Polarization Transfer in $(\vec{p},\vec{n})$ Reactions at 318 and 494 MeV and the Effective Interaction

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The polarization transfer observable $D_{LL}(0°)$ has been measured for ^{2}H$(\vec{p},\vec{n})2p$, ^{12}C$(\vec{p},\vec{n})^{12}$N, and ^{14}C$(\vec{p},\vec{n})^{14}$N reactions with beam energies of 318 and 494 MeV. The deuterium results are in close agreement with free NN scattering constrained to the $\Delta J^\pi = 1^+$ channel. The results for the carbon targets, however, are systematically more negative than those for deuterium, which suggests a difference between the free and effective nucleon-nucleon interactions. Such a medium modification of the spin-dependent interaction may have important implications for interpretation of other intermediate-energy scattering experiments.

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Measurements of the nuclear spin response require an accurate knowledge of the characteristics of the probe responsible for the transition. For example, in the analysis of recent quasifree $(\vec{p},\vec{n})$ measurements it was necessary to assume that the probe characteristics are those of free nucleon-nucleon (NN) scattering [1,2]. It is likely that the NN interaction is changed when the reaction takes place in the nuclear medium, but the effects of distortions, inaccurate knowledge of the free interaction itself, and incomplete knowledge of the nuclear wave functions present obstacles against unambiguous evidence for such changes. Recent strategies have involved the study of transitions such as those to "stretched" nuclear configurations at bombarding energies where the optical potential and relevant components of the effective (free) interaction appear to be well determined [3,4]. Such studies have been used to explore the effective interaction in the momentum transfer range of approximately $q = 1$–3 fm^{-1}.

In this Letter we report evidence for a modification of the effective interaction near momentum transfer $q = 0$. Our result is based on the comparison of polarization transfer for several $\Delta J^\pi = 1^+$ transitions at a scattering angle of 0°. For this type of transition at this angle, angular momentum transfer of $\Delta L = 0$ dominates and the effects of details of the nuclear wave functions and spin-orbit distortions are minimized. Polarization transfer for 1^+ transitions at this angle is sensitive to the relative strength of the central and tensor-exchange interactions.

We have measured the longitudinal polarization transfer observable $D_{LL}(0°)$ for the ^{2}H$(\vec{p},\vec{n})$ and ^{12}C$(\vec{p},\vec{n})$ reactions at 318 MeV and 494 MeV, and for the ^{14}C$(\vec{p},\vec{n})$ reaction at 494 MeV. The final-state interaction in the ^{2}H$(\vec{p},\vec{n})2p$ reaction restricts the two residual protons to a $^1S_0$ state for small energy loss at 0°. This reaction is therefore well described as $\Delta J^\pi = 1^+$ and, under the assumption that nuclear medium effects are negligible for the deuteron, serves to characterize the free NN interaction amplitudes relevant to 1^+ transitions at 0°. The ^{2}H$(\vec{p},\vec{n})$ results reported here agree well with the recent lower-resolution measurements of McNaughton *et al.* [5]. Furthermore, both sets of ^{2}H measurements agree well with free NN scattering constrained to the $\Delta J^\pi = 1^+$ channel. The ^{12}C$(\vec{p},\vec{n})$ and ^{14}C$(\vec{p},\vec{n})$ results, however, differ systematically from the ^{2}H results and from estimates based on free NN amplitudes. Distorted-wave impulse approximation (DWIA) calculations do not reveal any significant effects from distortions or details of the transition density. Because our data-to-data comparison minimizes the reaction-model uncertainties that are unavoidable in comparisons to calculations only, we therefore argue that the systematic experimental difference between the polarization transfer for deuterium and carbon reflects a change in the effective interaction components pertinent to 1^+ transitions near $q = 0$.

Previous measurements of polarization transfer at 0° have been reported for Gamow-Teller (1^+) transitions in a variety of nuclei, ranging from ^{6}Li to ^{90}Zr, at energies ranging from 120 to 200 MeV [6,7]. The average value of the transverse polarization transfer coefficient $D_{NN}(0°)$ observed in these measurements is consistent with minimal tensor contributions at these energies. The present experiment explores Gamow-Teller reactions at higher energies, where the free NN interaction leads to expectations that the effects of tensor contributions will be more pronounced.

The present data were obtained with the neutron time-of-flight (NTOF) facility at LAMPF. The experimental techniques and equipment are described in more detail elsewhere [2,8]. We summarize the main points here.

