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Polarization transfer in the $^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N}$ reaction

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The first $(\vec{e},e'\vec{p})$ polarization transfer measurements on a nucleus heavier than deuterium have been carried out at Jefferson Laboratory. Transverse and longitudinal components of the polarization of protons ejected in the reaction $^{16}\mathrm{O}(\vec{e},e'\vec{p})$ were measured in quasielastic perpendicular kinematics at a Q^2 of 0.8 $(\mathrm{GeV}/c)^2$. The data are in good agreement with state of the art calculations.

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Polarization transfer in the $(\vec{e},e'\vec{p})$ reaction on a proton target is a direct measure of the ratio of the electric and magnetic form factors of the proton, G_E^p/G_M^p. When such measurements are carried out on a nuclear target, the polarization transfer observables are sensitive to the form factor ratio of the proton embedded in the nuclear medium. Because such experiments involve the measurement of ratios of polarizations at a single kinematic setting, the systematic errors are small, and different from those in standard Rosenbluth separations.

We report here measurements of polarization transfer in the $^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N}$ reaction, the first such measurement on a nucleus heavier than deuterium [1]. The experiment, E89-033 at the Thomas Jefferson National Accelerator Facility (JLab), was part of the commissioning effort for Hall A [2]. It was the first experiment to use a polarized beam at JLab, and the first to use the focal plane polarimeter (FPP) mounted on the high-resolution hadron spectrometer. Comparison of the results with state-of-the-art calculations lays the ground work for high precision tests of changes of the form factors in the nuclear medium. The distorted-wave impulse approximation (DWIA) provides a good description of the reaction, and the predictions are shown to be insensitive to various theoretical corrections.

The issue of possible modification of the properties of hadrons in the nucleus has been attracting experimental and theoretical attention for some years. It remains unsettled. Interpretations of inclusive (e,e') cross-section measurements in the y-scaling regime suggest that the radius of the nucleon is changed by less than a few percent at least for values of the four-momentum transfer squared (Q^2) up to about 1 $(\mathrm{GeV}/c)^2$ [3]. These measurements are primarily sensitive to the magnetic form factor. Measurements of the Coulomb sum rule over a similar region in Q^2 indicate that the electric form factor in $^3\mathrm{He}$ is close to its free value [4], and some studies suggest that this is true in $^{12}\mathrm{C}$ and $^{56}\mathrm{Fe}$ as well [5], but recent work disputes this conclusion [6]. Measurements of the form factor ratio of the nucleon in nuclei by Rosenbluth separations in $(e,e'p)$ reactions indicated changes of about 25% at low Q^2 [7], but some other experiments and theoretical analyses disagree [8]. Recent theoretical work by the Adelaide group based on the quark-meson coupling model predicted changes in the ratio of the two form factors for $^{16}\mathrm{O}$ of roughly 10% at Q^2 around 1 $(\mathrm{GeV}/c)^2$ and about 20% or larger at about 2.5 $(\mathrm{GeV}/c)^2$ [9]. Changes of this magnitude have also been suggested previously [10].

For the free nucleon, the polarization transfer can be written in terms of the form factors as [11]

$$I_0 P_l' = \frac{E+E'}{m_p}\sqrt{\tau(1+\tau)}G_M^2\tan^2(\theta/2), \tag{1}$$

$$I_0 P_t' = -2\sqrt{\tau(1+\tau)}G_M G_E\tan(\theta/2), \tag{2}$$

$$I_0 = G_E^2+\tau G_M^2[1+2(1+\tau)\tan^2(\theta/2)], \tag{3}$$

$$\tau = Q^2/4m_p^2, \tag{4}$$

where E and E' are the energies of the incident and scattered electron, θ is the electron scattering angle, and m_p is the proton mass. P_l' and P_t' are the longitudinal and transverse polarization transfer observables, respectively. The two components of the actual polarization in the scattering plane [12] are hP_l', parallel to the proton momentum, and hP_t', perpendicular to the proton momentum; h is the electron beam polarization. The measured polarizations change sign when the electron helicity changes sign, so these polarization transfer quantities are insensitive to instrumental asymmetries in the detectors.

