Momentum Dependence of the Nuclear Isovector Spin Responses from $(\vec{p}, \vec{n})$ Reactions at 494 MeV

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Complete sets of polarization transfer coefficients have been measured for quasifree $(\vec{p},\vec{n})$ scattering from ^{2}H, ^{12}C, and ^{40}Ca at 494 MeV and scattering angles of 12.5°, 18°, and 27° (q = 1.2, 1.7, 2.5 fm^{-1}). These measurements yield separated transverse ($\boldsymbol{\sigma} \times \boldsymbol{q}$) and longitudinal ($\boldsymbol{\sigma} \cdot \boldsymbol{q}$) isovector spin responses. Comparison of the separated responses to calculations and to electron-scattering responses reveals a strong enhancement in the spin transverse channel. This excess transverse strength masks the effect of pionic correlations in the response ratio.

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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 ($\boldsymbol{\sigma} \cdot \boldsymbol{q}$) that is attractive, and the exchange of rho mesons produces a transverse interaction ($\boldsymbol{\sigma} \times \boldsymbol{q}$) 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 longitudinal spin response and a quenching and hardening (shift toward higher energy transfer) of the quasifree transverse spin response [1].

Recent measurements with the $(\vec{p},\vec{n})$ reaction at 494 MeV and 18° (1.7 fm^{-1}) revealed no apparent enhancement of the longitudinal spin response relative to the transverse spin response [2,3]. This result is consistent with similar results obtained with the $(\vec{p},\vec{p}\,')$ reaction [4–6]. Because some quenching appears to exist in the transverse response observed in (e,e') measurements [7,8], the $(\vec{p},\vec{n})$ and $(\vec{p},\vec{p}\,')$ response ratios have been interpreted as evidence against the expected enhancement in the spin-longitudinal response. A crucial step in confirming this conclusion is examination of the separated responses. In this Letter, we present new data and a new analysis of previous data that show that enhancements in the longitudinal spin response, if present, are largely overshadowed by an excess of strength in the transverse channels.

The data were obtained with the Neutron Time-of-Flight (NTOF) facility at the Los Alamos Meson Physics Facility (LAMPF). A description of the NTOF facility and pertinent experimental techniques can be found in the report of the first quasifree polarization transfer measurement at $\theta_{\rm lab} = 18°$ [3].

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 $^2{\rm H}(p,n)$ 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 $^7{\rm Li}(p,n)^7{\rm Be}$(g.s. + 0.43 MeV) transition at 0°, for which the cross section is $\sigma_{\rm c.m.}(0°) = 27.0$ mb/sr [9]. Systematic uncertainties are in the range 5%–7% for both the cross section normalizations and the polarimeter calibration [3].

A summary of the quasifree measurements is presented in Table I. The laboratory-frame momentum transfer $q_{\rm lab}$

TABLE I. Quasifree (p,n) measurements at E_p = 494 MeV. The beam energy for the 27° measurements was actually 493 MeV.

$\theta_{\rm lab}$	$\omega_{\rm free}$ (MeV)	$\omega_{\rm QF}$ (MeV)	$q_{\rm lab}$ (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

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corresponds to the peak of the quasifree distribution for ^{12}C(p,n) and ^{40}Ca(p,n), which is about $\omega_{\rm QF} - \omega_{\rm free} \approx$ 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 $\theta = 12.5^\circ$ and 18° and $\omega = 30-200$ MeV for $\theta = 27^\circ$. Because of space limitations, we show only the ^{12}C results in this Letter. However, the results for ^{40}Ca are essentially identical and will be presented later in an expanded article.

