G_P^E/G_P^M FOR BOUND PROTONS: FIRST RESULTS FOR ^{16}O WITH THE RECOIL POLARIZATION TECHNIQUE

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The first $(\vec{e}, e'\vec{p})$ polarization transfer measurements on a heavy nucleus have been made at TJNAF. The reaction $^{16}\mathrm{O}(\vec{e}, e'\vec{p})$ was used to study the transfer of polarization to the recoil proton in quasielastic kinematics. The preliminary data are in good agreement with standard calculations which assume no modification of the nucleon form factors in the nuclear medium.

1 Introduction

The combination of a high intensity, high polarization, continuous electron beam and a focal plane polarimeter makes possible a new generation of studies of the effects of the nuclear medium on the properties of the nucleon. 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, as shown below. 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 can be very small, in contrast to the usual Rosenbluth separations which require different kinematic settings.

Here we describe such an $(\vec{e}, e'\vec{p})$ experiment on an oxygen (waterfall) target, the first measurement of this sort carried out on a nucleus heavier than deuterium.[1] The experiment, E89-033 at Jefferson Laboratory, was part of the commissioning effort for Hall A. It was the first experiment requiring the use of polarized beam at the Laboratory, and the first to use the focal plane polarimeter (FPP) mounted on the High Resolution (hadron) Spectrometer.

The many difficulties involved in commissioning limited the statistical precision of the results we were able to achieve in a fixed beam time. Nevertheless this experiment does show that high precision tests of predicted changes in the form factors in the nuclear medium will soon be possible.

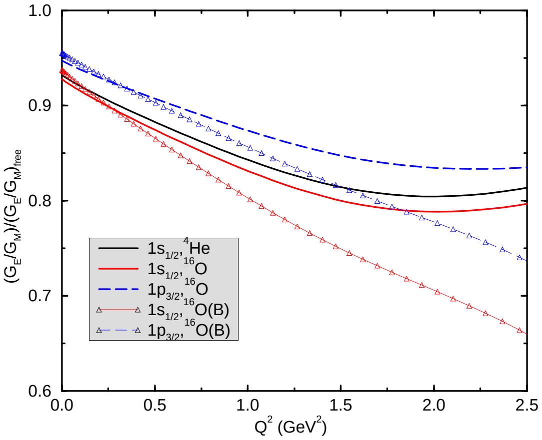

Figure 1. Predicted super-ratios of the in-medium form-factor ratios to the free form-factor ratios for states in ^{16}O and ^{4}He as a function of Q^2. The three curves that are highest at 2.5 GeV^2 have been calculated with a fixed bag constant; the two lower curves assume a density-dependent bag constant.[2]

An example of possible changes apparently consistent with all previous data is shown in Fig. 1. The curves are predictions by the Adelaide group[2] based on the quark-meson coupling model, a mean-field calculation using the bag model to describe the nucleons. The super-ratio of the predicted in-medium form-factor ratio to the free form-factor ratio is shown as a function of four-momentum transfer for several states in ^{16}O and ^{4}He. The curves with the triangles were calculated with density-dependent bag constants; the others were based on free values of the bag constant. At the momentum transfer of the present experiment, 0.8 GeV^2, the predicted changes are of the order of 10-15%; at the highest values of Q^2, changes up to about 30% are predicted.

For the free nucleon, the polarization transfer can be written in terms of the form factors as[3]

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

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

$$I_0 = G_E^2 + \tau G_M^2[1 + 2(1+\tau)\tan^2(\theta/2)]$$

$$\tau = Q^2/4m_p^2,$$

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 is the longitudinal polarization transfer, the polarization of the scattered proton P_l in the direction of its momentum for a 100% polarized electron beam. P'_t is the transverse polarization transfer, the polarization of the scattered proton P_t transverse to its momentum in the scattering plane for a 100% polarized electron beam.

The ratio of the transferred polarizations is then

$$\frac{P'_t}{P'_l} = \frac{-2m_p}{(E+E')\tan(\theta/2)}\frac{G_E}{G_M}.$$

The actual polarizations are hP'_l and hP'_t, where 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 false asymmetries in the detectors.

For a free proton target, then, the ratio of polarizations can be used to determine the ratio of the form factors without measuring an absolute cross section (although determination of the individual values of the form factors still requires knowledge of the cross section). The ratio is also independent of the beam polarization (assuming it is not zero) and of the analyzing power of the proton polarimeter. Because the measurement is made at a single angle, most systematic problems associated with absolute cross section measurements are eliminated.

For nuclear targets, the polarization transfer observables once more depend directly on the form factors, but the relationship is less straightforward.

