Antinucleon as a probe of nuclear spin and isospin excitations

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Using two models for the antinucleon-nucleon ($\overline{\rm N}$N) interaction, we obtain complex, energy dependent $\overline{\rm N}$N transition operators t appropriate for ($\overline{\rm N}$,$\overline{\rm N}'$) inelastic scattering studies on complex nuclei. It is shown that the spin-isospin dependence of the $\overline{\rm N}$N annihilation potential plays an important role in determining the dominant spin-isospin modes in the nuclear response. In particular, for the most realistic of our $\overline{\rm N}$N models, a large spin dependent component t_σ is obtained, leading to the strong excitation of isoscalar spin-flip states; this term is suppressed in the corresponding NN t matrix. The central spin and isospin independent term, t_0^c, is large for $\overline{\rm N}$N, at all relevant momentum transfers q. At high q the isoscalar spin-orbit (t_0^{LS}) and isovector tensor (t_τ^T) components are important. Cross section and analyzing power predictions for $\overline{\rm N}$ inelastic scattering as well as corrections due to energy and density dependence are discussed.

Intermediate energy nucleon-nucleus scattering continues to be an effective means for investigating diverse spin-isospin modes in nuclei. In addition to the strong excitation of normal parity, $\Delta T=\Delta S=0$ and isobaric analog $\Delta S=0$, $\Delta T=1$ states, one finds that at higher projectile energies, non-normal parity ($\Delta S=\Delta T=1$) transitions can dominate the nuclear response both at low momentum transfer q (Gamow-Teller states) and high q ("stretched" states). By using models such as the distorted wave impulse approximation (DWIA), one can trace the strength of spin-isospin modes in the nuclear response directly to dominant components of the nucleon-nucleon (NN) transition operator.[1-5] For example, the importance of high-spin states at high q can be understood in terms of the strong tensor and spin-orbit terms in the NN t matrix.[5] On the other hand, the difficulty in studying low spin $\Delta S=1$, $\Delta T=0$ nuclear states can be related to a small spin-spin component in the NN interaction.[5] The information obtained from (p,p′) and (p,n) data is enhanced by corroborative information obtained from related studies such as (e,e′) and (π,π').

With the advent of the low energy antiproton ring (LEAR) program at CERN, one is motivated to consider the potentialities of antinucleon-nucleus inelastic scattering as a probe of nuclear structure. One anticipates that useful information will be obtained, both because of the uniqueness of the nuclear response to the antinucleon probe, and because there will be some regions of overlap for states also easily studied in, for example, (p,p′), (e,e′), or (π,π') reactions.

The ($\overline{\rm N}$,$\overline{\rm N}'$) reaction has a special relationship to the (N,N′) reaction. The $\overline{\rm N}$N system offers the same spin-isospin degrees of freedom as NN. However, the detailed structure of the $\overline{\rm N}$N potential, although intimately related to the meson exchange NN potential via the G-parity transformation, is quite different from that of the NN potential. For example, the $\overline{\rm N}$N potential features an extremely strong isospin singlet ($T=0$) tensor component and a weaker two-particle spin-orbit ($\vec{\rm L}\cdot\vec{\rm S}$) potential compared to the NN system.[6] Thus, since one expects the t matrix to reflect at least some of the characteristics of the potential (see, however, the conclusions for the spin-orbit and tensor components of the t matrix obtained herein) and, as mentioned above, the nuclear response features can be related to the transition operator, there may be significant new features in the $\overline{\rm N}$ induced nuclear response.

There are additional features that distinguish the $\overline{\rm N}$N from the NN interaction. These are expected to have a dramatic effect on the qualitative features of the nuclear response. The $\overline{\rm N}$N interaction contains a very strong short range annihilation potential, denoted by $W(r)$, which may be spin-isospin and energy dependent. The potential $W(r)$ accounts for decay modes $\overline{\rm N}{\rm N}\rightarrow$ mesons, which are absent for the NN channel. Thus, in contrast to the nucleon, the $\overline{\rm N}$ is a strongly absorbed probe (mean free path <0.5 fm, comparable to the pion near the 3-3 resonance). One expects a strong influence on the $\overline{\rm N}$N transition operator coming from, for example, cross terms of the real potential

$$V(r,\vec{\sigma}_{\rm N},\vec{\sigma}_{\overline{\rm N}},\vec{\tau}_{\rm N},\vec{\tau}_{\overline{\rm N}})$$

and the annihilation part

$$W(r,\vec{\sigma}_{\rm N},\vec{\sigma}_{\overline{\rm N}},\vec{\tau}_{\rm N},\vec{\tau}_{\overline{\rm N}}) .$$

