Spin Transverse-Longitudinal Composition of the Isovector Effective *NN* Interaction from $^{10}\mathrm{B}(\vec{p},\vec{p}\,')$ at 200 MeV

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Cross section (σ), analyzing power (A_y), induced polarization (P), and normal polarization transfer coefficient ($D_{NN'}$) data have been measured for scattering of 200-MeV polarized protons from ^{10}B. Data for the 3^+, $T=0$ to 0^+, $T=1$ (1.74 MeV) isovector $0\hbar\omega$ stretched transition are compared to results of distorted-wave calculations. While σ, A_y, and P are reasonably described by calculations based on the free nucleon-nucleon (NN) t matrix, the $D_{NN'}$ data are not. The results suggest a larger transverse to longitudinal spin-dependent interaction ratio than is expected from free NN scattering.

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Differential cross section (σ) and analyzing power (A_y) data for stretched transitions in inelastic proton scattering at energies above 100 MeV were first used to obtain definitive information on the tensor component of the effective nucleon-nucleon (NN) interaction more than a decade ago [1]. Presently, more detailed information about the spin-dependent components of the effective NN interaction can be obtained as a result of the development of high-quality polarimeters [2–4] that allow the acquisition of precision polarization transfer data [5,6]. Data of this type for stretched transitions are of considerable interest because of recent QCD-based speculation [7,8] about modification of meson masses in the nuclear medium, which affects the spin-dependent effective NN interaction components [9–11] and the continuum response [12]. In this Letter we report a measurement of the normal polarization transfer coefficient ($D_{NN'}$) for the 3^+, $T=0$ to 0^+, $T=1$ (1.74 MeV) isovector $0\hbar\omega$ stretched transition in $^{10}\mathrm{B}(\vec{p},\vec{p}\,')$ at 200 MeV. This transition is essentially free from continuum background, permitting proton scattering cross sections and spin observables to be obtained over a range of momentum transfer broader than previously reported [5,6]. The $D_{NN'}$ data reported here are in strong disagreement with distorted-wave (DW) calculations based on standard t-matrix [13] and g-matrix [14] representations of the effective NN interaction derived from free NN scattering data. A substantial increase in the ratio of the transverse to longitudinal spin components of the NN interaction in the nuclear medium is required to resolve the discrepancy. This is in accord with the interaction modifications suggested by Ref. [8].

A qualitative illustration of the physical content of $D_{NN'}$ for isovector transitions can be obtained from plane-wave (PW) considerations. In the PW approximation, $D_{NN'}$ is related to the ratio of the transverse spin ($\bar{v}_\tau^t=\bar{v}_{\sigma\tau}^C+\bar{v}_\tau^T$) and longitudinal spin ($\bar{v}_\tau^l=\bar{v}_{\sigma\tau}^C-2\bar{v}_\tau^T$) couplings, which are combinations of the isovector central ($\bar{v}_{\sigma\tau}^C$) and isovector tensor ($\bar{v}_\tau^T$) components of the effective NN interaction including knockout exchange terms [15]. Specifically, neglecting small isovector spin-orbit and tensor exchange interference terms,

$$D_{NN'}\approx-(1+|\rho_J^t\bar{v}_\tau^t/\rho_J^l\bar{v}_\tau^l|^2)^{-1}, \tag{1}$$

where ρ_J^t and ρ_J^l are the transverse and longitudinal nuclear transition densities and J is the total angular momentum transfer. The ρ_J^t for the transition of interest has been determined from electron scattering [16] for 100 MeV/$c\le q\le 800$ MeV/c. For stretched transitions, $|\rho_J^t|^2/|\rho_J^l|^2=(J+1)/J$ to a very good approximation, so $D_{NN'}$ is essentially independent of nuclear structure. This allows for the determination of the relative strength of the transverse and longitudinal spin components of the effective NN interaction. In the meson-exchange picture $\bar{v}_\tau^l$ and $\bar{v}_\tau^t$ are largely determined by the exchange of one π and one ρ meson, respectively [17], and $\bar{v}_\tau^t/\bar{v}_\tau^l$ will be sensitive to any modification of mesonic properties in the medium.