The spin responses are obtained from (p,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 [10]. The c.m. coordinates are defined so that $\hat{\boldsymbol{n}}$ is perpendicular to the reaction plane, $\hat{\boldsymbol{q}}$ is along the direction of momentum transfer, and $\hat{\boldsymbol{p}} = \hat{\boldsymbol{n}} \times \hat{\boldsymbol{q}}$. From these c.m. observables four responses (R_0, R_n, R_q, R_p) corresponding to the spin operators σ_0, $\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$, $\boldsymbol{\sigma}\cdot\hat{\boldsymbol{q}}$, and $\boldsymbol{\sigma}\cdot\hat{\boldsymbol{p}}$ can be obtained. The responses to the two transverse operators $\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$ and $\boldsymbol{\sigma}\cdot\hat{\boldsymbol{p}}$ are identical [11] and can be equated to the response R_T to the transverse operator $(\boldsymbol{\sigma}\times\hat{\boldsymbol{q}})/\sqrt{2}$.

Two of the c.m. observables, D_q and D_p, can be used to directly project out partial cross sections proportional to the respective spin-longitudinal $(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{q}})$ and spin-transverse $(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{p}})$ responses. In a factorized impulse-approximation model, the relationship between cross section and spin response is given by

$$ID_q = C_K N_{\rm eff} |E|^2 R_q\,, \tag{1}$$

$$ID_p = C_K N_{\rm eff} |F|^2 R_p\,, \tag{2}$$

where I is the double-differential cross section, C_K is a kinematic factor, $N_{\rm eff}$ is a distortion factor represented as an effective number of neutrons [$\simeq$2.2–2.4 for ^{12}C(p,n)], and E and F are longitudinal and transverse nucleon-nucleon amplitudes, respectively. A more complete description of this model can be found in Refs. [3,10]. Some potential complications that are not explicitly accounted for are multistep contributions to the inclusive spectrum, spin-dependent distortions, and medium modification of the NN amplitudes.

The longitudinal-to-transverse response ratio R_q/R_p is obtained from Eqs. (1) and (2) in the form

$$\frac{R_q}{R_p} = \frac{D_q/D_p}{|E/F|^2}\,. \tag{3}$$

The amplitude ratio $|E/F|^2$ can be obtained from NN phase-shift solutions and should ideally be computed in an optimal reference frame [10]. This is the method used in our previous analysis of the 18° data [3]. Alternately, for energy loss near $\omega_{\rm free}$ the amplitude ratio can be replaced by the ratio $(D_q/D_p)_{^2\rm H}$ for ^{2}H(p,n). This then gives the response ratio entirely in terms of measured quantities:

$$\frac{R_q}{R_p} = \frac{D_q/D_p}{(D_q/D_p)_{^2\rm H}}\,. \tag{4}$$

Recent calculations indicate that the ^{2}H observables should be obtained by integrating over the smallest possible region centered on the peak of the ^{2}H(p,n) quasifree distribution [11,12]. This 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. In this analysis, we have used integration regions with widths of 15, 20, and 30 MeV for 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 response ratios obtained from the data-to-data ratio [Eq. (4)] are displayed in Fig. 1. Theoretical ratios have been calculated in a distorted-wave impulse-approximation (DWIA) model employing random-phase-approximation (RPA) responses generated with a $\pi + \rho + g'$ interaction ($g' = 0.6$) [13–16]. Delta-hole