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The polarized beam was provided by an optically pumped polarized ion source [9], with the polarization direction cycled through normal, reverse, and unpolarized states every 3 min. The beam was accelerated to energies of 318 or 494 MeV in the LAMPF linac, and nonaccelerating rf modules in the linac were used to manipulate the phase space of the beam to produce a time focus at the detector [10]. Beam polarization was continuously monitored by a pair of beamline polarimeters separated by a 28° bend. The average longitudinal (L-type) beam polarization delivered to target was about 54%.

The L-type polarization of neutrons produced at 0° by $(\vec{p},\vec{n})$ reactions was analyzed by first precessing the neutron spin in the vertical and horizontal dipole fields of clearing and sweep magnets in the neutron path. The fields of the two magnets were adjusted to produce approximately equal N and S type polarization components at the neutron detector. The neutron detector was stationed at a distance of 200 m for the measurements at 318 MeV, and at 400 m for the measurements at 494 MeV. These long flight paths were required for good TOF resolution. Uncertainty in the scattering angle $\theta_{\rm lab}$ is about 0.14°.

The neutron detector-polarimeter consists of four position-sensitive scintillator planes, each with a collection area of approximately 1.07 m^2. Each plane is subdivided into ten optically isolated cells with dimensions of 107 cm × 10 cm × 10 cm. Three planes consist of tanks of liquid scintillator (BC-517s), and the fourth is made up of individual bars of plastic scintillator (BC-408). The planes are arranged into front and back pairs, with an average separation of 140 cm between the front pair and the back pair. Thin scintillator planes preceding each pair serve to identify charged particles. Neutron polarization is analyzed using $(\vec{n},n)$ and $(\vec{n},p)$ reactions in the liquid scintillator in the front pair of detector planes. Time and position information is used to reconstruct the trajectory of neutrons or protons scattered into the back pair of planes. The incident neutron polarization is determined from the azimuthal intensity distribution of the scattered particles.

The effective analyzing power of the detector was determined using neutrons from the $0^+ \rightarrow 0^+$ ^{14}C$(\vec{p},\vec{n})^{14}$N(2.31 MeV) reaction at 494 MeV, and the $1^+ \rightarrow 0^+$ ^{2}H$(\vec{p},\vec{n})2p$ reaction at 318 MeV and 494 MeV. The ^{14}C$(\vec{p},\vec{n})$ reaction provides neutrons at 0° with the same polarization as the incident proton beam. The polarization transfer for the ^{2}H$(\vec{p},\vec{n})$ reaction has been independently measured by McNaughton *et al.* [5]. This reaction has been used as a calibration standard at 318 MeV, and as an independent check on the calibration at 494 MeV. The ^{14}C and ^{2}H calibrations at 494 MeV agree to better than 3%. The systematic uncertainty in the polarimeter calibration is about 5% over all energies.

The ^{14}C target consists of 170 mg/cm^2 of enriched carbon powder (89% ^{14}C) packed into a nickel cell. The nickel cell has a total wall thickness of 89 mg/cm^2 but provides negligible background under the peaks of interest. This was verified using an empty cell of the same dimensions. The ^{2}H$(\vec{p},\vec{n})$ data were obtained using a CD$_2$ target with an areal density of 780 mg/cm^2. The carbon content of this target also provided data for the ^{12}C$(\vec{p},\vec{n})^{12}$N(g.s.) reaction.

Spectra for the ^{14}C$(\vec{p},\vec{n})$ and CD$_2(\vec{p},\vec{n})$ reactions are presented in Fig. 1. The CD$_2$ spectrum shows both the strong $2p$ peak from the $1^+ \rightarrow 0^+$ ^{2}H$(\vec{p},\vec{n})$ reaction and the ^{12}N(g.s.) peak from the $^{\rm nat}$C$(\vec{p},\vec{n})$ reaction. The ^{2}H$(\vec{p},\vec{n})$ NTOF results reported here correspond to integrating the region with neutron energy loss < 16 MeV. The ^{12}C$(\vec{p},\vec{n})$ results were corrected for a small underlying background (10%) from the $2p$ distribution. This correction amounted to about a 2.5% change in D_{LL}.

