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TITLE: THE NUCLEAR SPIN-ISOSPIN RESPONSE TO QUASIFREE NUCLEON SCATTERING

AUTHOR(S): Taddeucci, Terry N. (P-23, LANL)

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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T.N. Taddeucci

Los Alamos National Laboratory, Los Alamos, NM 87545

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INTRODUCTION

Mesonic fields in the nucleus may reveal their presence through collective effects on the quasifree nuclear response. In the $\pi + \rho + g'$ model of the residual particle-hole interaction, the pion field at moderate momentum transfers (1–2 fm^{-1}) produces a spin-longitudinal interaction ($\boldsymbol{\sigma} \cdot \mathbf{q}$) that is attractive, and the exchange of rho mesons produces a transverse interaction ($\boldsymbol{\sigma} \times \mathbf{q}$) that is repulsive. Much interest was generated by an early prediction that an interaction with these characteristics would lead to an enhancement and softening (shift toward lower energy transfer) of the quasifree isovector longitudinal spin response and a quenching and hardening (shift toward higher energy transfer) of the quasifree isovector transverse spin response [1].

The quasifree isovector transverse spin response can be measured with the (e,e') reaction, which is about 97% isovector because of the relative magnitudes of the isovector and isoscalar nucleon magnetic moments. Most analyses of quasifree (e,e') data lead to the conclusion that the isovector $1p$–$1h$ response is indeed quenched. Electromagnetic probes such as the electron are not sensitive to the longitudinal spin response, however. The first information about this response was obtained from $(\vec{p},\vec{p}')$ measurements performed more than ten years ago with the High Resolution Spectrometer (HRS) at LAMPF

[2, 3]. After corrections for the isoscalar contribution to this reaction, these measurements yield the ratio of the longitudinal and transverse isovector spin responses. The surprising result obtained from analysis of these data was that there is no apparent enhancement of the spin longitudinal response relative to the spin transverse response.

The purely isovector $(\vec{p}, \vec{n})$ reaction is better suited for study of the isovector nuclear response. The construction of the Neutron-Time-of-Flight (NTOF) facility at LAMPF was strongly motivated by the need to follow up the initial $(\vec{p}, \vec{p}')$ measurements with similar and easier-to-interpret measurements using the $(\vec{p}, \vec{n})$ reaction. Measurements of the quasifree response using polarized beam commenced at NTOF in 1990. The first results obtained with the $(\vec{p}, \vec{n})$ reaction at 494 MeV and 18° (1.7 fm^{-1}) confirmed the $(\vec{p}, \vec{p}')$ analysis by revealing no enhancement in the ratio of spin longitudinal to spin transverse responses, this time without the problematic corrections for isoscalar contributions [4]. In addition, the $(\vec{p}, \vec{n})$ measurements provided the first look at the separated responses, rather than just the ratio [5].

Comparison of the transverse responses for ^{12}C and ^{40}Ca to (e, e') results at the same momentum transfer seemed to show good agreement between the two probes. This strengthened the conclusion that the longitudinal response, associated with the nuclear pion field, was the source of the problem. This perplexing result has fueled several diverse theoretical efforts that explore, separately, the effects of distortions and coupling to the Δ [6, 7, 8], in-medium changes in the nucleon-nucleon (NN) amplitudes and coupling constants [9, 10], and changes in the residual particle-hole interaction arising from density-dependence of hadron masses [11].

Unfortunately, the initial comparisons of the separated $(\vec{p}, \vec{n})$ responses to electron-scattering and to theoretical responses were incorrect by a factor of two because of misunderstandings about the proper normalization of the electron data and theoretical response definitions. Revised comparisons now reveal that the transverse response as measured by the $(\vec{p}, \vec{n})$ reaction appears to be much larger than that obtained in electron-scattering measurements. Analysis of the original $(\vec{p}, \vec{n})$ data and new data obtained at lower and higher momentum transfer shows that expected enhancements in the longitudinal spin response, if present, are largely overshadowed by an excess of strength in the transverse channels.

EXPERIMENTAL METHOD

A detailed description of the NTOF facility at LAMPF and pertinent experimental techniques can be found in the report of the first quasifree polarization transfer measurement [5]. This initial measurement (18°) took place in 1990 when the new optically pumped polarized ion source (OPPIS) first came on-

TABLE 1. Quasifree $(\vec{p},\vec{n})$ measurements at $E_p \simeq 494$ MeV.

θ_{lab}	ω_{free} (MeV)	ω_{QF} (MeV)	q_{lab} (fm^{-1})	Δq (fm^{-1})	targets
12.5°	28.9	53	1.21	1.19–1.50	CD_2, C
18.0°	58.1	82	1.72	1.70–1.87	CD_2, C, Ca
27.0°	121.7	138	2.52	2.52–2.63	CD_2, C, Ca

line for production use. The new data presented here were obtained during the 1992 (12.5°) and 1993 (27°) running periods at LAMPF. Regrettably, 1993 marks the end of polarized-beam experiments at LAMPF.