The experiment was performed at the Indiana University Cyclotron Facility using the high-resolution K600 magnetic spectrometer to momentum analyze the scattered protons. The incident 200-MeV proton beam polarization was normal to the scattering plane and its orientation was automatically reversed every 30 s. The beam polarization was typically about 75% for each spin orientation and was measured continuously throughout the run by monitoring $p+d$ elastic scattering via two polarimeters in the beam line [3]. The polarization of the scattered protons was measured by a polarimeter, based on $p+C$ elastic scattering, mounted in the focal plane of the spectrometer [4]. The ^{10}B targets were 99.5% enriched.

Differential cross sections and analyzing powers were measured for laboratory scattering angles of 7.5° to 80° (q about 84 to 790 MeV/c). Induced polarizations (P) and normal polarization transfer coefficients were measured from 20° to 60° (q about 223 to 625 MeV/c). Cross sections and spin observables were extracted for most of the states in the excitation energy region up to about 6.5 MeV. Only the elastic scattering cross section and the transition to the 0^+ level at 1.74 MeV are discussed in this Letter.

The elastic differential cross section data together with previously reported measurements, where no polarization information was obtained [18], are shown in Fig. 1. Only statistical errors are shown in the figures. The systematic uncertainty is estimated to be about 10% for the cross sections. The elastic data are important since they provide the basis for estimating the distortion effects needed to describe quantitatively the inelastic stretched transition of primary interest in this work. There is additional intrinsic interest in the elastic scattering measurements alone since ^{10}B is a nonspherical nucleus with ground-state spin $I_g=3$ and a large quadrupole moment $Q=8.47\pm0.6\ e\,\mathrm{fm}^2$ [19].

The solid curve in Fig. 1 is the result of a calculation following the approach of Carpenter and collaborators [20], who have made realistic, microscopic single-scattering model estimates of σ and A_y for the scattering of 200-MeV protons from five light nonzero spin nuclei ^{6,7}Li, ^{9}Be, and ^{10,11}B using the Hamburg g matrix [14], with Cohen-Kurath [21] shell-model densities adjusted to reproduce available weak and electromagnetic data, and employing an approximate treatment of knockout exchange. The theoretical result is in reasonable agreement with the data. The individual $J=0$–3 multipole contributions to the cross section are shown separately. The $J=0$ and $J=2$ multipole contributions, which are driven by the spin-independent central and spin-orbit components of the interaction, are clearly dominant. Since it is known [22] that the Franey-Love (FL) t matrix [13] gives a somewhat better representation of data for unnatural parity transitions than the Hamburg g matrix, additional calculations were made using the FL interaction to generate the $J=1$ and 3 multipole elastic scattering potentials. This change produces no essential modification in the cross section result shown in Fig. 1.

The σ, A_y, P, and $D_{NN'}$ data for the 3^+, $T=0\rightarrow0^+$, $T=1$ isovector stretched transition are shown in Fig. 2. The long-dashed curves in Fig. 2 are the results of DW calculations based upon the FL interaction and the spherical elastic scattering potential used to generate the results in Fig. 1. The transition density was constructed from a Woods-Saxon radial wave function [18] and the

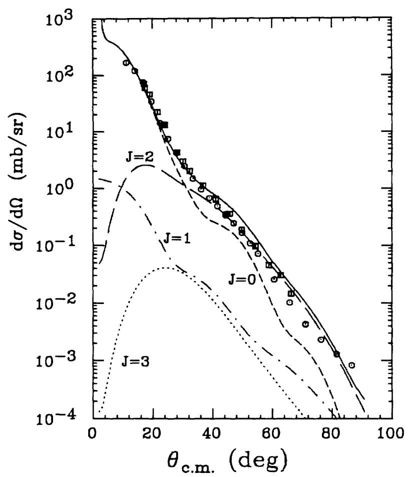

FIG. 1. The differential cross section data of the present work (circles) and of Ref. [18] (squares) for the elastic scattering of 200-MeV protons from ^{10}B compared with a theoretical prediction. The solid curve is the sum of the individual multipole contributions: $J=0$ (short-dashed curve), $J=1$ (dash-dotted curve), $J=2$ (long-dashed curve), and $J=3$ (dotted curve) for the Hamburg g matrix.

