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ANTIPROTON-NUCLEUS INELASTIC SCATTERING AND THE SPIN-ISOSPIN DEPENDENCE OF THE $N\bar{N}$ INTERACTION

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ABSTRACT

A general overview of the utility of antinucleon ($\bar{N}$)-nucleus inelastic scattering studies is presented, emphasizing both the sensitivity of the cross sections to various components of the $N\bar{N}$ transition amplitudes and the prospects for the exploration of some novel aspects of nuclear structure. We start with an examination of the relation between NN and $N\bar{N}$ potentials, focusing on the coherences pedicted for the central, spin-orbit and tensor components, and how these may be revealed by meausurements of two-body spin observables. We next discuss the role of the nucleus as a spin and isospin filter, and show how, by a judicious choice of final state quantum numbers (natural or unnatural parity states, isospin transfer $\Delta T=0$ or 1) and momentum transfer q, one can isolate different components of the $N\bar{N}$ transition amplitude. Various models for the $N\bar{N}$ interaction which give reasonable fits to the available two-body data are shown to lead to strikingly different predictions for certain spin-flip nuclear transitions. We suggest several possible directions for future $\bar{N}$-nucleus inelastic scattering experiments at LEAR, for instance the study of spin observables which would be accessible with polarized $\bar{N}$ beams, charge exchange reactions, and higher resolution studies of the $(\bar{p},\bar{p}')$ reaction. We compare the antinucleon and the nucleon as a probe of nuclear modes of excitation.

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1. INTRODUCTION

With the advent of the LEAR facility, one has begun to exploit the potentialities of antinucleon ($\bar{N}$)-nucleus inelastic scattering as a probe both of nuclear sturcture and the spin-isospin dependence of the two-body $N\bar{N}$ interaction. One anticipates that useful structure information will be obtained, because of the uniqueness of the nuclear response to the $\bar{N}$, and the possibility of comparative studies of ($\bar{p}$,$\bar{p}$'), (p,p'), e,e'), (π,π') and other inelastic scattering reactions.

Medium energy nucleon-nucleus scattering has been an effective way to investigate spin-isospin modes in nuclei, excited by a spin transfer ΔS and isospin transfer ΔT to the target nucleus. For example, the systematics of non-normal parity $\Delta S = \Delta T = 1$ transitions have been mapped out, and the very intriguing suppression of this Gamow-Teller strength[1] has been the object of much discussion. Using standard models such as the distorted wave impulse approximation[2] (DWIA), one is able to relate the strength of spin-isospin (and other) modes in the nuclear response to dominant components of the nucleon-nucleon (NN) transition operator. By varying the momentum transfer q to the nucleus, one can emphasize central (small q) or tensor and/or spin-orbit (higher q) components of the NN effective amplitude. A similar strategy has been suggested[3,4] for inelastic $\bar{N}$ scattering. It is one of the main purposes of this paper to exhibit the extent to which we can extract constraints on the two-body central and spin dependent $N\bar{N}$ interactions from an analysis of the existing LEAR data[5,6].

In Sect. 2, we explore the relation between the NN and $N\bar{N}$ meson exchange interactions, with emphasis on spin dependent observables for the $N\bar{N}$ system. We discuss phenomenological $N\bar{N}$ potentials in Sec. 3, which contain a very strong short range annihilation potential W(r) accounting for decay modes $N\bar{N}\to$mesons, absent for the NN channel. These models are used in Sec. 4 to construct transition amplitudes t appropriate to nuclear inelastic scattering processes of specified ΔS and ΔT. We emphasize how a strong spin dependence of W(r), present in the Paris model[7], shows up as a notable enhancement in isoscalar spin-flip inelastic transitions. In Sects. 5 and 6, we interpret the available data[5,6]) on the inelastic process $^{12}C(\bar{p},\bar{p}')^{12}C^*$ at 46 and 180 MeV, leading to various discrete states of ^{12}C. The excitation of isoscalar natural parity states [2^+(4.4 MeV) and 3^-(9.6 MeV)] is well described in a parameter-free DWIA framework, indicating the close connection between inelastic nuclear scattering and the underlying spin-isospin averaged $N\bar{N}$ central amplitude t_0. For spin-flip transitions to unnatural parity states [e.g. 1^+(12.7 MeV) and 1^+(15.1 MeV) in ^{12}C], the situation is less clear, since the preliminary LEAR data[8] do not permit us to easily isolate the cross section due to these excitations. With finer energy resolution ($\lesssim$ 300 keV or so) the separation of spin flip cross sections could be achieved, and one could obtain a significant constraint on the isovector tensor component of the $N\bar{N}$ interaction. Recommendations for higher resolution inelastic scattering studies with antinucleon beams are summarized in Sect. 7.

2. RELATION BETWEEN THE NN and $N\bar{N}$ INTERACTIONS: SPIN OBSERVABLES

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. (9), contributions to V arise from exchanges of nonets of scalar, pseudoscalar and vector mesons. In the work of the Stony Brook[10)] and Paris[11)] 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[9)] or other parametrized cutoffs[11)], for instance), 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 <u>real</u> 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[12] of the NN system, and their effect on the observables. The mosty dramatic effect of coherence in the NN system is seen in the $^{33}P_0$ 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 $\vec{\sigma}_1 \cdot \vec{\sigma}_2$, $\vec{L} \cdot \vec{S}$ 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 $L = J \pm 1$.

The coherence of $N\bar{N}$ tensor forces for $I = 0$ is most readily seen in spin observables[13], for instance the $\bar{p}p$ elastic polarization $P(\theta)$. If the spin-spin and spin-orbit parts of the $N\bar{N}$ potential are set to zero, $P(\theta)$ remains essentially unchanged, while if tensor forces are neglected, $P(\theta)$ almost vanishes. In contrast to the NN system, where $P(\theta)$ 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 $P(\theta)$ (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.

To summarize, a careful measurement of $N\bar{N}$ spin observables could provide an important constraint on the summed strenght 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.

3. PHENOMENOLOGICAL $N\bar{N}$ POTENTIALS

Simple black disk or boundary condition models are sufficient for a semi-quantitative understanding of $N\bar{N}$ 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, a full optical model treatment is necessary.

