$-nuclei could be formed in the $(\bar{p},\Lambda)$ reaction, but the cross sections at 0° are predicted[42] to be about 3 orders of magnitude smaller than for $(\bar{p},\bar{\Lambda})$ and the $\bar{\Lambda}$ states are mostly rather broad.

The field of $\bar{N}$-nuclear interactions is a potentially fascinating one, and almost totally unexplored. We will have to leave it for a future talk.

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