Another difference between the NN and $\overline{\rm N}$N interactions is that exchange terms are not present in the latter. Since much of the energy dependence [and, for selected states, important contributions[7] to the differential cross section and differences of spin observables ($P-A$)] originates in the NN exchange terms,[5] qualitative differences in the nuclear response owing to the lack of exchange terms in ($\overline{\rm N}$,$\overline{\rm N}'$) inelastic scattering could lead to useful new information.

In the present article, we explore the qualitative features expected for $\overline{\mathrm{N}}$-nucleus inelastic scattering, based on two models for the $\overline{\mathrm{N}}\mathrm{N}$ transition operator. Such studies have been useful guides for (p,p′) and for strongly absorbed probe-nucleus inelastic scattering such as (π,π') in the 3-3 resonance region.[8] We concentrate on the following points:

(1) the relative strength of the various components (central, tensor, spin-orbit, etc.) present in the $\overline{\mathrm{N}}\mathrm{N}$ t matrix, as a function of the underlying model for the real and imaginary $\overline{\mathrm{N}}\mathrm{N}$ potentials;

(2) the implications of the obtained t matrix for the excitation of various spin-isospin components in the nuclear response. One novel possibility is the appreciable excitation of low spin non-normal parity isoscalar "resonances";

(3) a comparison of various possible complications (such as medium modifications and Fermi motion) potentially important in both (N,N′) and $(\overline{\mathrm{N}},\overline{\mathrm{N}}')$ reactions, and their effect on predicted cross sections and spin observables such as $P-A$.

It is anticipated that the $\overline{\mathrm{N}}\mathrm{N}$ t matrix discussed in this paper will be applied using standard DWIA computer codes to systematically study the $(\overline{\mathrm{N}},\overline{\mathrm{N}}')$ reaction on nuclei, much as (p,p′) and (π,π') have been investigated previously.

We consider two models for the two body $\overline{\mathrm{N}}$-N potential, which we assume can be written in the form

$$(V\equiv V(\,|\vec{r}_{\mathrm{N}}-\vec{r}_{\overline{\mathrm{N}}}|\,)\,,$$

$$\begin{aligned}V_{\overline{\mathrm{N}}\mathrm{N}}&=V_c+V_\sigma\vec{\sigma}_{\mathrm{N}}\cdot\vec{\sigma}_{\overline{\mathrm{N}}}+V_\tau\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}+V_{\sigma\tau}\vec{\sigma}_{\mathrm{N}}\cdot\vec{\sigma}_{\overline{\mathrm{N}}}\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}\\&\quad+V_{LS}\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}+V_{LS\tau}\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}+V_TS_{12}\\&\quad+V_{T\tau}S_{12}\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}+V_{LS2}Q_{12}+V_{LS2\tau}Q_{12}\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}\\&\quad+iW+V_{\mathrm{ANN}}\,,\end{aligned}\tag{1}$$

where $\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}$, 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 $\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}$ counterparts are assumed to arise from t-channel meson exchanges. We base our study on two models for the $\overline{\mathrm{N}}\mathrm{N}$ potential.

In both models I and II, the real t-channel meson exchange potential $V_t(r)$ is obtained from the NN interaction of the Paris group[9,11] by the G-parity transformation (the sign of π and ω exchanges is changed, while two pion exchange remains the same). In model I, the earlier version[9] of the Paris potential was used,[10] with a short range cutoff of the form

$$\begin{aligned}V_t(r)&=V_{\mathrm{Paris}}\,(r_0)\quad r\le r_0\\&=V_{\mathrm{Paris}}\,(r)\quad r>r_0\,,\end{aligned}$$

where $r_0=0.8$ fm. In model I, we assume a complex annihilation potential of the form

$$V_{\mathrm{ANN}}(r)+iW(r)=-(V_0+iW_0)/[1+\exp(r/a)]\,.\tag{2}$$

In this work, we adopt the parameters $V_0=21$ GeV, $W_0=20$ GeV, and $a=0.2$ fm. In Ref. 10, it is shown that this choice allows one to obtain a good fit to the integrated $\overline{\mathrm{N}}\mathrm{N}$ inelastic, elastic, and charge exchange cross sections for $\overline{\mathrm{N}}$ laboratory kinetic energies between 80 and 430 MeV. This model[10] does tend to underestimate the backward elastic $\bar{\mathrm{p}}\mathrm{p}$ cross section. We include model I for "background" purposes. In this model the spin-isospin dependence of the nuclear response more closely reflects the $\{I,S\}$ dependence of the t-channel meson exchange potential, since the annihilation potential $V_{\mathrm{ANN}}+iW$ is taken to be spin and isospin independent.