An early optical model fit to the $N\bar{N}$ data was carried out by Bryan and Phillips[14]. They used an OBE Model for the t-channel meson exchange potential, and a local Woods-Saxon form

$$V_{ann}(r) + iW(r) = -(V_0 + iW_0)/1 + \exp\big((r-R)/a\big) \qquad (1)$$

for the complex annihilation potential. They chose $V_0 = 0$, $W_0 = 62$ GeV, $R = 0$ and $a = 1/6$ fm. This type of analysis was later redone by Dover and Richard[15], who used the Paris potential[11] 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[16] which had become available. A family of annihilation potentials was found[15] which fits the data (Model I with $V_0 = 21$ GeV, $W_0 = 20$ GeV, $R = 0$, $a = 1/5$ fm and Model II with $V_0 = W_0 = 500$ MeV, $R = 0.8$ fm, $a = 1/5$ fm are two examples). 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[15] appeared, $\bar{p}p$ backward ($\theta = 174°$) elastic scattering was measured with high precision by Alston-Garnjost et al.[17]. Although ref. (15) 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 (1). The Paris group[7] reanalyzed the $N\bar{N}$ data including all differential cross section and polarization information, using a more flexible phenomenological form

$$W(r) = \{g_c(1 + f_c E) + g_{SS}(1 + f_{SS}E)\vec{\sigma}_1\cdot\vec{\sigma}_2 + g_T S_{12} + \frac{g_{LS}}{4m^2}\vec{L}\cdot\vec{S}\,\frac{1}{r}\frac{d}{dr}\}\,\frac{K_0(2mr)}{r} \quad (2)$$

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 $1/2m \approx 0.1$ fm (held fixed), which reduces to a Yukawa form for large r. The form (2) is rather general, incorporating arbitrary spin, isospin and energy (E) dependence, as well as L and J dependence through the spin-orbit ($\vec{L}\cdot\vec{S}$) and tensor (S_{12}) terms. No real annihilation potential was considered, and an updated version[18] of the Paris potential was used for the t-channel exchange part.

Since numerous free parameters are involved in these fits[7], 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 $P(\theta)$, it is difficult to disentangle the effects of $\vec{\sigma}_1\cdot\vec{\sigma}_2$, $\vec{L}\cdot\vec{S}$ and S_{12} terms. Nevertheless, some interesting conclusions can be drawn from this analysis[7]. Firstly, the spin and isospin dependence of W(r) in ref. (7) is very strong. For s-waves, the values of W^{IS} stand in the ratio

$$W^{00}: W^{10}: W^{01}: W^{11} = \begin{cases} 1:0.81:0.11:0.073, & E = 0 \\ 0.92:1.0.15:0.035, & E = 100 \text{ MeV} \end{cases} \quad (3)$$

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) has a dramatic consequence in $\bar{N}$ inelastic scattering on nuclei[4]: isoscalar, spin-flip ($\Delta S = 1$) modes of nuclei, which are excited only very weakly in nucleon inelastic scattering, become very prominent in the N inelastic response function. This matter is discussed further in Sect. 6.

Recently, the Nijmegen group[19] has advanced a coupled channel model for $N\bar{N}$ scattering. They solved a relativistic Schrödinger equation, including an explicit coupling to effective mesonic annihilation channels. By comparing the predicted elastic polarizations $P(\theta)$, one sees that the Paris[7] and Nijmegen[19] models agree well in the angular region where data exist, but differ strongly in their predictions for $P(\theta)$ near $\theta = 90°$. The situation is similar for other spin obsrevables. This is due to the strong spin dependence of $N\bar{N}$ annihilation in ref. (7), which is absent in ref. (19).

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[20] models, which have some motivation in the context of quark rearrangement. The measurement of two-body $N\bar{N}$ spin observables at LEAR will be crucial in choosing between different theoretical models.

To summarize, we have introduced two models for the $N\bar{N}$ optical potential, in order to compare their predictions for $(\bar{N},\bar{N}')$ inelastic cross sections on nuclear targets. The models of Dover and Richard[15], referred to as DRI and DRII in subsequent sections, are characterized by an annihilation potential which is independent of spin and isospin. On the other hand, the model of Coté et al[7], labelled "PARIS" in the following discussion, has W(r) which is much stronger in the spin singlet than in the spin triplet state. These models give strikingly different predictions for isoscalar spin flip transitions in nuclei, as discussed in Sect. 6.

4. THE TRANSITION AMPLITUDES FOR $\bar{N}$ INELASTIC SCATTERING FROM NUCLEI

The two body $N\bar{N}$ potential $V_{N\bar{N}}$ is written in the form

$$\begin{aligned} V_{N\bar{N}} = {} & V_c + V_\sigma \vec{\sigma}_N \cdot \vec{\sigma}_{\bar{N}} + V_\tau \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} + V_{\sigma\tau} \vec{\sigma}_N \cdot \vec{\sigma}_{\bar{N}} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} \\ & + V_{LS} \vec{L}\cdot\vec{S} + V_{LS\tau} \vec{L}\cdot\vec{S} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} + V_T S_{12} \\ & + V_{T\tau} S_{12} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} + V_{LS2} Q_{12} + V_{LS2\tau} Q_{12} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} \\ & + iW + V_{ann}, \end{aligned} \tag{4}$$

where $\vec{L}\cdot\vec{S}$, Q_{12}, and S_{12} denote the usual two particle spin-orbit, quadratic spin-orbit, and tensor operators, respectively. The real potentials V_c, V_σ, V_{LS}, V_T, and V_{LS2} and their $\vec{\tau}_N \cdot \vec{\tau}_{\bar{N}}$ counterparts are assumed to arise from t-channel meseon exchanges. The potentials $V_{N\bar{N}}$ of models DRI, DRII and PARIS (Sect. 3) are converted to $N\bar{N}$ scattering t matrices by solving the nonrelativistic Schrödinger equation for nonidentical fermions. There are several ways to express the various independent terms in the transition operator for inelastic antinucleon scattering from nuclei. We adopt the formulation used by Love and Franey[2] in order to facilitate comparison with NN results and to make more transparent the connection between the $N\bar{N}$ t matrix and the spin-isospin excitations expected to dominate the nuclear response. Thus, in analogy with the potential given in Eq. (4), the t matrix is written in the form

$$
\begin{aligned}
t = {} & t_0^c + t_\sigma^c \vec{\sigma}_N \cdot \vec{\sigma}_{\bar{N}} + t_\tau^c \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} + t_{\sigma\tau}^c \vec{\sigma}_N \cdot \vec{\sigma}_{\bar{N}} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}} \\
& + (t_0^{LS} + t_0^{LS} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}}) \vec{L} \cdot \vec{S} + (t_0^T + t_\tau^T \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}}) S_{12}(\hat{q}) \\
& + (t_0^{TQ} + t_\tau^{TQ} \vec{\tau}_N \cdot \vec{\tau}_{\bar{N}}) S_{12}(\hat{Q}),
\end{aligned} \tag{5}
$$

where the various components t_i are functions of the c.m. energy and the momentum transfer $q(\vec{q} = \vec{p}_i - \vec{p}_f$, where $\vec{p}_i$ and $\vec{p}_f$ are the incoming and outgoing momenta in the two particle c.m. system, respectively). The spin-orbit ($\vec{L} \cdot \vec{S}$) and tensor $S_{12}(\hat{k})$ operators are defined, in momentum space, as in Ref. 2. Note that in defining the various components of the $N\bar{N}$ t matrix those central terms with a subscript τ (σ) are isovector (spin-vector) operators in the nuclear target space for ($\bar{N}$,$\bar{N}$') reactions on nuclei. The last term in Eq. (5) is a function of the total momentum $\vec{Q} = \vec{p}_i + \vec{p}_f$.