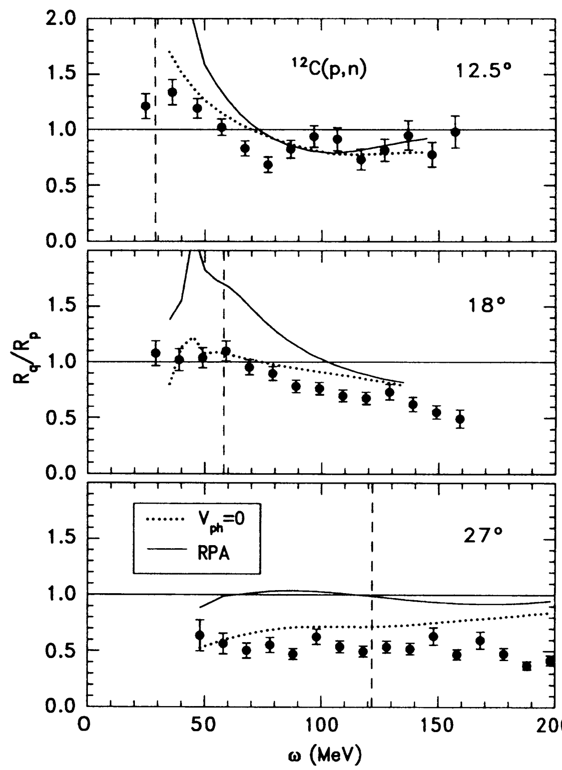

FIG. 1. Longitudinal-to-transverse response ratios for ^{12}C$(\vec{p},\vec{n})$ at 494 MeV. The ratios are calculated as the ratio of spin observables $(D_q/D_p)_{^{12}\rm C}/(D_q/D_p)_{^2\rm H}$ for ^{12}C with respect to ^{2}H, with the ^{2}H values determined from a narrow region centered on the energy loss for free scattering (dashed vertical lines). The error bars represent counting statistics only. Systematic uncertainty is in the range 1%–6%. 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).

(Δ-N^{-1}) contributions are included according to the standard universality ansatz, for which $g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta}$ and $f_{\pi NN} = 2.0 f_{\pi N\Delta}$. 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 + DWIA ratios also suggests that some important physics is being missed by describing the reaction entirely in terms of single-particle responses. Some insight into the shortcomings of the RPA + DWIA calculations can be gained by comparison of the separate longitudinal and transverse RPA responses to the experimental responses.

The separate R_q and R_p responses for ${}^{12}\mathrm{C}(p,n)$ are shown in Fig. 2. Experimental systematic uncertainty is in the range 6%–8% [3]. Model-dependent uncertainties associated with the distortion factor N_{eff} and NN amplitudes are on the order of 20% and 10%, respectively [3,14,17].

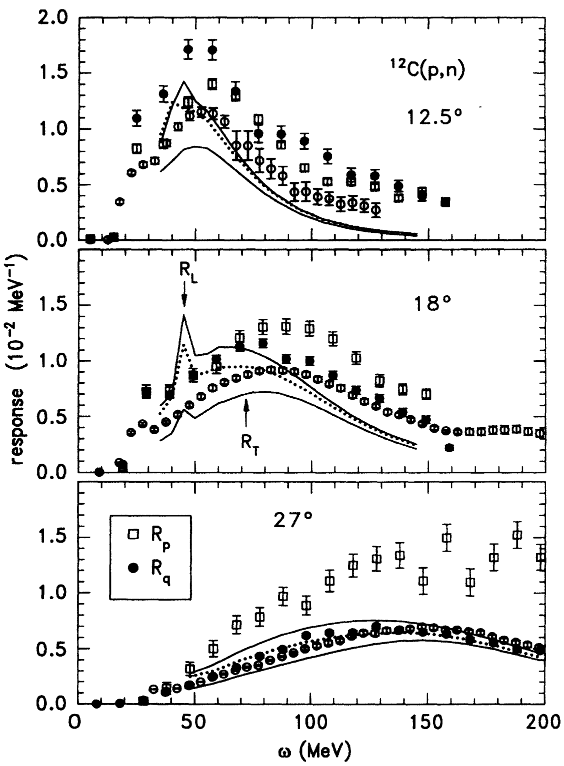

FIG. 2. Longitudinal R_q (solid circles) and transverse R_p (open squares) responses for ${}^{12}\mathrm{C}(p,n)$ at 494 MeV (with $N_{\mathrm{eff}} \simeq 2.2-2.4$) compared to longitudinal R_L and transverse R_T RPA responses (solid lines). The dotted line represents the free response obtained by setting the residual interaction to zero. The open circles represent the transverse spin response R_T for ${}^{12}\mathrm{C}(e,e')$ at $q = 250$, 350, and 500 MeV/c [18]. Error bars on the (p,n) responses represent counting statistics only.