In model II, the $\overline{\mathrm{N}}\mathrm{N}$ potential is taken from Coté *et al.*[12] Here $V_t(r)$ is taken, with the appropriate G parity transformation, from the version of the Paris potential given by Lacombe *et al.*[11] One assumes a spin-isospin and (linearly) energy dependent purely imaginary annihilation potential (i.e., $V_{\mathrm{ANN}}=0$) of the form

$$W(r)=\left[W_c+W_\sigma\vec{\sigma}_1\cdot\vec{\sigma}_2+W_{LS}\frac{1}{r}\frac{d}{dr}\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}+W_TS_{12}\right]K_0(\mu r)/r\,,\tag{3}$$

where $W_c=\alpha+\beta E$, $W_\sigma=\gamma+\delta E$, etc. The strength parameters are adjusted separately for each isospin channel. $K_0(\mu r)$ is a modified Bessel function of range

$$\frac{1}{\mu}=\frac{1}{2M_{\mathrm{N}}}=0.1\text{ fm}\,.$$

The parameters in $W(r)$ and in the short range cutoff used for the real part are adjusted[12] to reproduce all existing $\mathrm{N}\overline{\mathrm{N}}$ data (including 180° elastic $\bar{\mathrm{p}}\mathrm{p}$ scattering). Velocity dependent terms[12] are included exactly in our calculation. Model II has the feature that $W(r)$ depends rather strongly on spin and isospin (absorption is strongest for $S=T=0$ and weakest for $S=T=1$) as well as energy. In model II, the strong spin-isospin dependence of $W(r)$ has a marked effect on the spin-isospin selectivity of the inelastic nuclear response.

The potentials of models I and II are converted to $\overline{\mathrm{N}}\mathrm{N}$ 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. We adopt the formulation used by Love and Franey[5] in order to make comparison with earlier NN results and to make more transparent the connection between the $\overline{\mathrm{N}}\mathrm{N}$ t matrix and the spin-isospin resonances expected to dominate the nuclear response. Thus, in analogy with the real part of the potential given in Eq. (1), the t matrix is written in the form

$$\begin{aligned}t&=t_0^c+t_\sigma^c\vec{\sigma}_{\mathrm{N}}\cdot\vec{\sigma}_{\overline{\mathrm{N}}}+t_\tau^c\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}+t_{\sigma\tau}^c\vec{\sigma}_{\mathrm{N}}\cdot\vec{\sigma}_{\overline{\mathrm{N}}}\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}}\\&\quad+(t_0^{LS}+t_\tau^{LS}\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}})\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}+(t_0^T+t_\tau^T\vec{\tau}_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}})S_{12}(\hat{q})\\&\quad+(t_0^{TQ}+t_\tau^{TQ}\tau_{\mathrm{N}}\cdot\vec{\tau}_{\overline{\mathrm{N}}})S_{12}(\hat{Q})\,,\end{aligned}\tag{4}$$

where the various components t_i are functions of the c.m. energy and the momentum transfer q ($\vec{\mathrm{q}}=\vec{\mathrm{p}}_i-\vec{\mathrm{p}}_f$, where $\vec{\mathrm{p}}_i$ and $\vec{\mathrm{p}}_f$ 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. 5. Note that in defining the various components of the $\overline{N}N$ t matrix those central terms with a subscript τ (σ) are isovector (spin-vector) operators in the nuclear target space for $(\overline{N},\overline{N}')$ reactions on nuclei. The last term in Eq. (4) is a function of the total momentum $\vec{Q}=\vec{p}_i+\vec{p}_f$, and contains the quadratic spin-orbit part.