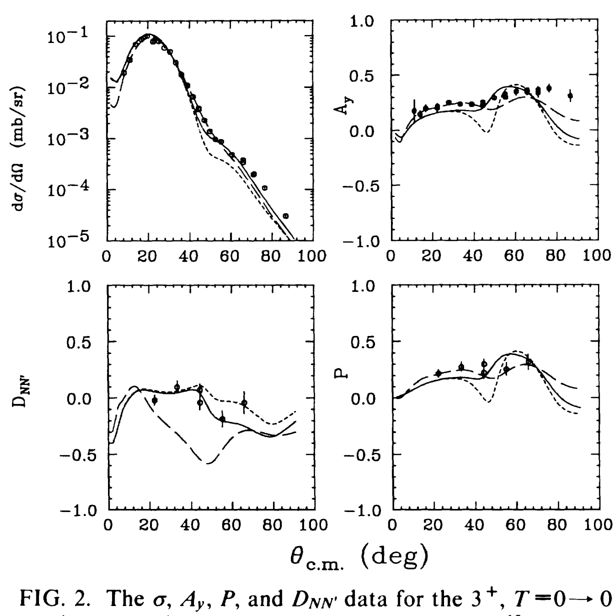

FIG. 2. The σ, A_y, P, and $D_{NN'}$ data for the 3^+, $T=0\rightarrow0^+$, $T=1$ (1.74 MeV) $0\hbar\omega$ stretched transition in the $^{10}\mathrm{B}(\vec{p},\vec{p}')$ reaction at 200 MeV compared with theoretical results. The long-dashed curves represent the results of DW calculations obtained with the FL interaction. The short-dashed curves are the results obtained with the composite $\pi+\rho$ FL interaction with $m^*/m=0.9$; the solid curves are obtained with $m^*/m=0.9$ and the modification of the imaginary interaction components shown in Fig. 3.

Cohen-Kurath $(p_{3/2})^2$ shell-model amplitude [21], which was adjusted slightly to fit the electron scattering data of Ref. [17]. The FL interaction gives a reasonable description of the σ, A_y, and P data; however, this interaction, which reasonably describes the $D_{NN'}$ data for free nucleon-nucleon scattering near 200 MeV, clearly fails to explain the $D_{NN'}$ data for ^{10}B. Additional results obtained using the Hamburg g matrix to generate the transition scattering potentials are not shown. This interaction gives a somewhat poorer representation of the data than the FL interaction. We have also investigated the sensitivity of the theoretical results to the approximate treatment of the knockout exchange amplitudes and variations in the optical potentials. The main qualitative features of the results are insensitive to these details. $D_{NN'}$ is particularly insensitive to distortion effects for $\theta_{c.m.} \lesssim 45°$.

The theoretical predictions for $D_{NN'}$ are much more negative than the data. The PW formula for $D_{NN'}$, Eq. (1), indicates that enhancement of the $|\bar{v}^t_\tau/\bar{v}^l_\tau|$ ratio will produce improved agreement between theory and experiment. Just such an effect is produced by the nuclear medium modification of the ρ-meson contribution to the isovector spin-dependent central and tensor interaction components suggested by Brown and Rho [8]. Specifically, in the $\pi+\rho$ picture of Ref. [8], the ρ coupling constant is enhanced by $(m/m^*)^2$, where m^* is the density-dependent nucleon effective mass, leading to an overall reduction of the magnitude of isovector tensor interaction and an enhancement of the isovector spin-dependent central interaction.

To illustrate the sensitivity of the present data to this effect, we have examined a modified interaction in which the real parts of the central and tensor components of the FL t matrix were replaced by an equivalent $\pi+\rho$ exchange model functional form [17]. The real parts of the transverse and longitudinal spin-dependent components of the composite $\pi+\rho$ FL interaction as a function of momentum transfer q are shown as dashed curves in Figs. 3(a) and 3(b), respectively. These correspond to $m^*/m = 1.0$. Also shown as solid and dash-dotted curves are the real interactions obtained with $m^*/m = 0.90$ and 0.85. In the region $q = 1-3$ fm^{-1}, it is seen that the real transverse component increases slightly with decreasing m^*/m and the longitudinal component initially decreases and then starts to increase again.