The NTOF detector/polarimeter consists of four position-sensitive scintillator planes. The collection area of each plane is approximately 102×107 cm^2. The planes are grouped into front and back pairs separated by approximately 1.4 m. The first three planes are stainless-steel tanks filled with liquid scintillator (BC-517s, H:C=1.7). The fourth plane is a set of ten plastic scintillator (BC-408) bars. Incident neutron energy is determined by time of flight to the front pair of detector planes, which also serve as polarization analyzers. Time, position, and pulse-height information from the front and back pairs of planes is used to kinematically select $n + p$ interactions. Neutron polarization is determined from the azimuthal intensity distribution of the $n+p$ events. Elastic (or p + C quasielastic) $(\vec{n},n)$ and $(\vec{n},p)$ events are identified and sorted separately. The detection efficiency of the system in polarimetry mode is about 6×10^{-3} for the (n,p) channel and about 1.5×10^{-3} for the (n,n) channel. The effective analyzing power for each channel is about 0.15 and 0.23, respectively.

Complete sets of polarization-transfer coefficients were measured for $(\vec{p},\vec{n})$ reactions on CD_2, natural C (98.9% ^{12}C), and natural Ca (96.9% ^{40}Ca) with an average beam energy of 494 MeV and a neutron flight path of 200 m. Overall energy resolution was about 2 MeV. Typical beam intensities were in the range from 50–100 nA, with beam polarization in the range from 0.50–0.65. Data for the ^{2}H(p,n) reaction were obtained from the cross-section-weighted difference of the CD_2 and C results. This subtraction is accurate to better than 3%. Cross sections were normalized relative to the ^{7}Li$(p,n)^7$Be(g.s.+0.43-MeV) transition at 0°, for which the cross section is $\sigma_{c.m.}(0°) = 27.0$ mb/sr [12].

A summary of the quasifree measurements is presented in Table 1. The momentum transfer q_{lab} corresponds to the peak of the quasifree distribution for ^{12}C$(\vec{p},\vec{n})$ and ^{40}Ca$(\vec{p},\vec{n})$, which is about $\omega_{QF} - \omega_{free} \approx 20$ MeV higher than the energy loss for free scattering. Because the measurements are made at a fixed angle, the momentum transfer is not constant, but varies slightly with energy loss across the spectrum. The range of values Δq corresponds to $\omega =$ 30–150 MeV for $\theta = 12.5°$ and 18°, and $\omega = 30$–200 MeV for $\theta = 27°$.

DATA REDUCTION

The spin responses are obtained from $(\vec{p},\vec{n})$ cross-section and polarization-transfer data by transforming the laboratory-frame polarization-transfer coefficients $\{D_{SS'}, D_{NN'}, D_{LL'}, D_{SL'}, D_{LS'}\}$ into a special set $\{D_0, D_n, D_q, D_p\}$ of c.m.-frame observables [13]. The c.m. coordinates are defined so that $\hat{\mathrm{n}}$ is perpendicular to the reaction plane, $\hat{\mathrm{q}}$ is along the direction of momentum transfer, and $\hat{\mathrm{p}} = \hat{\mathrm{n}} \times \hat{\mathrm{q}}$. From these c.m. observables four responses (R_0, R_n, R_q, R_p) corresponding to the spin operators $\boldsymbol{\sigma}_0$, $\boldsymbol{\sigma}\cdot\hat{\mathrm{n}}$, $\boldsymbol{\sigma}\cdot\hat{\mathrm{q}}$, and $\boldsymbol{\sigma}\cdot\hat{\mathrm{p}}$ can be obtained. The $(\vec{p},\vec{n})$ responses are defined by

$$R_j = \frac{1}{N}\frac{1}{(2J_i+1)}\sum_{i,f}|\langle f|\sum_{k=1,A}\sigma_{jk}\tau_k^- e^{-i\mathbf{q}\cdot\mathbf{r}_k}|i\rangle|^2\delta[\omega_{\mathrm{cm}}-(E_f-E_i)]\ . \qquad (1)$$

and are normalized such that

$$\int R_i(q,\omega)\,d\omega = 1 \qquad \text{as} \qquad q\to\infty\ . \qquad (2)$$

The responses to the two transverse operators $\boldsymbol{\sigma}\cdot\hat{\mathrm{n}}$ and $\boldsymbol{\sigma}\cdot\hat{\mathrm{p}}$ are identical [14] and can be equated to the response R_T to the transverse operator $(\boldsymbol{\sigma}\times\hat{\mathrm{q}})/\sqrt{2}$.