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 operators 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^c	$\pi=(-1)^{J,J+1}$	$t_\sigma^c, t_0^{LS}, t_0^T, t_0^{TQ}$
Isovector ($\Delta T=1$)	$\pi=(-1)^J$	t_τ^c	$\pi=(-1)^{J,J+1}$	$t_{\sigma\tau}^c, t_\tau^{LS}, t_\tau^T, t_\tau^{TQ}$

The magnitude $|t_i|$, momentum transfer dependence, and energy dependence of the various components of t are shown in Figs. 1 and 2. Some of the general characteristics of the results are summarized below. For the "central" components, t_i^c, of the transition operator we note the following.

The energy dependence and magnitude of t_0^c (not shown) are very similar in models I and II; both give a slowly rising $|t_0^c|$ which is about an order of magnitude larger than the $t_{\sigma\tau}^c$ component for model I. So, as for other probes, the spin-isospin independent term, t_0^c, is dominant at low momentum transfer. Except for t_τ^c in model II, the $q=0$ t matrices display rather little energy dependence between 100 and 300 MeV. The most dramatic (and potentially important) difference between the two models occurs for the t_σ^c term, which is predicted to be quite important (second only to t_0^c) for model II and the least important term in model I. The term t_σ^c plays a crucial role in exciting low spin $\Delta T=0$, non-normal parity states. Thus, if model II is qualitatively correct, $(\overline{N},\overline{N}')$ inelastic scattering should be valuable for exciting isoscalar spin-flip resonances. If model I were correct t_σ^c would, as in the case of NN scattering, be so small that the study of such states would be very difficult. The strong excitation of low J non-normal parity isoscalar states in $(\overline{N},\overline{N}')$ in model II is directly related to the strong spin-dependence of the imaginary part of the $\overline{N}N$ annihilation potential. From the gentle energy dependence of the various central terms shown in Fig. 1, one sees that there is no particular $\overline{N}$ energy which is strongly preferred for studying low angular momentum isoscalar spin modes in nuclei, although $|t_\sigma^c|$ is largest at lower energies.

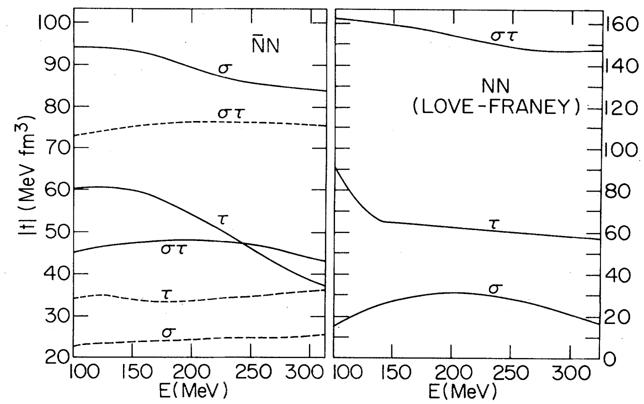

FIG. 1. The magnitudes of various spin-isospin components of the central part t^c of the $\overline{N}N$ t matrix are shown on the left as a function of laboratory kinetic energy E for fixed momentum transfer $q=0$. The solid curves correspond to model II [Coté *et al.* (Ref. 12)] for the $\overline{N}N$ potential, while the dashed curves refer to model I [Dover and Richard (Ref. 10)]. On the right, we display the corresponding components of the NN t matrix for comparison. The NN curves are taken from Love and Franey (Ref. 5).

For nucleon-nucleon scattering, all the $t_i^c(q)$ have a pronounced dip for $200\le q\le 400$ MeV/c in the energy range from 100 to 200 MeV. This dip originates from a change in sign of the NN interaction, depending on the range. In contrast, the $\overline{N}N$ t matrix shown in Fig. 2 has no minimum below 400 MeV/c for the important t_0^c component. The other $\overline{N}N$ central components do have broad

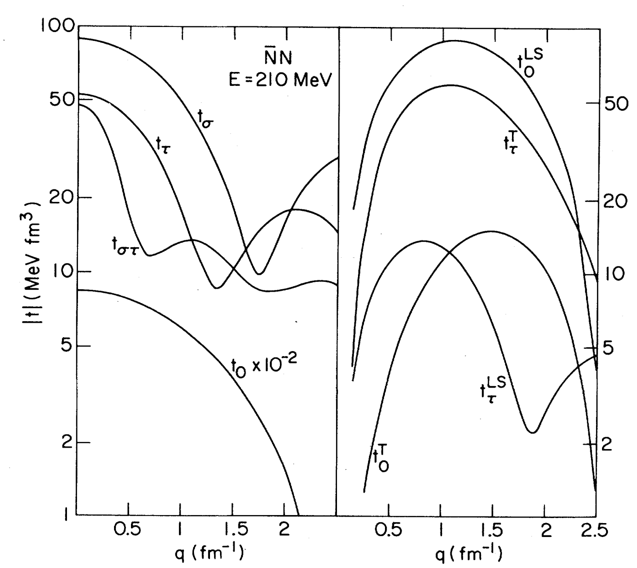

FIG. 2. The magnitude of various components of the $\overline{N}N$ t matrix as a function of q for fixed $E=210$ MeV. The central components are shown on the left and the spin-orbit and tensor components are on the right. All curves refer to model II of Ref. 12.