The ratio of the transferred polarizations is then

$$\frac{P_t'}{P_l'} = \frac{-2m_p}{(E+E')\tan(\theta/2)}\frac{G_E}{G_M}. \tag{5}$$

For a free proton target, the ratio of polarizations can be used to determine the ratio of the form factors with small systematic errors; systematic problems associated with Rosenbluth separations are eliminated. The ratio is independent of the beam polarization (assuming it is not zero) and of the analyzing power of the proton polarimeter. One experimental datum requires a coincidence measurement at a single kinematic setting. The systematic error on the ratio of polarizations in the present experiment is about ±0.022, due almost entirely to uncertainty in the precession of the proton's spin in the hadron spectrometer. Even smaller errors were achieved in the subsequent E93-027 measurements of the free form-factor ratio on a liquid-hydrogen target at a Q^2 of 0.79 $(\mathrm{GeV}/c)^2$ [13].

For nuclear targets, the polarization transfer observables depend sensitively on the nucleon form factors, but they depend also on the motion of the nucleon and on the nuclear wave functions. Even in the plane-wave impulse approximation (PWIA), the simple expression above for the ratio of transferred polarizations is modified by the change in kinematics. In addition, the observables may also be modified by other effects not included in the PWIA, such as final-state interactions of the outgoing proton, meson exchange and isobar currents, off-shell effects and the distortion of spinors by strong Lorentz scalar and vector potentials [14–19].

Electrons from the CEBAF accelerator of energy 2.45 GeV and longitudinal polarization about 30% were focused on a waterfall target with three foils whose total thickness was about 0.39 $\mathrm{g/cm^2}$. Scattered electrons were detected in the focal plane array of the high resolution electron spectrometer in Hall A at a fixed laboratory angle of 23.4° and a fixed central energy of 2.00 GeV, the quasielastic peak. Protons with a fixed central momentum of 973 MeV/c were detected in coincidence with electrons in the focal plane array of the hadron spectrometer. Measurements in quasiperpendicular kinematics were made at proton angles of 53.3° (for hydrogen data only), 55.7°, and 60.5°, corresponding to central missing momenta p_m of 0, 85, and 140 MeV/c; the acceptance was typically about ± 40 MeV/c around the central value. Elastic scattering from hydrogen dominates the spectrum at 53.3° (so that no ^{16}O data could be obtained) and is visible also at 55.7°. The missing-mass resolution of about 1 MeV was sufficient to easily distinguish the $p_{1/2}$ ground state of ^{15}N from the strongly excited $p_{3/2}$ state at 6.32 MeV, but small contributions from nearby weakly excited states could not be entirely excluded. In the continuum, a peak corresponding primarily to knockout of nucleons from the $s_{1/2}$ shell rises weakly above a (physics) background presumably related to multiparticle knockout.

The JLab focal plane polarimeter (FPP) was designed and built by a collaboration of Rutgers, William & Mary, Georgia, Norfolk State, and Regina [20–22]. The polarimeter, consisting of four tracking straw chambers and a graphite analyzer set to a thickness of 22.5 cm for this experiment, is mounted in the hadron spectrometer behind vertical drift chambers and scintillators in the focal plane. The analyzing power A_c of the FPP was taken from the parametrization by McNaughton *et al.* [23]. Measured values of A_c, obtained by analyzing data from scattering on hydrogen, have been shown to agree well with this parametrization [13]. The beam polarization was measured at varying intervals with a Mott polarimeter in the injector beam line. For the 85 MeV/c data point on ^{16}O, values of the beam polarization determined from the Mott polarimeter and from the FPP results for hydrogen are in good agreement, well within the 5% systematic error assigned to the beam polarization in the subsequent analysis of the oxygen data. The result for the ratio $\mu(G_E/G_M)$ of hydrogen measured in this experiment at a Q^2 of 0.8 (GeV/c)^2 is 0.92 ± 0.05, in agreement with previous results and with the values subsequently measured with higher precision [13].