The factorized plane-wave impulse approximation (PWIA) offers a convenient means of predicting polarization transfer (PT) observables for simple transitions [11]. In this approximation the N-nucleus partial cross sections are described as a product of free NN amplitudes and nuclear transition densities. With isospin indices suppressed, the free NN interaction can be represented in a standard form as [12]

$$M(q) = A + C(\sigma_{1n} + \sigma_{2n}) + B\sigma_{1n}\sigma_{2n} + E\sigma_{1q}\sigma_{2q} + F\sigma_{1p}\sigma_{2p} , \quad (1)$$

or alternately as a sum of central, spin-orbit, and tensor components

$$M(q) = \overbrace{A + \frac{1}{3}(B+E+F)\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}}^{\text{central}} + \overbrace{C(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\hat{\mathbf{n}}}^{\text{spin}-\text{orbit}} + \underbrace{\frac{1}{3}(E-B)S_{12}(\hat{\mathbf{q}}) + \frac{1}{3}(F-B)S_{12}(\hat{\mathbf{p}})}_{\text{tensor}} , \quad (2)$$

where

$$\mathbf{q} = \mathbf{k}_i - \mathbf{k}_f, \quad \mathbf{p} = \frac{1}{2}(\mathbf{k}_i + \mathbf{k}_f), \quad \text{and} \quad \hat{\mathbf{n}} = \hat{\mathbf{p}} \times \hat{\mathbf{q}}.$$

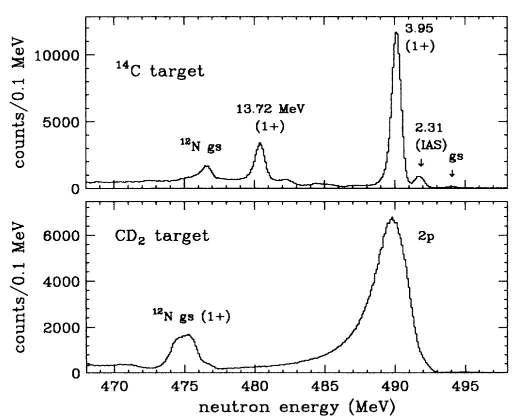

FIG. 1. Zero-degree spectra for the ^{14}C(p,n) and CD$_2(p,n)$ reactions at 494 MeV and $\theta_{\rm lab} = 0°$. The energy resolution obtained in the ^{14}C(p,n) measurements averaged about 750 keV (FWHM). Excitation energies for a few states are indicated.

For transitions in which a single (L,S,J) angular-momentum amplitude is dominant the PT coefficients reduce in the PWIA to ratios of linear combinations of the free NN amplitudes [11]. In particular, for zero-degree $(C=0,\ E=B)$ $\Delta J^\pi = 1^+$ transitions with $\Delta L = 0$,

$$D_{LL}(0^\circ) = \frac{F^2 - 2B^2}{F^2 + 2B^2}. \tag{3}$$

If the tensor-exchange interaction is zero $(F = B)$, then $D_{LL}(0^\circ) = -1/3$. Deviations of D_{LL} from this nominal value of $-1/3$ therefore directly reflect the strength $F-B$ of the $S_{12}(\hat{\mathbf{p}})$ tensor interaction.

The zero-degree PT observables are not independent. For Gamow-Teller transitions the longitudinal and transverse coefficients are related according to

$$1 + D_{LL}(0^\circ) + 2D_{NN}(0^\circ) = 0. \tag{4}$$

This relation makes it possible to convert and compare the present D_{LL} measurements with previous D_{NN} results.

Our new D_{LL} results, the recent results of McNaughton *et al.* [5] for $^2\mathrm{H}(\vec{p},\vec{n})$, and previous measurements from IUCF [6,7,13] are plotted in Fig. 2. The IUCF data have been converted from D_{NN} to D_{LL} using Eq. (4). Also plotted are two predictions based on free NN scattering constrained to the $\Delta J^\pi = 1^+$ channel. The dashed line represents the parametrized calculations for $^2\mathrm{H}(\vec{p},\vec{n})$ performed by Bugg and reported in the paper by McNaughton [5]. The solid line represents the prediction of Eq. (3) using free NN amplitudes from a phase-shift analysis by Bugg and Bryan [14]. The parametrized calculation by Bugg agrees quite well with the $^2\mathrm{H}(\vec{p},\vec{n})$ data. The two calculations also agree well below 500 MeV. At higher energies the difference is due to new additions to the NN database that were not included in the earlier phase-shift analysis [14]. Calculations by Bugg and Wilkin [15] indicate that, aside from the angular momentum constraint imposed by the $^1S_0$ final state, details of the deuteron wave function have negligible effect on the value of D_{LL}. Such details produce deviations in the expected value of D_{LL} that differ by less than 1% from the true "free" value, and are well within the experimental uncertainty. The net polarization transfer is also insensitive to the exact region of integration over the $^2\mathrm{H}(\vec{p},\vec{n})$ excitation energy distribution [8,16].