In general, the low q components of the transition operator are responsible for exciting low angular momentum nuclear final states near the peak cross section for such states, while the components dominant at high q are responsible for exciting high spin states. It is useful to record which final nuclear states can be excited via various terms in the transition operator assuming a J = T = 0 nuclear target initial state. Thus, we summarize below the opeators able to excite various final states of spin J and parity π in transitions with spin and isospin transfers ΔS and ΔT:

	Non-spin flip ($\Delta S = 0$)	Spin flip ($\Delta S = 1$)
Isoscalar ($\Delta T = 0$)	$\pi = (-1)^J$ t_0, t_0^{LS}	$\pi = (-1)^{J,J+1}$ $t_\sigma, t_0^{LS}, t_0^T$, t_0^{TQ}
Isovector ($\Delta T = 1$)	$\pi = (-1)^J$ t_τ, t_τ^{LS}	$\pi = (-1)^{J,J+1}$ $t_{\sigma\tau}, t_\tau^{LS}, t_\tau^T$, t_τ^{TQ}

(6)

To compute cross sections for $\bar{N}$ inelastic scattering on nuclei, we use the distorted wave impulse approximation (DWIA). In DWIA, many-body cross sections and spin observables are directly related to the underlying two-body t-matrices. This approximation has been frequently applied[21]) to medium energy nucleon inelastic scattering with success. In this approach, the inital and final state distorting potentials are calculated from the same t-matrix used to obtain transition operators of different spin-isospin character in Eq. (6). For J = T = 0 target, the elastic scattering optical potential is obtained from a convolution of the spin-isospin averaged amplitude t_0 with the nuclear density ρ. Nuclear medium convections to this simple "$t\rho$" approximation have been discussed in the talk of von Geramb[22] at this conference. The comparison between DW theory and the LEAR data[5,6] is also treated in detail in ref. (22) for elastic $\bar{N}$-nucleus scattering. Here, we focus attention on <u>inelastic</u> $\bar{N}$ scattering, which tests other components of the t-matrix besides t_0, in particular the tensor components t^T which enter strongly in spin-flip transitions.

In plane wave approximation (PWA), the inelastic differential cross section $d\sigma/d\Omega$ has the form

$$\frac{d\sigma}{d\Omega} \propto \left|t_i\right|^2 + \left|t_i^{LS}\right|^2 \text{ (normal parity state, } \Delta S = 0 \text{ dominant)}$$

$$\propto \left|t_i^{LS}\right|^2 + \left|T_{\sigma i} + t_i^{T\alpha}\right|^2 + \left|t_{\sigma i} + t_i^{T\beta}\right|^2 + \xi\left|t_{\sigma i} + t_i^{T\gamma}\right|^2) \text{(non-normal}$$

parity, $\Delta S = 1$), ($I = \tau$ for $\Delta T = 1$ transitions only), where (7)

$$t_i^{T\alpha} = t_i^T - 2t_i^{TQ},\ t_i^{T\beta} = t_i^T + t_i^{TQ},\ t_i^{T\gamma} = -2t_i^T + t_i^{TQ}$$

which shows explicitly the interplay between central, spin-orbit and tensor amplitudes. In Eq. (7), we have assumed a specific angular momentum transfer and suppressed nuclear structure factors (except for ξ, which is equal to 2 for stretched configurations[2]). We see that central and tensor amplitudes interfere in $\Delta S = 1$ transitions, while the spin-orbit contributions add incoherently. In PWA, the asymmetry A associated with the excitation of the various spin-isospin modes is given by

$$A(q) = \frac{2(t_{Ri}^{LS}t_{Ii}^{c} - t_{Ii}^{LS}t_{Ri}^{c})}{\left|t_i^c\right|^2 + \left|t_i^{LS}\right|^2} \text{ (normal parity, } \Delta S = 0 \text{ dominant)},$$

$$A(q) = \frac{2[t_{Ri}^{LS}(t_{Ii}^{c}+t_{Ii}^{T\beta}) - t_{Ii}^{LS}(t_{Ri}^{c}+t_{Ri}^{T\beta})]}{\left|t_i^{LS}\right|^2 + \left|t_i^c+t_i^{T\alpha}\right|^2 + \left|t_i^c+t_i^{T\beta}\right|^2 + \xi\left|t_i^c+t_i^{T\gamma}\right|^2} \text{ (non-normal parity, } \Delta S = 1 \text{ dominant)}, \quad (8)$$

where R(I) denotes the real (imaginary) parts of the t matrix.

The existence of inelastic scattering data obtained with polarized proton beams has led to considerable interest in understanding the origins of nonzero values of P − A (polarization minus analyzing power) in (p,p'). Besides explicit Q value effects, such mechanisms as exchange, energy, and velocity dependence of the transition operator and multistep processes have been discussed[23] as contributors to (P − A). Since exchange effects are absent for $N\bar{N}$, and the spin-isospin components have different energy and momentum transfer dependence than those appearing in the NN opeator, the study of (P − A) for antinucleon inelastic scattering should provide useful additional information. In Sect. 6, we present some predictions for P ± A in $\bar{N}$ inelastic scattering.

Let us now examine some of the characteristic features of the $N\bar{N}$ transition amplitudes. The q dependence of the central components t_0, t_σ, t_τ and $t_{\sigma\tau}$ for several typical energies is displayed in Fig. 1. These curves refer to the PARIS model[7] introduced in Sect. 3. These central terms dominate the inelastic nuclear response for small q. We note that $|t_0|$ is by far the largest amplitude: the $\Delta S = \Delta T = 0$ inelastic cross sections will thus be the most prominent. Relative to t_σ, t_τ and $t_{\sigma\tau}$, the amplitude t_0 is even more dominant for $\bar{N}N$ than for NN. Thus spin flip excitations induced by the $\bar{N}$ will be difficult to isolate in a coarse resolution $(\bar{p},\bar{p}')$ experiment, if natural parity T = 0 states lie close in energy.

Next to $|t_0|$, Fig. 1 shows that $|t_\sigma|$ is the most important amplitude for the PARIS model. The term $|t_\sigma|$ plays a crucial role in exciting low spin $\Delta T = 0$ non-normal parity states. Thus if the PARIS model[7] is correct, $(\bar{p},\bar{p}')$ inelastic scattering could be a valuable tool for exciting isoscalar spin-flip resonances. The relative strength of $|t_\sigma|$ in the Paris model is directly connected to the strong spin dependence of the absorptive potential W(r). In the Dover-Richard models DRI and DRII, this spin dependence is absent, and $|t_\sigma|$ is very small, as for the case of (p,p'). For the DR models, the Gamow-Teller $N\bar{N}$ transition amplitude $t_{\sigma\tau}$ is the most important (after t_0), a situation analogous to the (N,N') case.

The strong model dependence of t_σ suggests a simple test for a strong spin dependence of W(r), namely the <u>ratio</u> of $(\bar{p},\bar{p}')$ cross sections to isoscalar and isovector spin flip excitations. The special case of the 1^+ states at 12.7 MeV (T = 0) and 15.1 MeV (T = 1) in ^{12}C was considered in Ref. (4). Differences of an order of magnitude for such ratios at q = 0 were found in the PARIS and DR models. We return to this point in Sect. 6.