Results for the transverse and longitudinal components of the polarization at the two central values of the missing momentum for the two bound states, $p_{1/2}$ and $p_{3/2}$, and for the region of the unbound $s_{1/2}$ state are shown in Fig. 1. The missing energy cuts on the latter extended from about 29 to 55 MeV. The polarizations are given in the scattering (lab) frame, defined by the incident and outgoing electron [12,15]. The errors shown are statistical. Systematic errors on the individual polarizations are about $\pm 6\%$, primarily due to the uncertainty in the polarization of the beam. Small acceptance averaging corrections are included [21], as are the effects of corrections to the dipole approximation for spin transport of the proton in the hadron spectrometer [21,22]. Both corrections are generally less than about 2%. Radiative corrections to the polarizations, expected to be much smaller than the statistical errors here, have not been made [24].

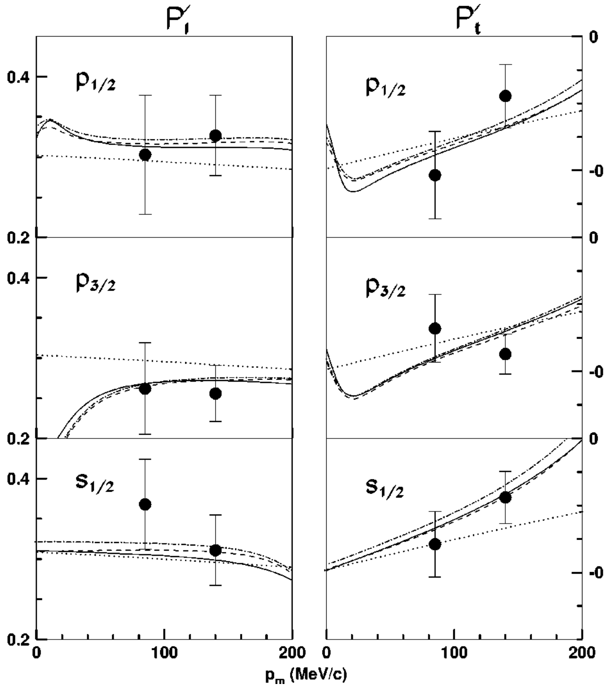

FIG. 1. Measured values of the polarization transfer observables P'_l and P'_t for the $^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N}$ reaction at $Q^2 = 0.8$ (GeV/c)^2. The theoretical curves represent plane-wave calculations (dotted) and distorted-wave calculations without spinor distortions (dashed) and with spinor distortions (dash-dot) by Kelly [18] and by Udias *et al.* [19] (solid).

The curves in Fig. 1 represent theoretical calculations based upon one-body currents and free [25] proton form factors. PWIA results, shown as dotted lines, are identical for the three states and, at $p_m = 0$, are equal to those for the free proton [15]. The p_m dependence in the PWIA calculations is dominated by the rotation of the spin axes to bring the $\hat{l}$ direction parallel to the ejectile momentum. Convection currents proportional to the initial momentum of the bound proton also produce small changes of the recoil polarizations. Final-state interactions included in DWIA calculations produce small state-dependent deviations from PWIA. The DWIA calculations by Kelly [15] are based upon a relativized Schrödinger equation and an effective momentum approximation (EMA) to the current operator. The dashed curves assume that lower and upper components of bound and ejectile spinors are related in the same way as for free protons [15]. The dash-dotted curves include relativistic dynamics (spinor distortions) through the effect of Dirac scalar and vector potentials upon the effective current operator [18]. The solid curves show the results of calculations by Moya de Guerra and Udias [19] who solve the Dirac equation directly without using the EMA. All DWIA calculations shown used the same input as the calculations of unpolarized observables in Ref. [26]. These include the EDIAO optical model of Cooper *et al.* [27], NLSH bound-state wave functions [28], the Coulomb gauge, and the cc2 off-shell current operator. For modest p_m, the recoil polarization is relatively insensitive to variations of these choices.