In a factorized impulse-approximation model, the relationship between the measured cross section and polarization transfer and the spin responses is given by

$$ID_0 = N_{\mathrm{eff}}C_K(|A|^2R_0 + |C|^2R_n)\ , \qquad (3)$$
$$ID_n = N_{\mathrm{eff}}C_K(|C|^2R_0 + |B|^2R_n)\ , \qquad (4)$$
$$ID_q = N_{\mathrm{eff}}C_K|E|^2R_q\ , \qquad (5)$$
$$ID_p = N_{\mathrm{eff}}C_K|F|^2R_p\ , \qquad (6)$$

where I is the double-differential cross section, C_K is a kinematic factor, and N_{eff} is a distortion factor represented as an effective number of neutrons. The distortion factor is assumed to be spin-independent and has values in the range $N_{\mathrm{eff}} \simeq 2.2$–$2.4$ for $^{12}\mathrm{C}(\vec{p},\vec{n})$ and $N_{\mathrm{eff}} \simeq 4.5$–$5.0$ for $^{40}\mathrm{Ca}(\vec{p},\vec{n})$. The NN amplitudes in these equations are from the standard KMT representation [15]:

$$M_{12} = A + C(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\hat{\mathrm{n}} + B\boldsymbol{\sigma}_1\cdot\hat{\mathrm{n}}\boldsymbol{\sigma}_2\cdot\hat{\mathrm{n}} + E\boldsymbol{\sigma}_1\cdot\hat{\mathrm{q}}\boldsymbol{\sigma}_2\cdot\hat{\mathrm{q}} + F\boldsymbol{\sigma}_1\cdot\hat{\mathrm{p}}\boldsymbol{\sigma}_2\cdot\hat{\mathrm{p}}\ . \qquad (7)$$

In the analysis of the data, the NN amplitudes are obtained from an optimal-frame transformation that provides the best factorization from the transition matrix [13]. The main effect of this transformation is to split the spin-orbit (C) amplitude into two unequal pieces, and is important only away from the peak of the quasifree distribution. Some other complications that are not explicitly accounted for in this simple factorized model are multistep contributions to the inclusive spectrum, spin-dependent distortions, and medium modification of the NN amplitudes.

The longitudinal response R_q and transverse response R_p are extracted from the data in a straightforward way by dividing the partial spin cross sections by the corresponding product of distortion and kinematic factors and NN amplitudes. The non-spin response R_0 and the transverse response R_n can in principle be obtained by matrix inversion of Eqs. (3)–(4). However, the amplitudes A and C are small and introduce large uncertainties into the formal solution for R_0 and R_n. For the case of R_n, a better approach is to take advantage of the relative sizes of the C and B amplitudes and rewrite Eq. (4) in the form

$$ID_n = N_{\text{eff}} C_K |B|^2 R_n \left(1 + \frac{|C|^2 R_0}{|B|^2 R_n}\right) . \tag{8}$$

For momentum transfer of $q \simeq 1.7$ fm^{-1}, the quantity in parentheses has a value of about 1.07 (assuming that the response ratio R_0/R_n is of order unity). Large uncertainties in the ratio in parentheses thus translate into relatively small uncertainties in the extracted response R_n. The ability to obtain this independent transverse response is very important. Spin-dependent distortions should have different effects upon the the in-plane and out-of-plane polarization observables and partial cross sections, while the underlying responses R_n and R_p should be identical. The consistency of the R_n and R_p responses extracted from the data thus puts some limits on the importance of spin-dependent distortions.

In the context of the factorized impulse approximation, the longitudinal-to-transverse response ratio R_q/R_p is a robust quantity in the sense that several common theoretical and experimental normalization factors cancel out. This ratio can be obtained from Eqs. (5)–(6) in the form

$$\frac{R_q}{R_p} = \frac{D_q/D_p}{|E/F|^2} . \tag{9}$$

The amplitude ratio $|E/F|^2$ can be obtained from NN phase-shift solutions. This is the method used in the previous analysis of the 18° data [5]. Alternately, for energy loss near ω_{free} the amplitude ratio can be replaced by the ratio $(D_q/D_p)_{^2\text{H}}$ for $^2\text{H}(\vec{p},\vec{n})$. This then gives the response ratio entirely in terms of measured quantities:

$$\frac{R_q}{R_p} = \frac{D_q/D_p}{(D_q/D_p)_{^2\text{H}}} . \tag{10}$$

This approach relies on the assumption that the response ratio R_q/R_p for $^2\text{H}(\vec{p},\vec{n})$ is near unity. Recent calculations indicate that this assumption will be closely met if the ^{2}H observables are obtained by integrating over the smallest

TABLE 2. Ratio of longitudinal to transverse polarization transfer for ^{2}H($\vec{p},\vec{n}$) at 494 MeV.

θ_{lab}	ω (MeV)	D_q/D_p
12.5°	25–40	0.653 ± 0.055
18.0°	50–75	1.70 ± 0.11
27.0°	109–139	5.34 ± 0.65

possible region centered on the peak of the ^{2}H($\vec{p},\vec{n}$) quasifree distribution [14, 16]. This procedure minimizes effects from the initial deuteron D-state and from tensor correlations in the 2p final state and gives the closest measure of the free $|E/F|^2$ ratio. Integration regions with widths of 15, 20, and 30 MeV have been used in the present analysis of the ^{2}H data at 12.5°, 18°, and 27°, respectively. The width of the region was increased in approximate proportion to the momentum transfer to account for the spreading of the quasifree distribution. The polarization-transfer ratios for ^{2}H($\vec{p},\vec{n}$) are shown in Table 2.