minima below $q=400$ MeV/c, but these are apparently owing to diffraction and not zeros in the underlying interaction.

Before discussing the results for the tensor and spin-orbit terms, it may be helpful to indicate that for the NN t operator, one must take account of the antisymmetrization requirements of the Pauli principle. As a result, for NN scattering each of the t_i given in Eq. (4) has the form

$$t_i^l = t_i^l(q) \mp (-1)^l t_i^l(Q) \text{ (+ for tensor only)}, \tag{5}$$

where l is the relative orbital angular momentum in the two body c.m. system. Most of the considerable energy dependence[5] present in the two body NN t matrix is contained in the second term on the right-hand side (rhs) of Eq. (5). This term is treated exactly (as the exchange term) in modern DWIA computer codes. The $S_{12}(\hat{Q})$ which appears in Eq. (4) as a *direct* term in the $\bar{\text{N}}$N t matrix is present only as an *exchange* term in the NN t matrix. The *residual* energy dependence for NN not contained in the exchange term in Eq. (5) is usually treated only in terms of an approximate "diagonal" Fermi averaging of the operator.

The noncentral spin-orbit and tensor terms t^{LS} and t^T are also shown in Fig. 2 for model II. For both models I and II, the isoscalar spin-orbit term t_0^{LS} dominates for all q of interest over the isovector spin-orbit term t_τ^{LS} in the energy range 100—300 MeV. (The t_τ^{LS} component is also small in the NN sector.) Similarly, the isovector tensor component t_τ^T dominates the isoscalar tensor term t_0^T, with both terms showing only a modest energy dependence. The magnitude of the dominant t_0^{LS} and t_τ^T terms are generally within 30% of each other. For low momentum transfers ($\lesssim 100$ MeV/c) both t_0^{TQ} and t_τ^{TQ} (not shown) are larger than the other noncentral terms, but still smaller than the central components which tend to dominate at low q.

For both models I and II, the component t_0^c is larger than the other components for $q \le 400$ MeV/c and thus normal parity, $\Delta T=0$, final nuclear states should be prominent in the nuclear response at all momentum transfers. In model II, which we consider to be the more realistic, the next most important central component is t_σ^c, over a broad range of E and q. In contrast to the nucleon, we find that $\bar{\text{N}}$ inelastic scattering should lead to significant excitation of isoscalar spin-flip resonances. At larger momentum transfers, the isoscalar spin-orbit t_0^{LS} and isovector tensor component t_τ^T are comparable and dominate. Note that by studying ($\bar{\text{p}}$,$\bar{\text{n}}$) reactions one eliminates all $\Delta T=0$ states from the spectrum. Thus, for antinucleon charge exchange, spin-flip components should dominate the nuclear response [at low (high) q owing to the $t_{\sigma\tau}^c$ (t_τ^T) component]. The ($\bar{\text{p}}$,$\bar{\text{n}}$) reaction is much like the (n,p) reaction, in that for $N=Z$ nuclei one studies analogs of the Gamow-Teller resonances, while for $N>Z$ nuclei, the reaction can be used to investigate $T_>$ resonances without lower isospin resonance contamination.