All DWIA calculations are in reasonable agreement with

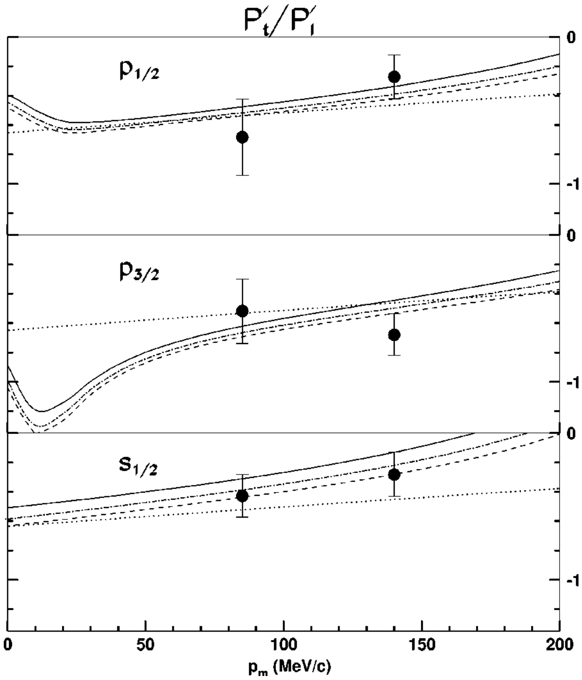

FIG. 2. Measured values of the ratio of polarization transfer observables $P_t'/\ P_l'$ for the $^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N}$ reaction at $Q^2=0.8$ $(\mathrm{GeV}/c)^2$. The theoretical curves represent plane-wave calculations (dotted) and distorted-wave calculations without spinor distortions (dashed) and with spinor distortions (dash-dotted) [18]. The solid curves use a modified current operator in which nucleon form factors depend upon local density as predicted by Lu *et al.* [9]; spinor distortions are included.

the measured data. The two calculations which include relativistic dynamics are very similar over the relevant range of p_m. This is expected, since the results of the calculation of unpolarized observables in Ref. [26] suggested that Kelly's formulation is a good approximation to the more accurate approach of Udias *et al.* for $p_m \lesssim 300$ MeV/c. The effects of relativity on the recoil polarization are small for this range of p_m and are dominated by distortion of the ejectile spinor.

Contributions from meson exchange (MEC) and isobar (IC) currents can also affect the recoil polarizations. Early calculations of the effects of MEC and IC were carried out by the Pavia group [14], and preliminary calculations by Radici [16] of this group for the present kinematics have been made. Predictions of these effects using a different approach have been published recently by Ryckebusch *et al.* [17] for the present kinematics. The scale of these effects is typically comparable to the differences among the three DWIA curves shown. The DWIA with small corrections thus provides a firm baseline for considering changes in the form factor.

The ratios of the P_t' to P_l' data for the three states are plotted in Fig. 2. Three of the theoretical curves shown there correspond to those in Fig. 1, namely the PWIA (dots), and the DWIA without spinor distortion (dashes) and with spinor distortion (dash-dot) by Kelly [18]. The data are in good agreement with the three predictions, as expected from Fig. 1. The ratio of the experimental and theoretical values of P_t'/P_l' for the summed p state data is 0.95 ± 0.18 using either DWIA calculation.

Deviations from unity significantly outside theoretical and experimental uncertainties would be evidence for changes in the nucleon form factor ratio in the nuclear medium. As noted in the introduction, the Adelaide group [9] obtained density-dependent form factors using a quark-meson coupling model and found changes in the form-factor ratio for ^{16}O of about 10% for $Q^2=0.8$ $(\mathrm{GeV}/c)^2$. The sensitivity of the $(e,e'p)$ reaction to such changes has been estimated by Kelly using a local-density approximation to the current operator. The fourth curve (solid) in Fig. 2 shows that the 10% change in the form-factor ratio translates into changes of roughly 5% in the P_t' to P_l' ratio [18]. The reduced sensitivity of knockout at small p_m can be understood by comparing the averaging procedure used by Lu *et al.* with one more closely related to the matrix elements involved in the $(e,e'p)$ reaction.