RESULTS

The response ratios obtained from the data-to-data ratio [Eq. (10)] are displayed in Fig. 1. The results for ^{12}C($\vec{p},\vec{n}$) and ^{40}Ca($\vec{p},\vec{n}$) are essentially identical. Theoretical ratios have been calculated in a distorted-waves impulse-approximation (DWIA) model employing random-phase-approximation (RPA) responses generated with a $\pi+\rho+g'$ interaction ($g'=0.6$) [6, 7, 8, 17]. Delta-hole (Δ–N^{-1}) contributions are included according to the standard universality ansatz, for which $g'_{NN}=g'_{N\Delta}=g'_{\Delta\Delta}$ and $f_{\pi NN}=2.0f_{\pi N\Delta}$. Two cases are shown: the solid lines correspond to calculations employing the full RPA response, and the dotted lines correspond to setting the residual interaction to zero (free response). The free-response calculations give a good description of the data at all three angles. While this result highlights the possible importance of distortion effects, the disagreement with the full RPA ratios also suggests that some important physics is being missed by describing the reaction entirely in terms of single-particle responses.

A clearer understanding of the response ratios is obtained by examining the separate responses and comparing them to appropriate benchmarks. Three comparisons are especially interesting: transverse spin responses obtained from electron scattering, the free Fermi-gas response, and RPA responses. The separate R_q and R_p responses for ^{12}C($\vec{p},\vec{n}$) are shown in Fig. 2, and those for ^{40}Ca($\vec{p},\vec{n}$) are show in Fig. 3. These responses are obtained assuming a

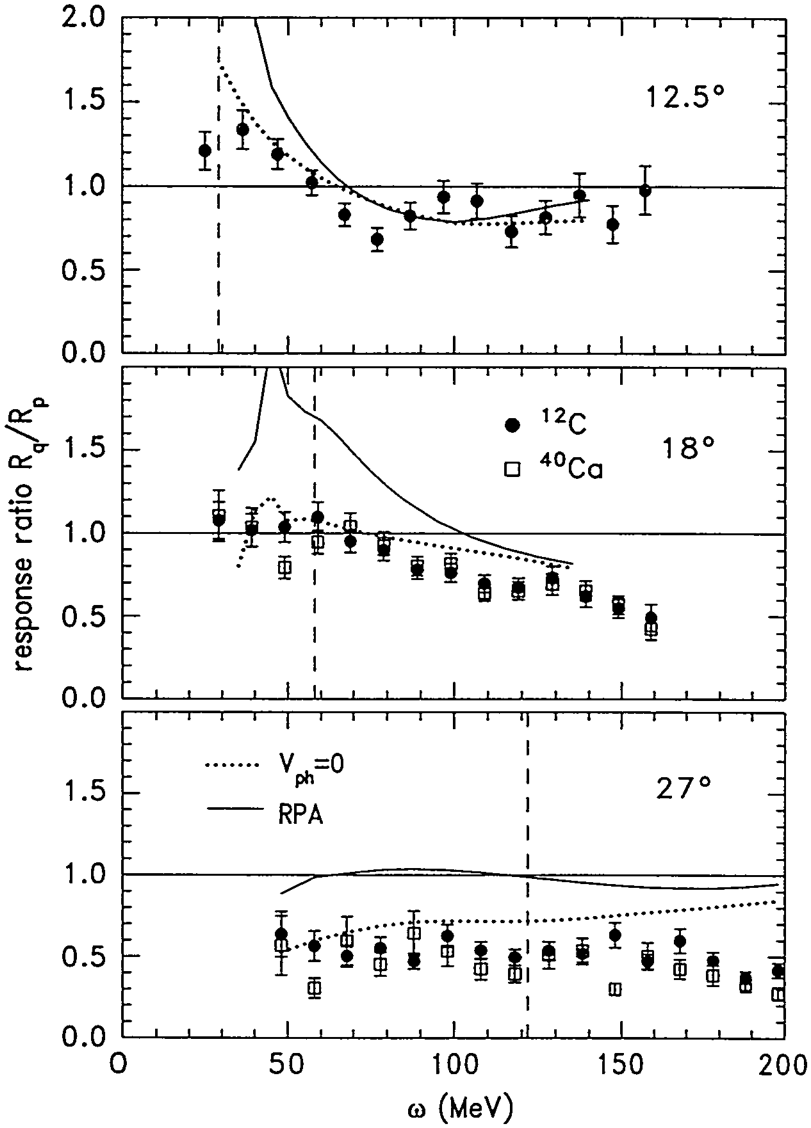

FIGURE 1. Longitudinal-to-transverse response ratios for $^{12}C(\vec{p},\vec{n})$ (solid circles) and $^{40}Ca(\vec{p},\vec{n})$ (open boxes). The ratios are calculated as the ratio of spin observables $(D_q/D_p)/(D_q/D_p)_{^2H}$ for ^{12}C or ^{40}Ca with respect to ^{2}H, with the ^{2}H values determined from a narrow region centered on the energy loss for free scattering (dashed vertical lines). The solid lines represent analogous ratios calculated in a RPA+DWIA model. The dotted lines represent DWIA calculations with the residual interaction set to zero (free responses).