The results of distorted-wave calculations based on this composite $\pi+\rho$ FL interaction with $m^*/m = 1.0$ are essentially identical to those for the FL interaction shown in Fig. 2. The short-dashed curves in Fig. 2 are the scattering results obtained by using the interaction with $m^*/m = 0.9$ [23]. The improvement in $D_{NN'}$ is clear, although there is some deterioration in the quality of the results for σ, A_y, and P. These defects can largely be removed by making adjustments in the small imaginary interaction components. As an illustration of this point, the solid curves in Fig. 2 have been obtained with m^*/m $= 0.9$ and an adjustment of the imaginary components indicated by the solid curve in Figs. 3(c) and 3(d). It is significant that this final correction has the desired effect on σ, A_y, and P at back angles ($\theta_{c.m.} \gtrsim 45°$, $q \gtrsim 2.3$ fm^{-1}) but produces no change in $D_{NN'}$ at $q < 2.3$ fm^{-1}. $D_{NN'}$ at low q is indeed determined primarily by $|\bar{v}^t_\tau/\bar{v}^l_\tau|$, which changes by more than a factor of 6 at $q \approx 1.6$ fm^{-1} as m^*/m goes from 1.0 to 0.9. Systematics [1] preclude such a large violation of the approximate stretched-state constraint on the $|\rho^t_J/\rho^l_J|$ ratio, which also enters Eq. (1).

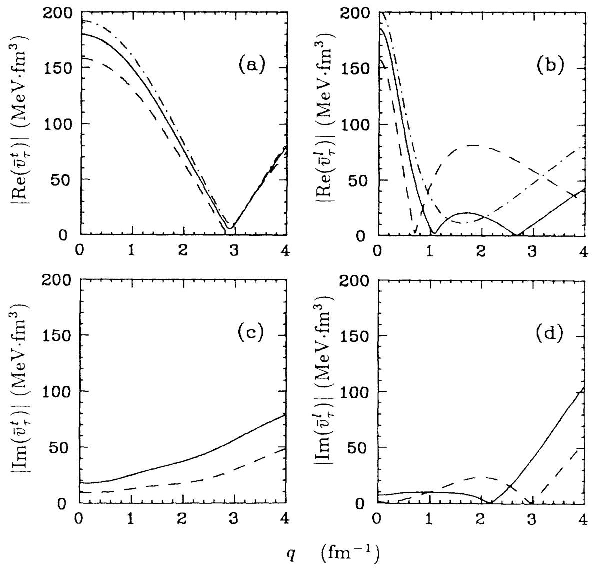

FIG. 3. (a) Modulus of real parts of $\bar{v}^t_\tau$ for the composite $\pi+\rho$ FL interaction with $m^*/m = 1.0$ (dashed curve), $m^*/m = 0.9$ (solid curve), and $m^*/m = 0.85$ (dash-dotted curve); (b) the same as (a) for $\bar{v}^l_\tau$; (c) modulus of the imaginary part of $\bar{v}^t_\tau$ for the composite $\pi+\rho$ FL interaction (dashed curve) and the modified imaginary interaction used to generate the final results in Fig. 2 (solid curve); (d) the same as (c) for $\bar{v}^l_\tau$.

In conclusion, the spin-dependent parts of the free effective nucleon-nucleon interaction are not consistent with the normal polarization transfer coefficient data for the $0\hbar\omega$ isovector stretched transition in ^{10}B. Given that ρ^t_J for this excitation is well known from electron scattering, ρ^l_J is reasonably constrained by the stretched nature of the transition, and the single-scattering model is reliable for 200-MeV protons, then these results provide a clear signature of the need for an increase in the expected $|\bar{v}^t_\tau/\bar{v}^l_\tau|$ ratio for the effective nucleon-nucleon interaction. The $\pi+\rho$ model value of $m^*/m = 0.9$ obtained corresponds to $\rho \approx \rho_0/3$, which is expected for a surface transition. Stephenson and Tostevin [11] and Hintz, Lellena, and Sethi [10] have reported similar values in stretched-state studies of spin observables data in ^{16}O and cross section data in ^{208}Pb, respectively. It is intriguing that these results are consistent with the theoretical suggestion of Brown and Rho concerning modification of the ρ

meson in the nuclear medium. Measurements of the in-plane polarization transfer coefficients for ^{10}B are in progress to further study this issue. Additional work on the consequences of these interaction modifications for other transitions is also in order.