Lu *et al.* [9] estimated the effect of density dependence upon the electromagnetic form factors for a bound nucleon in orbital ϕ_α by using average form factors of the form

$$\overline{G}_\alpha(Q^2)\propto\int d^3r\ \ w_\alpha(r)G[Q^2,\rho_B(r)], \tag{6}$$

where ρ_B is the ground-state baryon density for the residual nucleus. Here proportionality denotes division by a similar integral omitting G. The static weighting factor $w_\alpha(r)=|\phi_\alpha(r)|^2$ determines the effective density for different orbits. For the $(e,e'p)$ reaction, however, a more realistic weighting factor is that suggested by van der Steenhoven *et al.* [29]:

$$w_\alpha=\exp(i\boldsymbol{q}\cdot\mathbf{r})\chi^{(-)}(\mathbf{p}',\mathbf{r})^*\phi_\alpha(\mathbf{r}), \tag{7}$$

where χ is the distorted wave for ejectile momentum $\mathbf{p}'$, $\mathbf{q}$ is the momentum transfer, and $\mathbf{p}_m=\mathbf{p}'-\mathbf{q}$. In the interests of simplicity, recoil corrections and details of the current operator have been suppressed. In the plane-wave approximation, the weighting factor becomes

$$w_\alpha^{(\mathrm{PWIA})}=\exp(-i\mathbf{p}_m\cdot\mathbf{r})\phi_\alpha(\mathbf{r}), \tag{8}$$

and for $p_m\rightarrow0$ reduces to simply ϕ_α. In kinematic regimes explored thus far, this linear dependence upon ϕ_α reduces the effect of density dependence in the reaction, although the effect does increase with p_m. In the actual calculations shown here, Kelly [18] applies a local-density approximation to the current operator itself and performs an unfactorized DWIA calculation without using these simple weighting factors. Furthermore, absorption and nonlocality corrections also reduce interior contributions to the average form factor.

Much more precise measurements of the P_t'/P_l' ratio are now possible. The polarized beam at JLab has shown a marked improvement in intensity, lifetime, and polarization since the commissioning experiment so that the statistical errors can be greatly reduced within reasonable running times, and systematic errors are already small. Conditions at the MAMI accelerator at Mainz are also appropriate for a high precision measurement at low Q^2. Experiments on ^{4}He have recently been carried out at both machines. However, although recoil polarization provides a direct signal for medium modifications of nucleon form factors, the effect in $(e,e'p)$ reactions is smaller than previously expected. A rigorous interpretation will require a unified relativistic treatment of the reaction and form-factor models, including two-body currents.

The present experiment confirms the accuracy of the DWIA description of the reaction mechanism in this kinematical regime. The measured ratio of the transverse to longitudinal polarization transfers for the proton embedded in ^{16}O at a Q^2 of 0.8 $(\mathrm{GeV}/c)^2$ is in good agreement with calculations based on the free proton form factor with an experimental uncertainty of about 18%. The current generation of polarization transfer experiments should substantially improve this limit, but reliable identification of changes in the form factor in the medium remains an ambitious undertaking.