common value for $N_{\rm eff}$ in both spin channels. The dotted curves represent the free Fermi-gas response $R_{\rm FG}$ calculated at a Fermi momentum of $k_F = 192$ MeV/c. This value corresponds to the average density $\langle\rho\rangle = 0.34$–$0.36\rho_0$ sampled by the $(\vec{p},\vec{n})$ probe at this energy. The Fermi-gas response has been shifted by 18 MeV for ^{12}C and by 15 MeV for ^{40}Ca to account for the ground-state Q-value.

The solid curves in Figs. 2–3 represent ^{12}C(e,e') responses at momentum transfers of $q = 250$, 350, and 500 MeV/c [18] and ^{40}Ca(e,e') responses at 330 and 500 MeV/c [19, 20, 21]. These responses have been converted to per-nucleon responses according to

$$\frac{4\pi}{M_T} S_T \simeq \frac{A}{2}\left(\frac{q}{2m}\right)^2 (\mu_p - \mu_n)^2 G_M^2 R_T \,, \tag{11}$$

where $\mu_p = 2.79$, $\mu_n = -1.91$, G_M is the nucleon magnetic form factor, and A is the target nucleon number. The transverse isovector electron response is defined by

$$R_T = \frac{1}{A}\frac{1}{(2J_i+1)}\sum_{if} |\langle f| \sum_{k=1,A} \frac{\boldsymbol{\sigma}_k \times \hat{\rm q}}{\sqrt{2}} \tau_k^z e^{-i{\rm q}\cdot{\rm r}_k} |i\rangle|^2 \delta[\omega - (E_f - E_i)] \,, \tag{12}$$

and has the same integral normalization as the $(\vec{p},\vec{n})$ response. Equation (11) ignores isospin-mixing effects, the small contribution from the isoscalar response, and the small convection current contribution [24]. With these approximations the response R_T corresponds to the spin operator $(\boldsymbol{\sigma} \times \hat{\rm q})/\sqrt{2}$. This is the proper normalization for comparison to the R_p and R_q $(\vec{p},\vec{n})$ responses, and is a factor-of-two smaller than in our previous comparison to the 18° data [5].

Because it is simple to calculate and has a well-defined integral, the free Fermi-gas response serves as a useful baseline for comparison [22, 23]. The integral of this response is equal to $(y/2)(3-y^2)$ for $y < 1$ and is unity for $y > 1$, where $y = q/(2k_F)$. The integrals of the experimental responses can be easily estimated by comparison. The Fermi-gas response is in good qualitative agreement with the main features of the data, particularly when compared to the longitudinal response. However, it is well known from analysis of electron-scattering that comparison to the free response can be very misleading. In the (e,e') reaction, a quenched single-particle transverse response and compensating higher-order contributions result in a total response very close in magnitude to the free response near the peak of the quasifree distribution [24, 25].

A more realistic theoretical response is given by the RPA. A comparison to the data is shown in Fig. 4 for ^{12}C$(\vec{p},\vec{n})$ and ^{40}Ca$(\vec{p},\vec{n})$ at 18°. The RPA responses shown here are the same as those used in the ratios of Fig. 1. These