The energy dependence of $|t_0|$ at q = 0 is shown in Fig. 2 for the case of (N,N') and $(\bar{N},\bar{N}')$. We note that $|t_0|$ is considerably larger for $N\bar{N}$ than for NN, and has the opposite energy dependence. These characteristic differences show up strikingly in the inelastic scattering to isoscalar natural parity states (see Sect. 5). The amplitude t_0 is largely imaginary for $N\bar{N}$, reflecting the influence of the large absorptive potential.

The comparison of Gamow-Teller amplitudes $|t_{\sigma\tau}|$ for NN and $N\bar{N}$ is given in Fig. 3. Unlike the situation for $|t_0|$, we see that $|t_{\sigma\tau}|$ is considerably suppressed for $N\bar{N}$ relative to NN. This is again the effect of strong absorption for the $\bar{N}$. Note that there is substantial model dependence for the $\bar{N}$ case, which shows up in small angle cross sections to unnatural parity states.

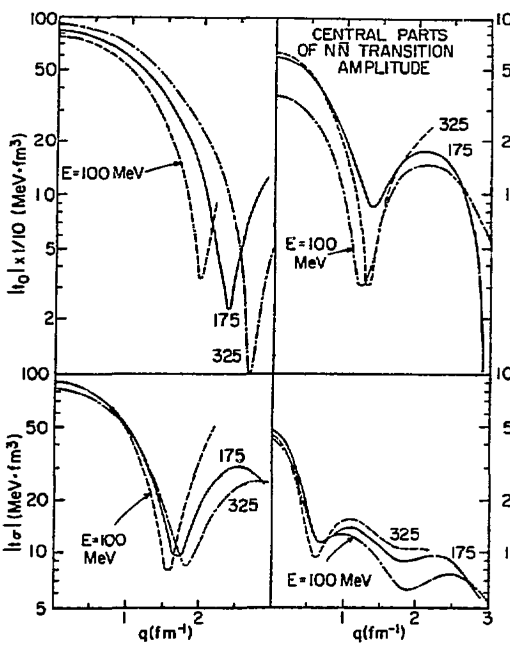

Fig. 1. Magnitude of the central parts t_0, t_σ, t_τ, and $t_{\sigma\tau}$ of the $N\bar{N}$ transition amplitudes for several lab kinetic energies E as a function of momentum transfer q (PARIS Model).

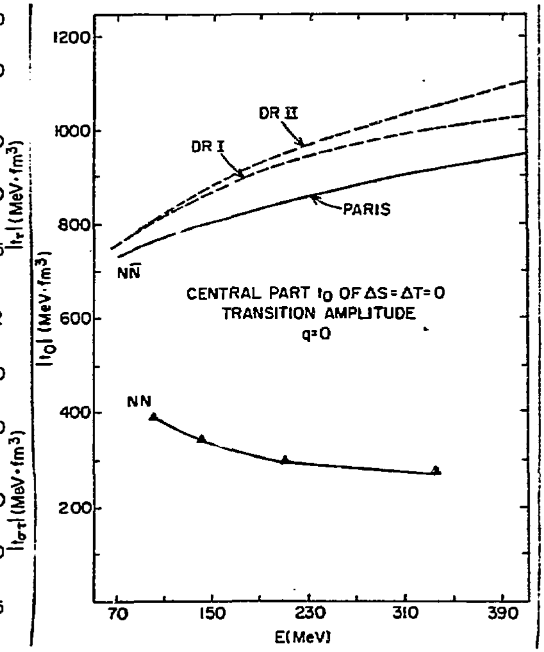

Fig. 2. Spin-isospin average amplitudes $|t_0|$ for q = 0, as a function of E. The NN curve is from ref. (2), and the various $N\bar{N}$ models are from refs. (7,15).

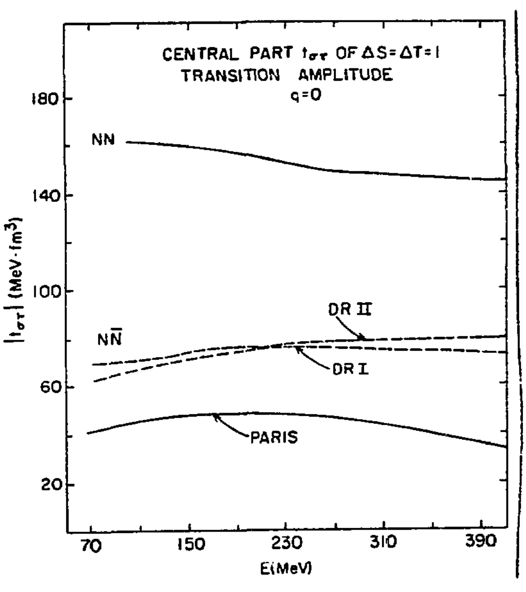

Fig. 3. Gamow-Teller transition amplitudes $t_{\sigma\tau}$ at q = 0, as a function of E. The NN curve is from Love and Franey[2], while the $N\bar{N}$ amplitudes refer to the PARIS[7] or Dover-Richard[15] models.

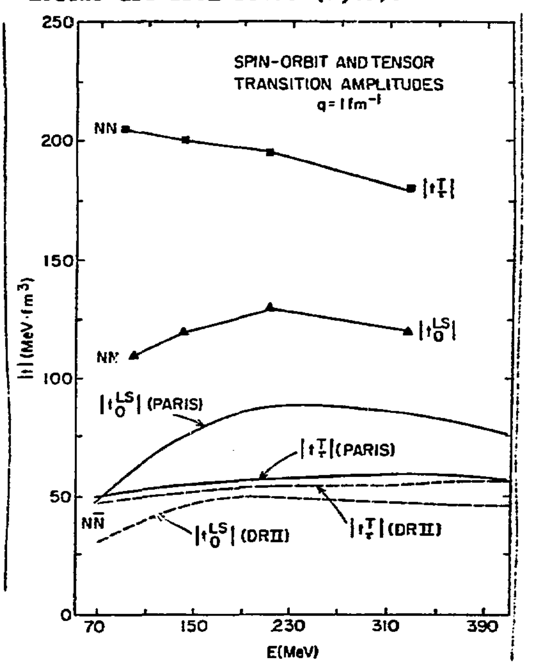

Fig. 4. Isoscalar spin-orbit and isovector tensor amplitudes t_0^{LS} and t_τ^T at q=1 fm^{-1} for the NN and $N\bar{N}$ cases.