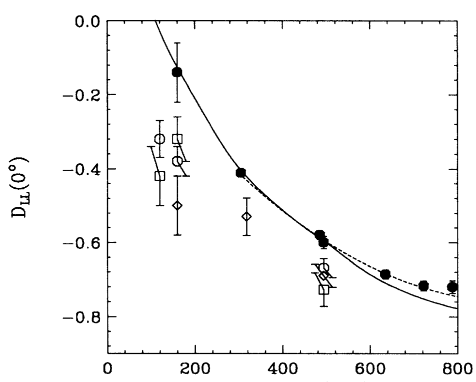

FIG. 2. Zero-degree polarization transfer for $^2\mathrm{H}(\vec{p},\vec{n})$ (solid circles), $^{14}\mathrm{C}(\vec{p},\vec{n})$ (open circles = 3.95 MeV, boxes = 13.72 MeV), and $^{12}\mathrm{C}(\vec{p},\vec{n})$ (diamonds). Data points at 318 MeV and 494 MeV are from the present experiment. The ^{12}C and ^{14}C data below 300 MeV are from D_{NN} measurements [6,7] converted using Eq. (4). The error bars are statistical, except for ^{2}H points from McNaughton *et al.* [5] at 305, 485, 635, 722, and 788 MeV, which include systematic uncertainties. The dashed line corresponds to calculations by Bugg reported in Ref. [5]. The solid line corresponds to the Bugg and Bryan phase shift amplitudes obtained from Ref. [14].

The $^{12}\mathrm{C}(\vec{p},\vec{n})$ and $^{14}\mathrm{C}(\vec{p},\vec{n})$ results in Fig. 2 systematically fall below the values for $^2\mathrm{H}(\vec{p},\vec{n})$. At 494 MeV the average ^{2}H value is -0.59 ± 0.01 while the average of the three carbon measurements is -0.69 ± 0.02. Because the ^{2}H and carbon measurements were made under the same conditions, the difference is largely unaffected by systematic uncertainty in the polarimeter calibration. Factors that may contribute to this difference include details of the nuclear wave functions, distortion effects, or differences between the effective and free NN amplitudes.

The nuclear wave functions can influence the value of D_{LL} by invalidating the assumptions that lead to Eq. (3). For example, a large $\Delta L = 2$ amplitude can change the relative importance of the tensor contribution. We have investigated the likely size of wave-function and distortion effects by performing distorted-wave impulse approximation (DWIA) calculations for 500 MeV scattering. The calculations were done with the distorted-waves code DW81 [17], using the 515-MeV t-matrix interaction of Franey and Love [18] and optical potentials obtained from Jones *et al.* [19]. Calculations were done for the $^{12}\mathrm{C}(\vec{p},\vec{n})^{12}\mathrm{N}$(g.s.) and $^{14}\mathrm{C}(\vec{p},\vec{n})^{14}\mathrm{N}$(3.95 MeV) reactions using the wave functions of Lee and Kurath [20] with the $\Delta L = 0$ amplitude reduced to give the correct β-decay transition strength. Additional calculations were done using pure p-shell particle-hole configurations: $\frac{1}{2} \to \frac{1}{2}$, $\frac{1}{2} \to \frac{3}{2}$, and $\frac{3}{2} \to \frac{3}{2}$, for target masses ranging from $A =$ 6–15. The calculations were performed with both the full set of optical potentials and with the optical potentials set to zero (plane waves limit). The effect of distortions is to make the calculated values of D_{LL} more positive by an amount $\Delta D_{LL} \approx 0.02$, which is in the wrong direction and is too small to explain the difference between the experimental results for deuterium and carbon. The wave-function differences simply introduce a spread of about $\delta D_{LL} = \pm 0.02$ in the calculated values. This is again too small to be a plausible explanation for the observed differences. Finally, variations in D_{LL} associated with a nonzero reaction Q value are small: for $^{12}\mathrm{C}(p,n)$, with $Q = -18.1$ MeV, the change in D_{LL} amounts to about -0.02 compared to what it would be for zero energy loss. The effect on the other transitions is much smaller. We therefore conclude that, within the context of this reaction model, the effective isovector interaction amplitudes F and B for scattering from carbon are different from the free NN amplitudes near zero momentum transfer. This difference is evident at lower energies, where the low-momentum-transfer interaction appears to be predominantly central, and also near 500 MeV, where the tensor interaction has a significant effect on the observed polarization transfer (and a much smaller $\approx 5\%$ effect on the cross section).