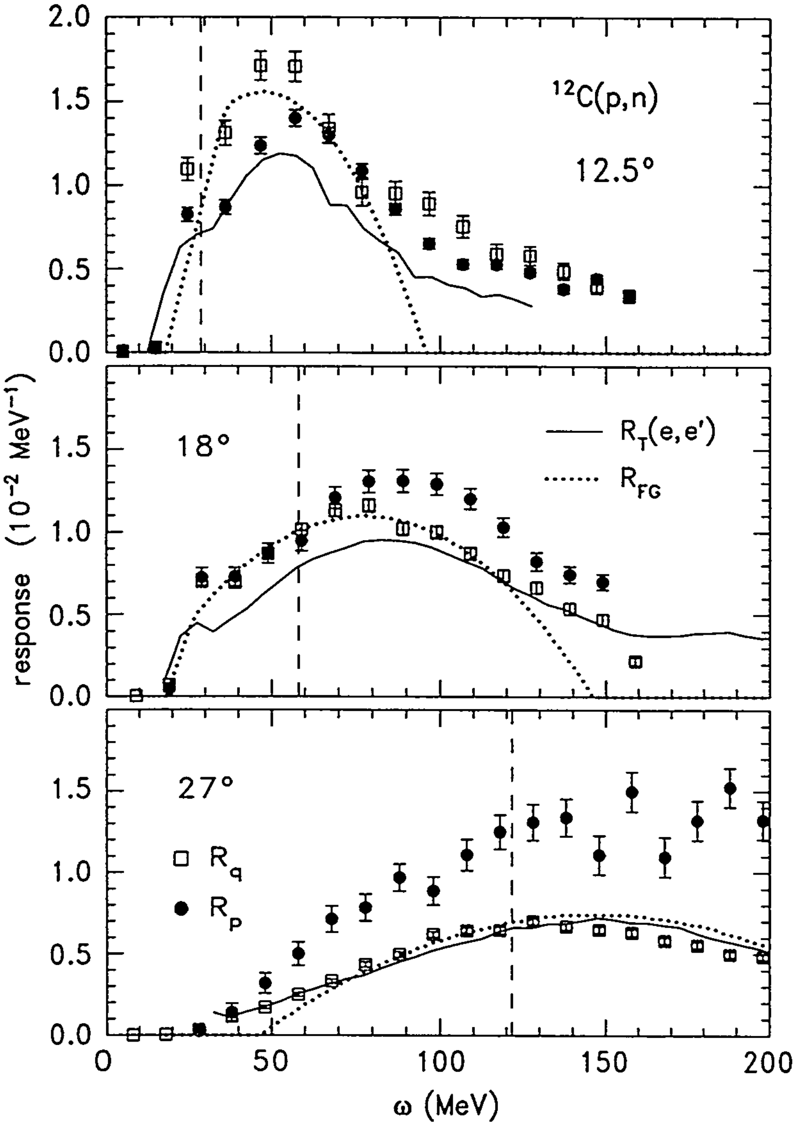

FIGURE 2. Longitudinal R_q (open boxes) and transverse R_p (solid circles) spin responses for $^{12}C(\vec{p},\vec{n})$ compared to $^{12}C(e,e')$ transverse spin responses R_T for q =250, 350, and 500 MeV/c (solid lines) [18]. The dotted lines represent the free Fermi-gas response. The dashed vertical lines mark the energy loss for free scattering.

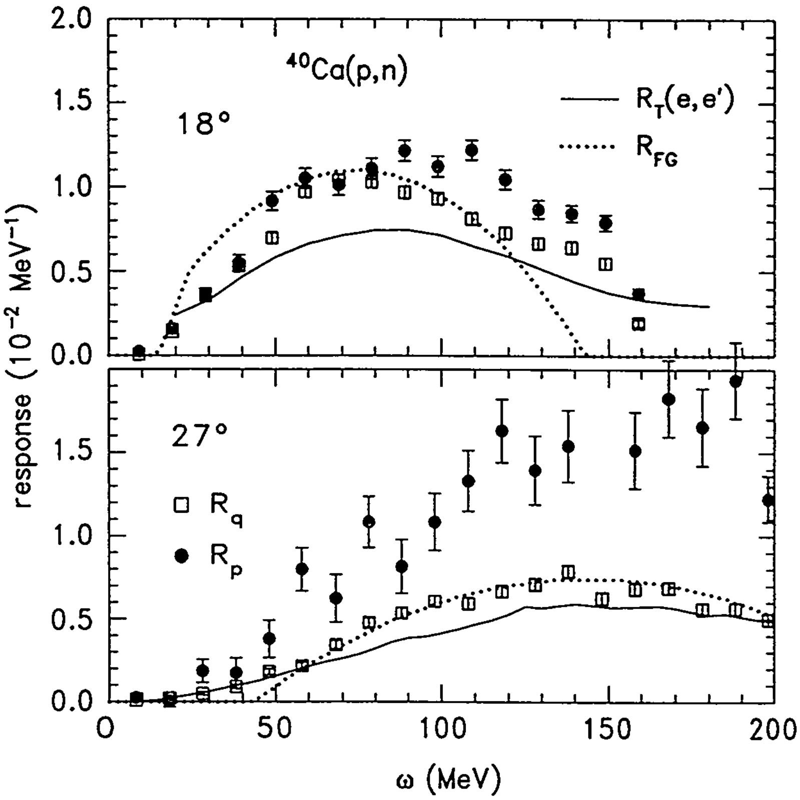

FIGURE 3. Longitudinal R_q (open boxes) and transverse R_p (solid circles) spin responses for ^{40}Ca($\vec{p},\vec{n}$) compared to ^{40}Ca(e,e') transverse spin responses R_T for q =330 and 500 MeV/c (solid lines) [19, 20, 21]. The dotted lines represent the free Fermi-gas response. The dashed vertical lines mark the energy loss for free scattering.

responses were shown in our previous analysis of the 18° data [5], but the normalization in that earlier comparison was too high by a factor of two because of a misunderstanding regarding an isospin operator ($\tau_{-1} = \sqrt{2}\tau^{-}$) omitted from the response definitions [13]. In this corrected comparison, the longitudinal RPA response is in reasonably good agreement with the data, but the transverse RPA response is about a factor-of-two too small.