For larger q, the non-central parts of t control the nuclear response. The isovector tensor and isoscalar spin-orbit pieces $|t_\tau^T|$ and $|t_0^{LS}|$ at $q = 1\ fm^{-1}$ are displayed in Fig. 4. For both the NN and $N\bar{N}$ cases, these are considerably larger than $|t_0^T|$ and $|t_\tau^{LS}|$. From a meson exchange viewpoint, this reflects the dominant role of isovector π and ρ exchange for tensor amplitudes and isoscalar ω,σ exchange for spin-orbit amplitudes. Note that once again, as for $|t_{\sigma\tau}|$, the strong absorption for the $N\bar{N}$ system leads to a suppression of $|t_\tau^T|$ and $|t_0^{LS}|$ relative to the NN case. Thus unnatural parity spin flip states at $q \sim 1\ fm^{-1}$ are expected to be more weakly excited by $\bar{N}$'s than by N's. This is borne out by the DWIA calculations presented in Sect. 6.

5. EXCITATION OF NATURAL PARITY STATES BY ANTINUCLEONS

In addition to elastic scattering measurements, the first LEAR experiments on $^{12}C(\bar{p},\bar{p}')^{12}C^*$ by Garreta et al[5,6] deduced cross sections for the low-lying natural parity states in ^{12}C, namely the 2^+ (4.4 MeV, T = 0) and 3^- (9.6 MeV, T = 0) levels. The 2^+ data at 47 MeV are shown in Fig. 5, while the 2^+ and 3^- data at 180 MeV are shown in Figs. 6 and 7. The (p,p') data[24] at 46 MeV and 185 MeV (ref. 25) are also shown for comparison. One notes that at 46 MeV, the 2^+ cross section at peak is about a factor of three smaller for $(\bar{p},\bar{p}')$ than for (p,p'), while at 180 MeV the situation is reversed, with the $(\bar{p},\bar{p}')$ cross section to the 2^+ now a factor of three <u>larger</u> than for $(\bar{p},\bar{p}')$. This is a consequence of the opposite energy dependences of $|t_0|$ for NN and $N\bar{N}$ shown in Fig. 2, and represents a reassuring confirmation of the DWIA approach as well as the spin-isospin averaged properties of the theoretical $N\bar{N}$ amplitudes. Note that $|t_0|$ dominates $\Delta T = 0$ $(\bar{p},\bar{p}')$ transitions to natural parity states in the angular range shown in Figs. 5-7. The solid curves in Figs. 5-7 correspond to the PARIS model, but the results for models DRI and DRII are practically the same for the 2^+ and 3^- cross sections. Any reasonable model for the $N\bar{N}$ interaction will give about the same results for $|t_0|$, the largest amplitude, if it reproduces the observed $N\bar{N}$ elastic and total cross sections. Different models can vary considerably in their predictions for spin-dependent amplitudes (e.g. t_σ), however, since these are relatively unconstrained by the available two-body $N\bar{N}$ data.

The nuclear structure transition amplitudes used for the $(\bar{p},\bar{p}')$ DWIA calculations were scaled to fit the experimental longitudinal (e,e') form factors. This yields the good agreement in absolute normalization shown in Figs. 5-7. The positions of the maxima and minima in the angular distributions are also very well reproduced. The maxima (minima) in the 2^+ and 3^- cross sections correspond to minima (maxima) in the $\bar{p}$ elastic scattering angular distribution. This is the well-known Blair phase rule[26], and is typical of a strong absorption situation.

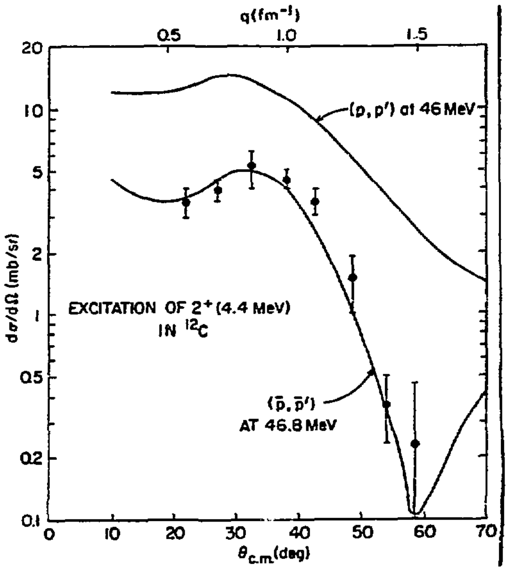

Fig. 5. Angular distribution for the excitation of 2^+ (4.4 MeV, T = 0) state in ^{12}C by protons and antiprotons at 46 MeV. The data are from Garreta et al[5].

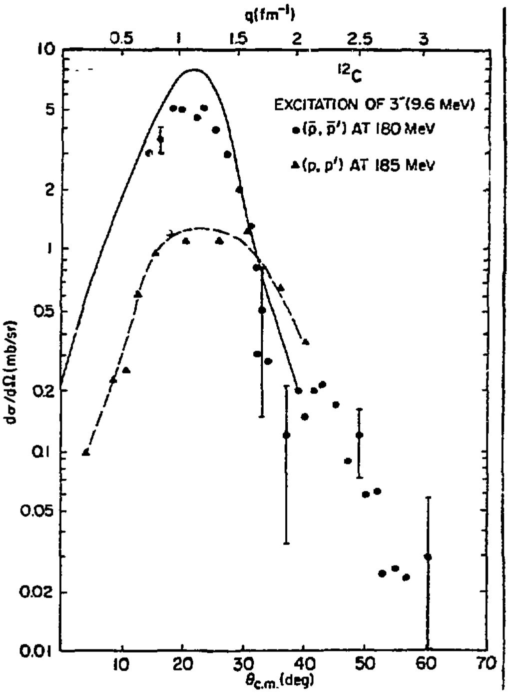

Fig. 7. Cross sections for exciting the 3^- (9.6 MeV, T = 0) state in ^{12}C by $\bar{p}$ and p at 180 MeV; data and curves as in Fig. 6.

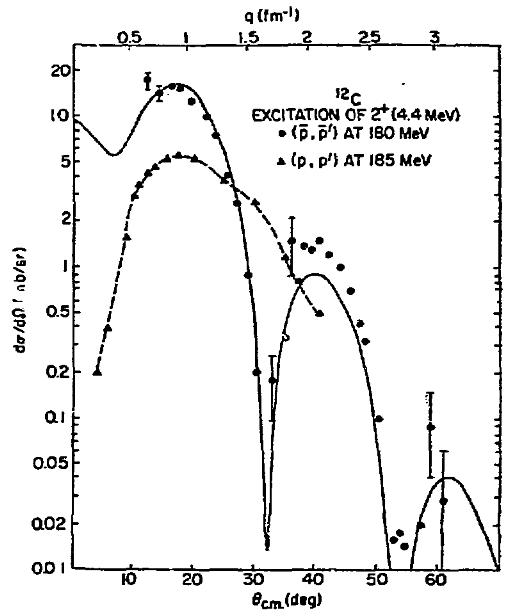

Fig. 6. Excitation of the 2^+ (4.4 MeV, T = 0) state by p and $\bar{p}$ inelastic scattering at 180 MeV. The data are from refs. (6,25), while the solid curve is a DWIA calculation from refs. (4,27).