The data presented here suggest the need for careful consideration of medium effects in the analysis of intermediate-energy nucleon-nucleus scattering. It is important to note that such effects are evident here for the *spin-dependent* interaction, which plays a central role in studies of current interest. For example, in (p,p') and (p,n) reactions the nuclear response to the transverse spin operator $\boldsymbol{\sigma} \times \mathbf{q}$ is primarily driven by the transverse F and B amplitudes in the nucleon-nucleon interaction. These amplitudes contribute directly to the observations reported here. If these amplitudes are altered at larger momentum transfers as well, then the transverse response derived from quasifree (p,n) cross sections (by dividing out the *free* amplitudes) will have the wrong magnitude.

Candidate models for exploring nuclear-medium effects include the relativistic model of Horowitz and Murdock [21] or the vector-meson rescaling model of Brown and Rho [22–24]. A rescaled ρ-meson mass will affect both the central and tensor components of the interaction. At least two groups have investigated such effects in inelastic proton scattering by making appropriate adjustments to the t-matrix interaction used in DWIA calculations [3,4]. For the present case, we emphasize that it is the tensor-*exchange* interaction $S_{12}(\hat{\mathbf{p}})$ that produces the large deviation of D_{LL} from its central-only value of $-1/3$. This term has no counterpart in local coordinate space meson-exchange interactions. It is therefore difficult to assess whether the effect reported here is consistent with the results of the (p,p') studies, which are mainly sensitive to the *direct* tensor interaction. For example, a calculation employing the modified tensor interaction of Hintz *et al.* [4] for 325 MeV scattering drives $D_{LL}(0^\circ)$ in the wrong direction. Additional work is clearly needed to make a consistent connection to the (p,p') results at larger momentum transfer.

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[1] J.B. McClelland *et al.*, Phys. Rev. Lett. **69**, 582 (1992).
[2] X.Y. Chen *et al.*, Phys. Rev. C **47**, 2159 (1993).
[3] Edward J. Stephenson and Jeffrey A. Tostevin, in *Spin and Isopin in Nuclear Interactions*, Proceedings of the International Conference, Telluride, Colorado, 11–15 March 1991, edited by Scott W. Wissink, Charles D. Goodman, and George E. Walker (Plenum, New York, 1991), p. 281; N.M. Hintz, A. Sethi, and A.M. Lallena, *ibid.*, p. 287.
[4] N.M. Hintz, A.M. Lallena, and A. Sethi, Phys. Rev. C **45**, 1098 (1992).
[5] M.W. McNaughton *et al.*, Phys. Rev. C **45**, 2564 (1992).
[6] T.N. Taddeucci *et al.*, Phys. Rev. Lett. **52**, 1960 (1984).
[7] T.N. Taddeucci, Can. J. Phys. **65**, 557 (1987).
[8] D.J. Mercer, Ph.D. thesis, University of Colorado, 1992.
[9] R.L. York *et al.*, in *Proceedings of the International Workshop on Polarized Ion Sources and Polarized Gas Jets, February 1990, Tsukuba, Japan* (KEK Report No. 90-15 A, November 1990), p. 170.
[10] J.B. McClelland *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **276**, 35 (1989).
[11] J.M. Moss, Phys. Rev. C **26**, 727 (1982).
[12] A.K. Kerman, H. McManus, and R.M. Thaler, Ann. Phys. (N.Y.) **8**, 551 (1959).
[13] H. Sakai *et al.*, Phys. Rev. C **35**, 344 (1987).
[14] D.V. Bugg and R.A. Bryan, phase shift solution dated November 1991, parametrized in the Scattering Analysis Interactive Dial-in program (SAID) of R.A. Arndt and L.D. Roper, Virginia Polytechnic Institute and State University (unpublished).
[15] D.V. Bugg and C. Wilkin, Nucl. Phys. **A467**, 575 (1987).
[16] D.V. Bugg (private communication).
[17] R. Schaeffer and J. Raynal, program DWBA70 (unpublished); J. R. Comfort, extended version DW81 (unpublished).
[18] M.A. Franey and W.G. Love, Phys. Rev. C **31**, 488 (1985).
[19] K.W. Jones *et al.*, Phys. Rev. C **33**, 488 (1985).
[20] T.-S.H. Lee and D. Kurath, Phys. Rev. C **21**, 293 (1980).
[21] C.J. Horowitz and D.P. Murdock, Phys. Rev. C **37**, 2032 (1988); C.J. Horowitz, in *Spin and Isopin in Nuclear Interactions* (Ref. [3]), p. 415.
[22] G.E. Brown, E. Osnes, and M. Rho, Phys. Lett. **163B**, 41 (1985).
[23] G.E. Brown and M. Rho, Phys. Lett. B **237**, 3 (1990).
[24] G.E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720 (1991).