As noted earlier, an important experimental question is the consistency of the results for the two independent transverse responses R_n and R_p that can be obtained from ($\vec{p},\vec{n}$) quasifree scattering. A comparison of these two responses is made in Fig. 5 for ^{12}C($\vec{p},\vec{n}$) and in Fig. 6 for ^{40}Ca($\vec{p},\vec{n}$). The agreement between the two responses is extremely good. This agreement may serve as a useful constraint in testing more complicated reaction models, such as the DWIA, that in principle can take into account the different spin-dependent distortion effects in each channel. A theoretical comparison of this sort has not yet been done.

The transverse ($\vec{p},\vec{n}$) responses R_p and R_n are larger than the corresponding

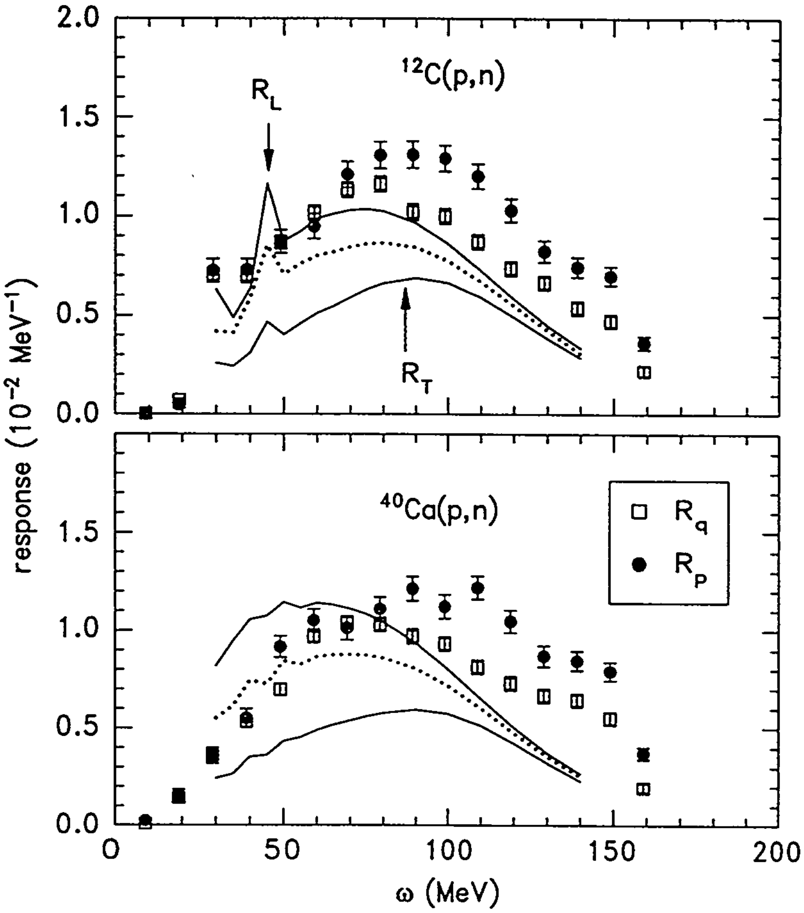

FIGURE 4. Longitudinal R_q (open squares) and transverse R_p (solid circles) responses for ^{12}C($\vec{p},\vec{n}$) at 494 MeV and 18° compared to longitudinal R_L and transverse R_T RPA responses. The dotted line represents the free response obtained by setting the residual interaction to zero.

transverse (e,e') response R_T at all momentum transfers. They are twice as large as the electron response at 27° ($q = 2.5$ fm^{-1}). At this angle the transverse $(\vec{p},\vec{n})$ strength is also twice the free $1p$–$1h$ (Fermi-gas) strength. This excess of strength may signal the presence of higher-order contributions such as multiple scattering or $2p$–$2h$ excitations. Contributions from $2p$–$2h$ configurations (including meson-exchange currents) are believed to contribute significantly to the electron transverse response [24, 25]. The present data suggest that such effects may be even more important for $(\vec{p},\vec{n})$ reactions, particularly at the highest momentum transfer.

The above comparisons show that expected enhancements in the longitudinal spin response are largely masked by an excess of strength or cross section in the transverse $(\vec{p},\vec{n})$ channel. Understanding the separated responses or spin-dependent partial cross sections is therefore at least as important as study of the ostensibly simpler response ratio in seeking evidence for collective effects