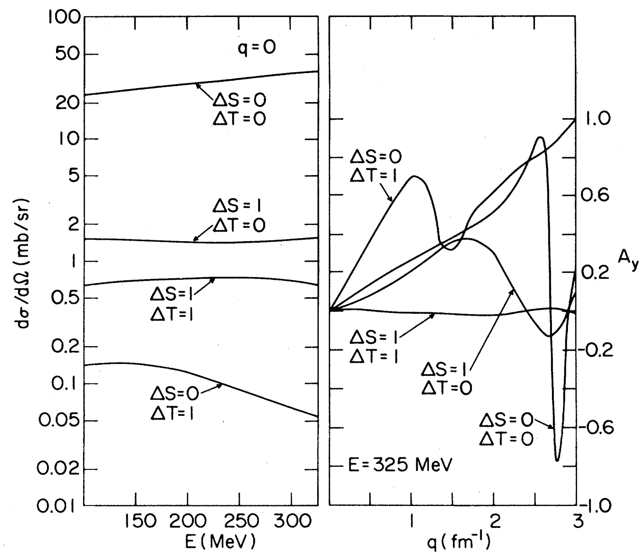

FIG. 3. Differential cross sections $d\sigma/d\Omega$ and asymmetries A_y for transitions of different spin-isospin character ΔS, ΔT in $\bar{\text{N}}$-nucleus inelastic scattering. The cross sections, shown for $\theta=0°$ as a function of energy, are given by Eq. (6), with t multiplied by a dimensional factor $[E_{\text{c.m.}}/4\pi(\hbar c)^2]^2$ to give units of mb/sr. The nuclear structure factors characteristic of inelastic transitions to particular final states are not included in $d\sigma/d\Omega$. The asymmetries A_y, obtained from Eq. (8), are plotted as a function of q for fixed $E=325$ MeV. All curves refer to model II.

As a general guide to the relative strength of the various terms in the nuclear response, we show in Fig. 3 the predicted energy dependence of various spin-isospin flip cross sections. We use the Love-Franey formula[5]

$$\frac{d\sigma}{d\Omega} \propto (|t_i^c|^2 + |t_i^{LS}|^2) \text{ (normal parity state, } \Delta S=0 \text{ dominant)} \tag{6a}$$

$$\propto (|t_{\sigma i}^{LS}|^2 + |t_{\sigma i}^c + t_i^{T\alpha}|^2 + |t_{\sigma i}^c + t_i^{T\beta}|^2 + \xi |t_{\sigma i}^c + t_i^{T\gamma}|^2) \text{ (non-normal parity, } \Delta S=1), \tag{6b}$$

($i=\tau$ for $\Delta T=1$ transitions only), where

$$t_i^{T\alpha} = t_i^T - 2t_i^{TQ}, \quad t_i^{T\beta} = t_i^T + t_i^{TQ}, \quad t_i^{T\gamma} = -2t_i^T + t_i^{TQ}. \tag{7}$$

Equation (6) assumes the plane-wave-impulse approximation and a specific angular momentum transfer, and suppresses nuclear structure factors. For both the differential cross section and asymmetry predictions we have assumed $\xi=2$, which is appropriate[5] for stretched states. Equation (6) is discussed in more detail in Ref. 5, and has been used previously to estimate the strength of various terms in (p,p′) reactions. The results for $d\sigma/d\Omega$ shown in Fig. 3 reflect the sizable excitation of the $\Delta S=1$, $\Delta T=0$ mode at low q. Through the influence of t_0^{LS}, this spin flip mode remains prominent at high q.

A similar procedure can be used to make qualitative predictions for the asymmetry A_y associated with excitation of the various spin-isospin modes. These are shown as a function of momentum transfer for $E=325$ MeV in Fig. 3. The expressions used for our predictions are[5]

$$A_y(q)=\frac{2(t_{Ri}^{LS}t_{Ii}^{c}-t_{Ii}^{LS}t_{Ri}^{c})}{|t_i^c|^2+|t_i^{LS}|^2}\quad \text{(normal parity, } \Delta S=0 \text{ dominant)}\,, \tag{8a}$$

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

where R (I) denotes the real (imaginary) parts of the t matrix components. The results indicate characteristically different and measurable asymmetries for all but the $\Delta S=\Delta T=1$ modes, where the asymmetry is predicted to be essentially zero in the energy and momentum transfer range studied.