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[1] D. Eyl *et al.*, Z. Phys. A **352**, 211 (1995); B.D. Milbrath *et al.*, Phys. Rev. Lett. **80**, 452 (1998).
[2] JLab Experiment E89-033, C.C. Chang, C. Glashausser, S. Nanda, and P. Rutt, spokespersons (unpublished).
[3] I. Sick, Comments Nucl. Part. Phys. **18**, 109 (1988).
[4] R. Schiavilla, R.B. Wiringa, and J. Carlson, Phys. Rev. Lett. **70**, 3856 (1993).
[5] J. Jourdan, Phys. Lett. B **353**, 189 (1995).
[6] Z.-E. Meziani (private communication); Z.-E. Meziani and J. Morgenstern, Phys. Rev. Lett. (submitted).
[7] G. van der Steenhoven *et al.*, Phys. Rev. Lett. **57**, 182 (1986); **58**, 1727 (1987); D. Reffay-Pikeroen *et al.*, *ibid.* **60**, 776 (1988).
[8] G. van der Steenhoven, Nucl. Phys. **A527**, 17c (1991), and references therein; L. Lapikas, *ibid.* **A553**, 297c (1993); K.I. Blomqvist *et al.*, Z. Phys. A **351**, 353 (1995).
[9] D.H. Lu *et al.*, Nucl. Phys. **A634**, 443 (1998); D.H. Lu *et al.*, Phys. Lett. B **417**, 217 (1998); D.H. Lu *et al.*, Phys. Rev. C **57**, 2628 (1998).
[10] L.S. Celenza, A. Rosenthal, and C.M. Shakin, Phys. Rev. C **31**, 232 (1984); R.L. Jaffe, F.E. Close, R.G. Roberts, and G.G. Ross, Phys. Lett. **134B**, 449 (1984); Ulf-G. Meissner, Phys. Rev. Lett. **62**, 1013 (1989); I. T. Cheon and M. T. Jeong, J. Phys. Soc. Jpn. **61**, 2726 (1992); M.R. Frank, B.K. Jennings, and G.A. Miller, Phys. Rev. C **54**, 920 (1996).
[11] A.I. Akhiezer and M.P. Rekalo, Fiz. Elem. Chastits At. Yadra **3**, 555 (1974) [Sov. J. Part. Nucl. **3**, 279 (1974)]; R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981).
[12] A. Raskin and T.W. Donnelly, Ann. Phys. (N.Y.) **191**, 78 (1989).
[13] JLab Experiment E93-027, C.F. Perdrisat, V. Punjabi, and M.K. Jones, spokespersons; M.K. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000).
[14] S. Boffi, C. Giusti, F.D. Pacati, and M. Radici, Nucl. Phys. **A518**, 639 (1990).
[15] J.J. Kelly, Phys. Rev. C **56**, 2672 (1997); Adv. Nucl. Phys. **23**, 75 (1996).
[16] M. Radici (private communication).
[17] Jan Ryckebusch, Dimitri Debruyne, Wim Van Nespen, and Stijn Janssen, Phys. Rev. C **60**, 034604 (1999).
[18] J.J. Kelly, Phys. Rev. C **60**, 044609 (1999).
[19] E. Moya de Guerra and M. Udias (private communication); J.M. Udias, J.A. Caballero, E. Moya de Guerra, J.E. Amaro, and T.W. Donnelly, Phys. Rev. Lett. **83**, 5451 (1999).
[20] M.K. Jones *et al.*, in *Intersections Between Particle and Nuclear Physics*, edited by T.W. Donnelly, AIP Conf. Proc. 412 (AIP, Woodbury, NY, 1997), p. 342.
[21] K. Wijesooriya, Ph.D. thesis, College of William & Mary, 1999.
[22] S. Malov, Ph.D. thesis, Rutgers University, 1999.
[23] M. McNaughton *et al.*, Nucl. Instrum. Methods Phys. Res. A **241**, 435 (1985).
[24] A. Afanasev, I. Akusevich, and N. Merenkov (private communication).
[25] P. Mergell, U.-G Meissner, and D. Drechsel, Nucl. Phys. **A596**, 367 (1996).
[26] J. Gao *et al.*, Phys. Rev. Lett. **84**, 3265 (2000).
[27] E.D. Cooper *et al.*, Phys. Rev. C **47**, 297 (1993).
[28] M.M. Sharma, M.A. Nagarajan, and P. Ring, Phys. Lett. B **312**, 377 (1993).
[29] G. van der Steenhoven, H.P. Blok, E. Jans, L. Lapikas, and P. K.A. de Witt Huberts, Phys. Rev. Lett. **59**, 1376 (1987).