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[1] R. A. Lindgren *et al.*, Phys. Rev. Lett. **42**, 1524 (1979); F. Petrovich *et al.*, Phys. Lett. **95B**, 166 (1980); S. Yen *et al.*, Phys. Lett. **105B**, 421 (1981).

[2] J. B. McClelland *et al.*, Los Alamos Report No. LA-UR-84-1671, 1984 (unpublished).

[3] A. K. Opper *et al.*, IUCF Scientific and Technical Report-1988 (unpublished), p. 88; S. W. Wissink *et al.*, J. Phys. (Paris), Colloq. Suppl. 22, **51**, C6-557 (1990).

[4] S. W. Wissink, in *Spin and Isospin in Nuclear Interactions,* edited by S. W. Wissink *et al.* (Plenum, New York, 1991), p. 253.

[5] C. Olmer, in *Antinucleon- and Nucleon-Nucleus Interactions,* edited by G. E. Walker *et al.* (Plenum, New York, 1985), p. 261.

[6] E. Donoghue *et al.*, Phys. Rev. C **43**, 213 (1991).

[7] T. Hatsuda and S. Houng Lee, Phys. Rev. C **46**, R34 (1992).

[8] G. E. Brown and M. Rho, Phys. Lett. B **237**, 3 (1990); Phys. Rev. Lett. **66**, 2720 (1991).

[9] A. Hosaka and H. Toki, Nucl. Phys. **A529**, 429 (1991).

[10] N. M. Hintz, A. M. Lellena, and A. Sethi, Phys. Rev. C **45**, 1098 (1992).

[11] E. J. Stephenson and J. A. Tostevin, in *Spin and Isospin in Nuclear Interactions* (Ref. [4]), p. 281.

[12] L. B. Rees *et al.*, Phys. Rev. C **34**, 627 (1986); J. B. McClelland *et al.*, Phys. Rev. Lett. **69**, 582 (1992).

[13] M. A. Franey and W. G. Love, Phys. Rev. C **31**, 488 (1985).

[14] H. V. von Geramb and W. Bauhoff, Universitat Hamburg report (unpublished); H. V. von Geramb, in *The Interaction Between Medium Energy Nucleons in Nuclei,* edited by H. O. Meyer, AIP Conf. Proc. No. 97 (AIP, New York, 1983), p. 44.

[15] W. G. Love *et al.*, Can. J. Phys. **65**, 536 (1987); W. G. Love, M. A. Franey, and F. Petrovich, in *Spin Excitations in Nuclei,* edited by F. Petrovich *et al.* (Plenum, New York, 1984), p. 205.

[16] R. S. Hicks *et al.*, Phys. Rev. Lett. **60**, 905 (1988).

[17] J. Speth, V. Klemt, J. Wambach, and G. E. Brown, Nucl. Phys. **A343**, 382 (1980).

[18] P. R. Lewis *et al.*, Nucl. Phys. **A532**, 583 (1991); P. R. Lewis, Ph.D. thesis, University of Melbourne, 1990 (unpublished).

[19] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 1 (1988).

[20] A. W. Carpenter, F. Petrovich, R. J. Philpott, and J. A. Carr (to be published); A. W. Carpenter, Ph.D. thesis, Florida State University, 1988 (unpublished); C. W. Glover *et al.*, Phys. Rev. C **41**, 2487 (1990); C. W. Glover *et al.*, Phys. Rev. C **43**, 1664 (1991).

[21] S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).

[22] C. Olmer *et al.*, Phys. Rev. C **29**, 361 (1984).

[23] The $\pi+\rho$ model interaction has been scaled by m^*/m to fix the peak differential cross section for the transition of interest. The appearance of this empirical factor suggests that medium modifications to the correlation corrections in the $\pi+\rho$ model may be necessary. This factor is included in the curves shown in Fig. 2.