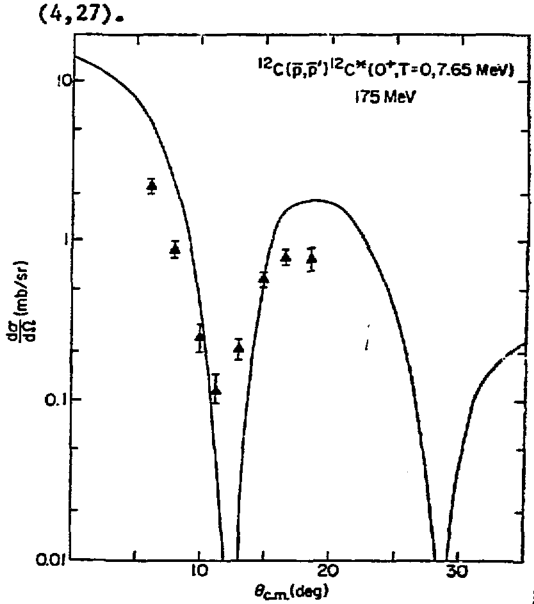

Fig. 8. Angular distribution for the 0^+ (7.65 MeV, T = 0) level in ^{12}C, excited in ($\bar{p}$,$\bar{p}$') at 175 MeV. The preliminary data are from ref. (8), and the solid curve is a DWIA calculation[27].

There are preliminary LEAR data[8] on the excitation of the 0^+ (7.65 MeV, T = 0) level in ^{12}C with $\bar{p}$'s at 180 MeV. These data are shown as triangles in Fig. 8, together with the results of a DWIA calculation using the PARIS $N\bar{N}$ amplitudes. The 0^+ (g.s.) → 0^+ (7.65 MeV) transition is dominated by the same (strong) amplitude $|t_0|$ responsible for the 2^+ and 3^- excitations. The agreement with theory is reasonable for the angular shape, but not so good for the absolute normalization. This transition was discussed in more detail by von Geramb[22] at this conference.

To summarize, the agreement between theory and experiment is rather good for $(\bar{p},\bar{p}')$ inelastic scattering to collective I = 0 natural parity levels in ^{12}C. Here one tests the spin-isospin averaged $N\bar{N}$ amplitude $|t_0|$, which is relatively well determined by optical model fits to the $N\bar{N}$ data. There seems to be no need for large corrections to the free space amplitude $|t_0|$ due to nuclear medium effects. This is due to the strongly absorbing character of the $\bar{N}$ optical potential, which restricts the inelastic reaction to the far nuclear surface where the density is low.

6. SPIN FLIP EXCITATIONS

We now turn our attention to the excitation of unnatural parity states via the $(\bar{p},\bar{p}')$ reaction. Such spin flip excitations are driven by the central amplitudes t_σ (for $\Delta T = 0$) and $t_{\sigma\tau}$ (for $\Delta T = 1$) at small q and the spin-orbit and tensor pieces t^{LS} and t^T at larger q. These components of the $N\bar{N}$ interaction are less well determined than the dominant term t_0. In principle, one would like to use $(\bar{p},\bar{p}')$ cross sections to unnatural parity nuclear states to derive some constraints on the two-body spin dependent $N\bar{N}$ amplitudes. In practice this goal has not yet been realized, because of the experimental difficulty of isolating small spin flip excitations from a large background of $\Delta T = \Delta S = 0$ states excited by t_0.

We now focus on the excitation of 1^+ and 2^- states in ^{12}C via the $(\bar{p},\bar{p}')$ reaction. As mentioned above, for small angle inelastic $\bar{N}$ scattering ($\theta \lesssim 5°$), the central parts t_σ ($\Delta T = 0$) and $t_{\sigma\tau}$ ($\Delta T = 1$) provide the most important contributions to the unnatural parity transition amplitudes. In this region the DR and PARIS models are sharply distinguished by the ratio $|t_\sigma/t_{\sigma\tau}|^2$, which is small in the former and large in the latter case. At $\theta = 0°$, for energies $100 < E < 300$ MeV, we find[4)]

$$R_t = \left|t_\sigma/t_{\sigma\tau}\right|^2 \approx 4 \quad \text{(PARIS model)}, \qquad \approx 1/9 \quad \text{(DR model)}, \tag{9}$$

The large difference in this ratio between the two models is a direct consequence of the very strong spin dependence of the $N\bar{N}$ absorptive potential in the PARIS model[7].

One measure of the ratio R_t is provided by the ratio R of the N cross section to the 1^+ excited state in ^{12}C at 12.7 MeV (T = 0, excited by t_σ at small θ) divided by that to the state at 15.1 MeV (T = 1, excited by $t_{\sigma\tau}$). These two states have similar nuclear structure factors, and in the plane wave approximation at θ = 0°, neglecting the tensor parts of t, we would have just $R = R_t$. Abso ve effects modify this simple result but in a calculable way.

The results at E = 175 MeV for the ratio

$$R(\theta) = [d\sigma(1^+, T = 0)/d\Omega] \times [d\sigma(1^+, T = 1)/d\Omega]^{-1} \tag{10}$$

Table 1.

θ_{cm} (deg)	R(θ)[PARIS]	R(θ)[DR]
0	0.44	0.05
5	0.60	0.11
10	0.38	0.15
15	0.30	0.16

are shown in Table 1, while the predicted cross sections to the $1^+(T = 1)$ state at 15.1 MeV are shown in Fig. 9. Apparently the small angle region (θ < 5°) offers an excellent opportunity to distinguish between the PARIS and DR models. For a model with strong spin dependence of W, such as PARIS the ratio, R, is <u>enhanced by an order of magnitude</u> relative to a model with no spin dependence, such as DR, so that for the PARIS model the 12.7 MeV state should be observable in the inelastic $\bar{p}$ spectrum. Note that the cross sections (Fig. 9) to the 15.1 MeV state are very similar in the two models, even at smaller angles, so most of the change in R comes from the large variation in the cross section to the 12.7 MeV state. As θ increases, R becomes less definitive as a means of distinguishing between models for the two-body $N\bar{N}$ interaction. For θ > 5°, the central parts of the $N\bar{N}$ t-matrix no longer provide the most important contribution. For example, in model P we have for the 1^+ (15.1 MeV) transition

$$d\sigma/d\Omega = \begin{matrix} 0.21,\ 0.21,\ 0.33 \text{ mb/sr at } 0°, \\ 0.0014,\ 0.0028,\ 0.20 \text{ mr/sr at } 10°, \end{matrix} \tag{11}$$

for {C, C + LS, C + LS + T}, i.e., central terms only, central + spin-orbit and central + spin-orbit + tensor terms included in the calculation of dσ/dΩ. Even at 0°, we see that tensor terms are fairly important. For θ = 10°, the tensor terms in fact dominate. Another point worth noting is that R is considerably less than R_t [eq. (9)], the PWA result. This difference arises from the stronger damping of the isoscalar transition due to absorption.