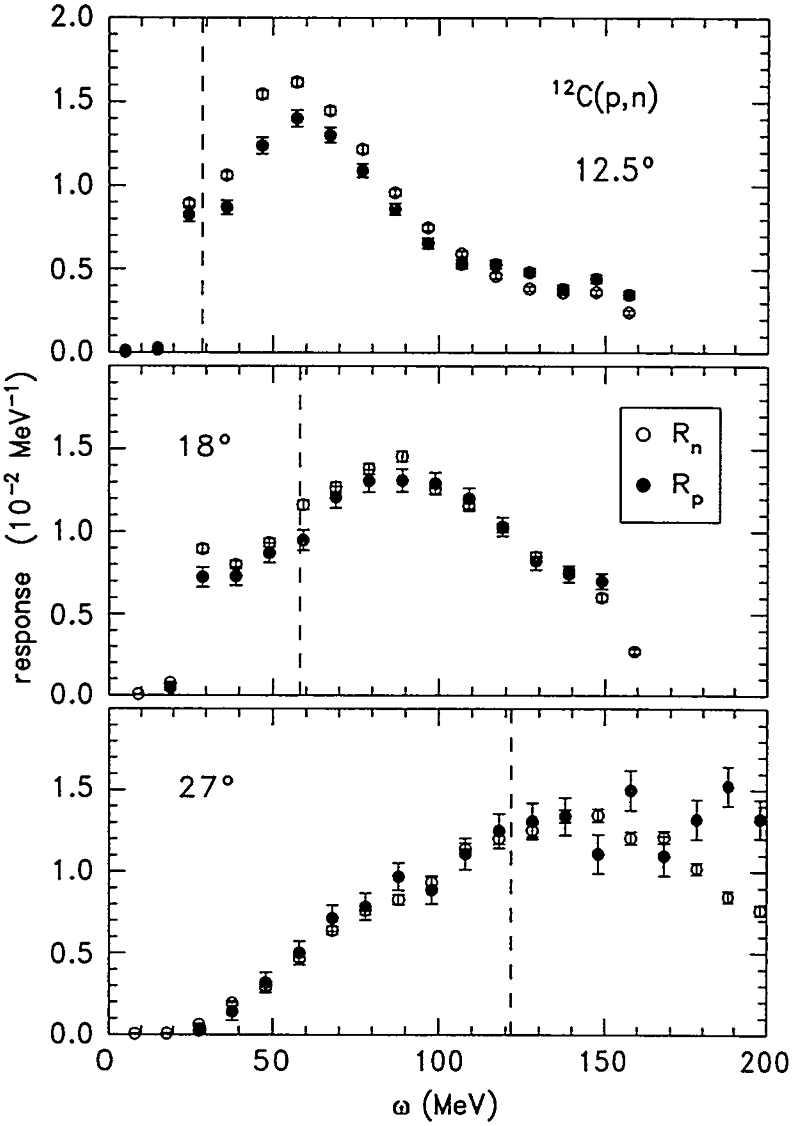

FIGURE 5. Transverse R_n (open circles) and transverse R_p (solid circles) responses for $^{12}C(\vec{p},\vec{n})$ at 494 MeV.

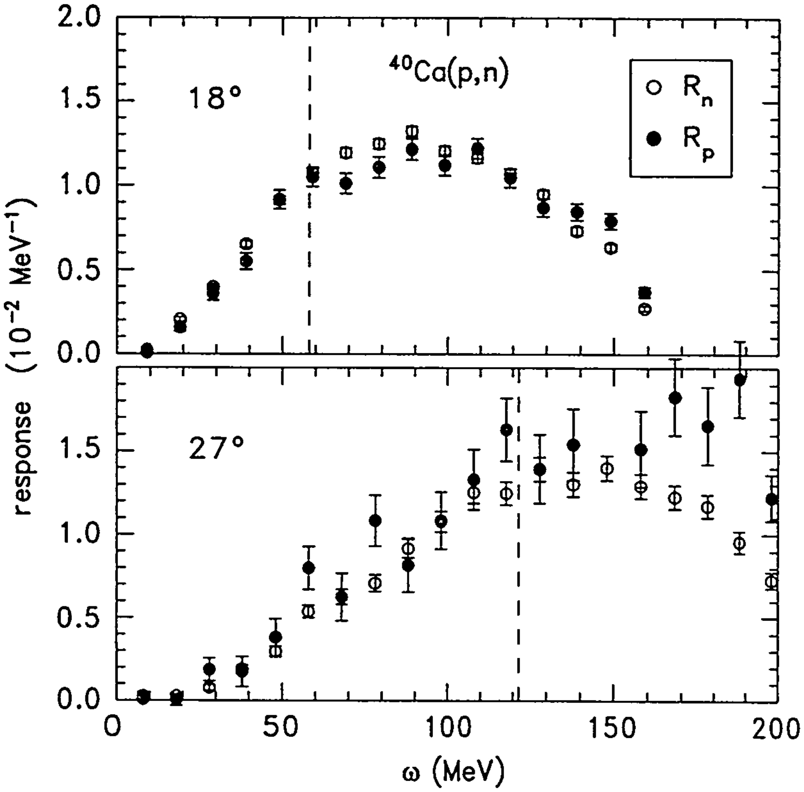

FIGURE 6. Transverse R_n (open circles) and transverse R_p (solid circles) responses for ^{40}Ca($\vec{p},\vec{n}$) at 494 MeV.

from mesonic fields in the nucleus. Some important questions that remain to be addressed are the medium dependence of the NN amplitudes (the free values have been assumed in the present analysis), contributions from multiple scattering (and its spin dependence), contributions from higher-order processes such as $2p-2h$ excitations, and the role of spin dependence in the distortion factor.

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