The curves in Fig. 2 represent RPA responses calculated for fixed laboratory scattering angle. Responses calculated for fixed momentum transfer were shown in our previous analysis of the 18° data [3], but the normalization in that earlier comparison was too high by a factor of 2 because of a misunderstanding regarding an isospin operator (τ_{-1}) omitted from the response definitions [10]. In Fig. 2, the larger solid curve in each panel corresponds to the longitudinal response, the smaller solid curve is the transverse response, and the dotted curve is the free response. The experimental longitudinal response is substantially larger than the RPA response at 12.5°, in good agreement in magnitude at 18°, and slightly smaller at 27°. In contrast, the experimental transverse response is about twice as large as the transverse RPA response at all angles.

The transverse (p,n) response can be compared to the transverse response measured in electron scattering. The open circles in Fig. 2 represent the ${}^{12}\mathrm{C}(e,e')$ responses of Barreau *et al.* [18] for momentum transfers of $q = 250$, 350, and 500 MeV/c. These responses have been converted to per-nucleon responses according to

$$\frac{4\pi}{M_T} S_T \simeq \frac{A}{2}\left(\frac{q}{2m}\right)^2 (\mu_p - \mu_n)^2 G_M^2 R_T \,, \qquad (5)$$

where $\mu_p = 2.79$, $\mu_n = -1.91$, G_M is the nucleon magnetic form factor, and A is the target nucleon number. Equation (5) ignores isospin-mixing effects, the small contribution from the isoscalar response, and the small convection current contribution [7]. With these approximations the response R_T corresponds to the spin operator $(\boldsymbol{\sigma} \times \hat{q})/\sqrt{2}$. This is the proper normalization for comparison to the R_p and R_q (p,n) responses and is a factor of 2 smaller than in our previous comparison to the 18° data [3].

The transverse electron response agrees well in shape with the transverse (p,n) response, but it is smaller in magnitude at all angles. The normalization factor that must be applied to the electron response to match the magnitude of the (p,n) response is approximately 1.25, 1.4, and 1.9 for 12.5°, 18°, and 27°, respectively. The electron responses are larger than the transverse RPA responses at all angles. This result is consistent with previous theoretical comparisons to electron scattering. Typically, the one-particle–one-hole (1p-1h) transverse response with RPA correlations is smaller than the corresponding electron response, and agreement in magnitude is restored only by including higher-order contributions, such as 2p-2h excitations [7,8] and exchange currents [19].

We make the following observations based on the above comparisons:

The experimental longitudinal response is consistent in magnitude with RPA predictions, except at the smallest angle (12.5°), where it is substantially larger. However, the size of the RPA enhancement, relative to the free response, is of the same order of magnitude as model-dependent uncertainties associated with extracting the experimental responses from the data.

In the transverse channel, at all angles the (p,n) response is much larger than both the corresponding RPA response and the electron response. This apparent excess of transverse strength is responsible for masking possible signatures of pionic enhancement in the response ratio R_q/R_p. If this enhancement is an artifact of the analysis ($N_{\rm eff}$ too small, for example), then it implies a transverse distortion factor $N_{\rm eff}^p$ that is twice as large as the longitudinal factor $N_{\rm eff}^q$. Alternately, possible contributions to the transverse channel that could account for part of the excess strength include 2p-2h excitations or multiple scattering.

We conclude from analysis of the present data, where separated responses are examined in addition to response ratios, that the presence of pionic enhancement in the longitudinal response cannot be ruled out. However, present reaction-model uncertainties are at least as large as the expected collective enhancement effects. In contrast, the transverse response is much larger than expected and not explained by current reaction models that contain only 1p-1h excitations. This excess of strength in the transverse channels makes the response ratio less suitable for searching for collective signatures than has been previously assumed.

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