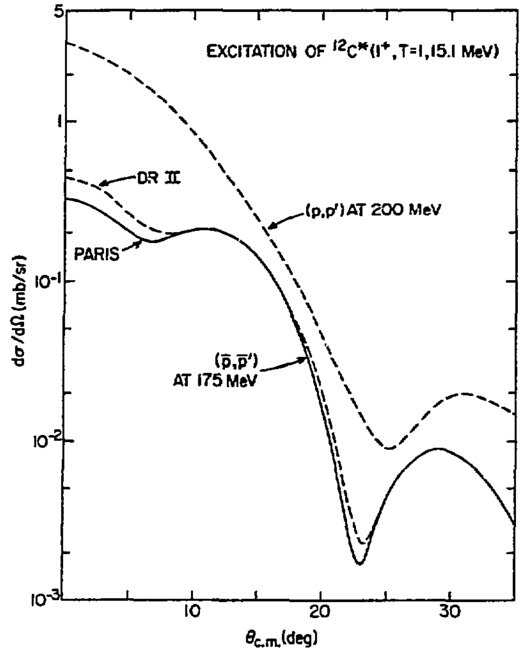

Fig. 9
Predicted (p,p') cross sections[4,27] in DWIA for exciting the 1^+(15.1 MeV, T = 1) level in ^{12}C. Results for the Paris[7] and Dover-Richard[15] NN models are shown, as well as the measured (p,p') cross section[28] for comparison.

A similar effect is seen in (p,n) calculations, and is attributed to the longer range of the one-pion-exchange contribution to $t_{\sigma\tau}$, which is absent in t_σ. For the PARIS model, the damping factors (ratio of PWA to DWIA results) at 0° are 16 for the 1^+ (T = 0) state and 2.8 for the 1^+ (T = 1) state.

The predicted[27] angular distribution shown in Fig. 9 for the 1^+ (15.1 MeV) excitation in ^{12}C displays a peak at small $\theta_{c.m.}$ due primarily to $t_{\sigma\tau}$ and a second maximum at larger angle arising from t_τ^T. The difference between the PARIS and DR models is not very significant, particularly for the tensor contribution. The (p,p') cross section[28] at 200 MeV is shown in Fig. 9 for comparison. Note that the $(\bar{p},\bar{p}')$ cross section to the 1^+ (15.1 MeV) state is predicted to be significantly smaller than that for (p,p') for all angles. That this must be so is seen directly from Figs. 3 and 4, which show the strong suppression of $t_{\sigma\tau}$ and t_τ^T for $N\bar{N}$ relative to NN. In addition, the absorptive effect due to wave function distortion further reduces the $(\bar{p},\bar{p}')$ cross sections relative to (p,p'). Recently, preliminary values[8] for the ^{12}C $(\bar{p},\bar{p}')$ cross sections at 180 MeV (summed over the excitation energy range 13.2 - 17 MeV) of about 1 mb/sr ($\theta_{c.m.}$ = 9.5 ± 4°) and 1.35 mb/sr ($\theta_{c.m.}$ = 15 ± 4°) have been given. These cross sections are much larger (even exceeding those for (p,p')!) than the values given in Fig. 9 for the 1^+ (15.1 MeV) level, and they rise rather than drop with increasing angle. Clearly, the large observed cross section cannot be identified with the 1^+ (15.1 MeV) level alone. It is known[28,29] from (p,p'), (e,e'), (π,π') and (α,α') studies that a broad level exists in ^{12}C centered at 15.3 MeV. This level, from its appearance in (α,α'), is evidently a natural parity, isoscalar excitation. As such, it will be strongly excited by the dominant $N\bar{N}$ amplitude t_0. If we assume the 15.3 MeV level is a 2^+, T = 0 state for which there is evidence from (α,α'), we can estimate its cross section by taking from Fig. 6 the measured peak cross section for the 2^+ (4.4 MeV, T = 0) state in ($\bar{p},\bar{p}'$) at 180 MeV, about 15 mb/sr for $\theta_{c.m.} \approx 15°$, and multiplying by the ratio of 2^+ (4.4 MeV)to 2^+ (15.3 MeV) cross sections as seen in (p,p'), or (α,α') of about 1/15. By this scaling argument, we estimate[27] a cross section for the $^{12}C(\bar{p},\bar{p}')^{12}C$(15.3 MeV, T = 0) reaction of order 1 mb/sr. This is much larger than the peak cross section of ~0.15 mb/sr predicted for the 1^+ (15.1 MeV) state, and about the same as the total observed[8] cross section in the 15 MeV region at $\theta_{c.m.} \approx 15°$. If the 15.3 MeV level were assumed to be 3^-, T = 0, the same scaling arguments go through. In any case, it is clear that the energy resolution (~1 MeV) of the first LEAR experiments[4,5,8] was not sufficient to resolve the clump of states in ^{12}C in the region of 14–16 MeV excitation. The very interesting unnatural parity (1^+ and 2^-) spin flip excitations in this energy region, which could in principle reveal the strength of spin dependent $N\bar{N}$ transition amplitudes, are masked by the very strong $\Delta S = \Delta T = 0$ excitation of the 15.3 MeV level. Higher resolution experiments are called for in order to isolate the spin flip strength in the ($\bar{p},\bar{p}'$) reaction. Alternatively, one could consider the study of the ($\bar{p},\bar{n}'$) charge exchange reaction, as a means of eliminating the dominant $\Delta T = 0$ background. The ($\bar{p},\bar{n}'$) reaction is similar to the (n,p) reaction, in that for N = Z targets one studies analogues of the Gamow-Teller resonances, while for N > Z nuclei, the (p,n') process can be used to investigate $T_>$ resonances without the contamination of lower isospin configurations.

We have also considered[4] the excitation of the 2^- states in ^{12}C at 18.3 MeV (T = 0) and 19.4 MeV (T = 1). Millener's wave functions[30] were used in the calculations after being modified to describe (p,p') cross sections at 200 MeV[28] and near 400 MeV[31]. The calculated peak cross sections occur near $0.6 fm^{-1}(\theta_{c.m.} \approx 12°)$ for the 18.3 MeV excitation and near $0.7 fm^{-1}(\theta_{c.m.} \approx 15°)$ for the 19.4 MeV excitation. For the 19.4 MeV excitation the calculated peak cross sections ($\approx$ 0.3 mb/sr) are essentially equal in the DR and PARIS models. For the 18.3 MeV state the cross section predicted by the PARIS model ($\approx$ 0.3 mb/sr) is nearly five times larger than that given by the DR model. This suggests that these transitions should also be helpful in distinguishing between different $N\bar{N}$ interactions.