We now compare the effects of medium modifications expected for ($\bar{\text{p}}$,$\bar{\text{p}}'$) reactions compared to those apparently present in (p,p′). The effect of Pauli blocking in intermediate states plays an important role in modifying the momentum transfer behavior of the central term in t_0^c in the NN sector. Qualitatively, this results in a decrease (increase) in the magnitude of the t_0^c term for q less (greater) than 300 MeV/c, and leads to considerable differences in predictions[13] for low spin, normal parity $\Delta T=0$ differential cross sections and asymmetries for ^{12}C, ^{16}O, and ^{40}Ca. For these states, the high density nuclear interior makes an important contribution, and the interplay between the isoscalar central and noncentral interactions at high q is important for determining the angular shapes of observables. An important feature is that the t_0^c component for NN has a prominent minimum between 200 and 400 MeV/c, as mentioned earlier, and this minimum moves as a function of the assumed Fermi momentum in nuclear matter Pauli blocking calculations. For the ($\bar{\text{p}}$,$\bar{\text{p}}'$) reaction, the situation is somewhat different. Although one does not antisymmetrize between the $\bar{\text{N}}$ projectile and the struck target nucleon, the Pauli principle does block the available target nucleon recoil states in the nuclear interior. However, the strong imaginary part of the $\bar{\text{N}}$-nucleus optical potential will suppress contributions from the high density nuclear interior where Pauli blocking effects become important. Moreover, the central term t_0^c (which has no minimum below $q=500$ MeV/c) dominates over the noncentral components even near 300 MeV/c, so the interplay between the components may be less important.

Current DWIA (N,N′) codes are not capable of treating exactly a transition operator whose parameters are a function of the two particle c.m. energy (except for the specific case of the exchange operator discussed earlier). The usual procedure is to treat the struck nucleon as being initially at rest. This ignores the initial Fermi motion of the struck nucleon. Using Fermi-averaged t matrices *does not* properly take into account the angle dependence of the Fermi-motion induced corrections. A more detailed treatment[14] demonstrates how energy dependent *central* spin-independent terms can contribute to the excitation of non-normal parity states. It will be interesting to apply these same corrections in ($\bar{\text{N}}$,$\bar{\text{N}}'$), where the energy dependence and relative size of the various components in the t matrix are quite different from (N,N′). The basic goal is to be able to separate nuclear structure uncertainties from reaction mechanism complications such as the energy and density dependence of the effective t matrix. It may be useful, therefore, that the t matrix corrections are different but relatively well defined for (N,N′) and ($\bar{\text{N}}$,$\bar{\text{N}}'$) transitions to the same final states.

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[7] as contributors to $(P-A)$. Since exchange effects are absent for $\bar{\text{N}}$N, and the spin-isospin components have different energy and momentum transfer dependence than those appearing in the NN operator, the study of $(P-A)$ for antinucleon inelastic scattering should provide useful additional information. It is interesting to note that $P-A=0$ in ($\bar{\text{N}}$,$\bar{\text{N}}'$) inelastic scattering (ignoring Q value effects) for $0^+\rightarrow 1^+$ transitions via t_σ^c if there are no multistep or energy dependent t-matrix corrections (note that exchange is absent).

In order to proceed to more quantitative predictions using the $\bar{\text{N}}$N transition operators obtained here, it will be necessary to carry out detailed DWIA calculations, using distorted waves generated either from the folding model or from phenomenological fits to $\bar{\text{N}}$-nucleus elastic scattering. This work is currently underway. We expect the strongly absorptive part of the optical potential to significantly modify angular distributions (as well as the overall magnitude) from plane wave estimates, especially for low spin states where the nuclear transition density is not surface peaked. However, we expect our predictions for *relative* excitation of various spin-isospin nuclear modes to survive even in the presence of strong absorption, much as in the case of (π,π') near the 3-3 resonance.

In this paper we have presented results for a $\bar{\text{N}}$N transition operator appropriate for use in DWIA studies of ($\bar{\text{N}}$,$\bar{\text{N}}'$) reactions on nuclei. We have used two models to generate the transition operators. We consider model II to be more realistic, since it results from a more extensive fit to the two-body $\bar{\text{N}}$N data, including the 180° elastic scattering. The fact that the annihilation potential $W(r)$ is spin, isospin, and energy dependent (as obtained in model II) is expected on the basis of quark rearrangement[15] and coupled channel models.[16] This feature of the annihilation potential plays an important role in determining the relative importance of various spin-isospin modes in $\overline{\text{N}}$ inelastic scattering. In particular, the term t_σ^c, which can be used to study low J, spin-flip isoscalar resonances, is appreciable in model II and negligible in model I. In general, the central term t_0^c is large for all relevant momentum transfers. For high momentum transfer, the isoscalar spin-orbit and isovector tensor terms are seen to be important (as in the case of the NN t matrix). We suggest that the $\overline{\text{N}}$ is a useful tool for exploring nuclear structure. Comparison of the spin-isospin nuclear response functions for $\overline{\text{N}}$ and N inelastic scattering should prove to be particularly valuable.

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