Other spin observables in ($\bar{p},\bar{p}'$) reactions could also be very useful in constraining the spin dependence of the $N\bar{N}$ amplitudes. For instance, the elastic polarization $P(\theta)$ in $\bar{p}$ + ^{12}C is significantly larger in the PARIS than in the DR model (at $\theta_{c.m.}$ = 40, we predict[4] P = 0.53 for the PARIS model and 0.25 for model DR, for example). Note that the quantity P–A (polarization minus asymmetry (see Eq. 8)) is in general not zero for inelastic scattering, and offers a sensitive test of the spin dependence of t. In Fig. 10, we

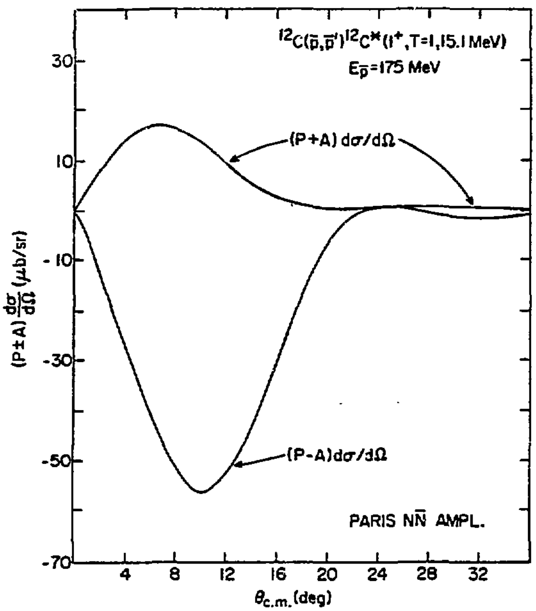

Fig. 10
Spin observables (P±A) dσ/dΩ for the 1^+ (15.1 MeV) state in ^{12}C, excited in $(\bar{p},\bar{p}')$ at 175 MeV.

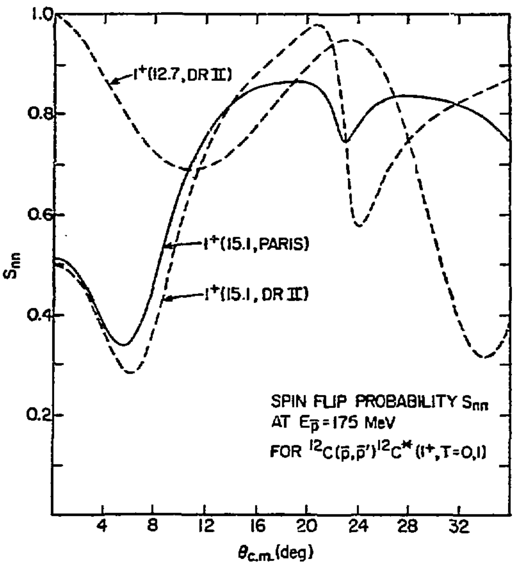

Fig. 11
Spin-flip probability S_{nn} for the 1^+ (15.1 MeV) state in ^{12}C, excited in $(\bar{p},\bar{p}')$ at 175 MeV.

display DWIA predictions[27] of (P±A) dσ/dΩ for the 1^+ (15.1 MeV) level in ^{12}C. The spin flip probability[32] S_{nn} for the 1^+ (T = 0 and 1) levels is shown in Fig. 11. Large spin effects are evident from these figures. The measurement of quantities like A and S_{nn} requires a polarized $\bar{p}$ (or $\bar{n}$) beam, however, which currently does not exist at LEAR.

Another intriguing consequence of a strong spin dependence of the N$\bar{N}$ absorptive potential W(r) is the possibility of relatively narrow excitations in the $\bar{N}$NN and $\bar{N}$NNN systems. This has been investigated by Baltz et al[33], who suggest that an $S_X = 3/2$, $I_X = 1/2$ state X of the $\bar{N}$NN system could be sufficiently long-lived to be observable in the $^3He(\bar{p},p)X$ reaction. For energies E = 100–200 MeV, the production cross section $(d\sigma/d\Omega)_{0°}$ for X is estimated[33] to be of order 0.5 mb/sr. If X has a width Γ < 15 MeV or so, it could be observable in the $(\bar{p},p)$ reaction above the large background[34] of exit protons from $\bar{p}$ annihilation followed by proton knockout by the annihilation pions. Such $(\bar{p},p)$ or $(\bar{p},n)$ experiments with ^3He or ^4He targets should be considered at LEAR.

7. RECOMMENDATIONS FOR THE ACOL ERA

The problem of $\bar{N}$-nucleus inelastic scattering has two main aspects. On the one hand, one can view inelastic $\bar{N}$-nuclear processes as a reflection of the spin and isospin dependence of the underlying two-body N$\bar{N}$ amplitudes. The connection between two-body and many-body $\bar{N}$ amplitudes is made explicit and transparent via the DWIA, an appropriate approximation at the intermediate energies available at LEAR. The nucleus can be fruitfully used as a spin-isospin filter (by choosing J^{π} and T of the nuclear state being excited) or as a discriminator of central or spin-orbit/tensor interactions (by choosing the momentum transfer q) in order to test theories of the two-body $N\bar{N}$ interaction. On the other hand, once the input $N\bar{N}$ amplitudes are known, one could utilize the unique features of the $\bar{N}$ as a probe to uncover some novel aspects of nuclear structure. At this stage, we are exploring the first aspect: we pick nuclear excited states of well-known character, for which detailed wave functions are available from studies of other reactions such as (e,e'), (π,π'), (p,p'), etc., and we try to test our models for the two-body force. For transitions excited by the spin-isospin averaged $N\bar{N}$ amplitude t_0, there is impressive consistency between the two-body models and the 2^+ and 3^- cross sections in ^{12}C measured[5,6] at LEAR. These natural parity, isoscalar excitations are more strongly excited in ($\bar{p}$,$\bar{p}$') by roughly <u>two orders of magnitude</u> than the predicted unnatural parity spin flip states (1^+,2^-). To test the spin dependent central and tensor amplitudes t_{σ}, $t_{\sigma\tau}$ and t_{τ}^{T}, for instance, <u>high resolution</u> ($\bar{p}$,$\bar{p}$') studies will be required. For p-shell targets, an energy resoltuion of 200-300 keV should be sufficient to separate some of the interesting spin flip levels from the large $\Delta S = \Delta T = 0$ background. The ($\bar{p}$,$\bar{n}$') reaction also merits attention. It offers another method (complementary to (p,n)) of studying the quenching of Gamow-Teller strength in nuclei. If a significant part of this quenching is due to Δ-hole admixtures (Δ (1236) is a J = T = 3/2 baryon resonance) in nuclear wave functions, the $\bar{p}$ could be a powerful tool in elucidating this question. The π and ρ contributions to the $N\bar{N} \rightarrow \Delta\bar{N}$ transition potential are <u>coherent</u>, so one might expect (N,N') inelastic scattering to be sensitive to Δ-hole components.

Spin observables such as P±A and S_{nn} are predicted[27] to exhibit strong angular and energy variations which mirror the spin dependence of the two-body $N\bar{N}$ amplitudes, particularly the isovector tensor component t_{τ}^{T}. If polarized $\bar{N}$ beams become available in the ACOL era, it would be interesting to measure such quantities and, even more importantly, the two-body $N\bar{N}$ spin observables[13], for which large effects of the coherent tensor force due to pion and vector meson exchange are predicted.

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