For example, the polarization observables may be affected by final state interactions of the outgoing proton, meson exchange currents, isobar configurations, or two-body currents.[4] We discuss such problems in the reaction mechanism below and note here only that the uncertainties attributable to such effects are generally small.[5]

2 Experiment 89-033

Experiment 89-033[6] was a measurement of polarization observables in the reaction $^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N}$. The beam energy was 2.445 GeV with a polarization of about 30%, the electron scattering angle was 23.4° and the central scattered electron energy was 2.000 GeV, the quasielastic peak. The central proton momentum was 973 MeV/c. The recoil proton was detected in quasi-perpendicular kinematics at angles of 50.8°, 53.3°, 55.7°, and 60.5°, corresponding to missing momenta of -85, 0, 85, and 140 MeV/c. Positive missing momentum corresponds to the case where the missing momentum vector points to smaller scattering angles on the proton side. Elastic scattering from hydrogen can be seen at spectrometer angles of 53.3° and 55.7°.

The target was a waterfall consisting of three foils with a total thickness of about 0.5 g/cm^2. The use of three separated foils allowed sufficient energy resolution to easily distinguish the $\mathrm{p}_{1/2}$ ground state of ^{15}N from the first excited state ($\mathrm{p}_{3/2}$). In the continuum, excitation of the $\mathrm{s}_{1/2}$ shell rises weakly above the (physics) background presumably related to multiparticle knockout.

The JLab focal plane polarimeter was designed and built by a collaboration of Rutgers, William & Mary, Georgia, and Norfolk State, and funded by the U.S. National Science Foundation. The polarimeter, consisting of four tracking straw chambers and a graphite analyzer, is mounted in the hadron spectrometer behind the spectrometer VDC's. The analyzing power of the FPP, A_c, was taken from the parametrization by McNaughton *et al.*[8] Measured values of A_c, obtained by analyzing data from scattering from hydrogen, have been shown to agree well with this parameterization.[9] The beam polarization was measured at varying intervals with a 5 MeV Mott polarimeter in the injector. For the 85 MeV/c data point on ^{16}O, where hydrogen appeared on the focal plane, values of the beam polarization determined from the Mott polarimeter and from the FPP results for hydrogen agreed very well, well within the 5% systematic error we assign to the beam polarization in the subsequent analysis of the oxygen data.

The polarization of the outgoing proton is measured for each electron-helicity state. By subtracting data for the two states, the polarization transfers P_l' and P_t' can be found, while the sum gives P_n. The preliminary result

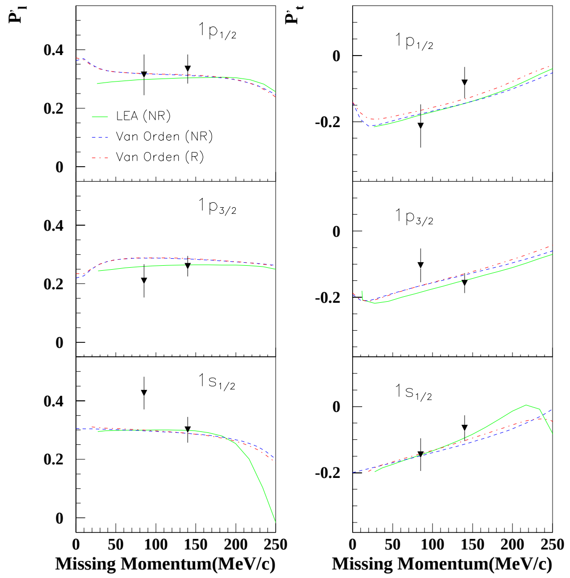

Figure 2. The preliminary polarization transfer data are compared with three DWIA calculations by Kelly[5] and by Van Orden[7] described in the text.

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for the ratio $\mu\frac{G_E}{G_M}$ in hydrogen measured in this experiment at a Q^2 of 0.8 GeV^2 is 0.90±0.05. This value is in agreement with previous results and with values subsequently measured in Experiment 93-027 at JLab with much higher precision.[9]

Preliminary 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 unbound $s_{1/2}$ state are shown in Fig. 2. These results are included in the Ph.D. thesis of K. Wijesooriya at William & Mary.[10] Another analysis of the same data with somewhat different methods by Sergey Malov at Rutgers is nearing completion. The errors shown are statistical; systematic errors are small. Small acceptance averaging corrections are included, as are the effects of corrections to the dipole approximation for spin transport of the proton in the HRS. Given the roughly symmetric coverage of the focal plane, the non-dipole corrections are less than about 2%.

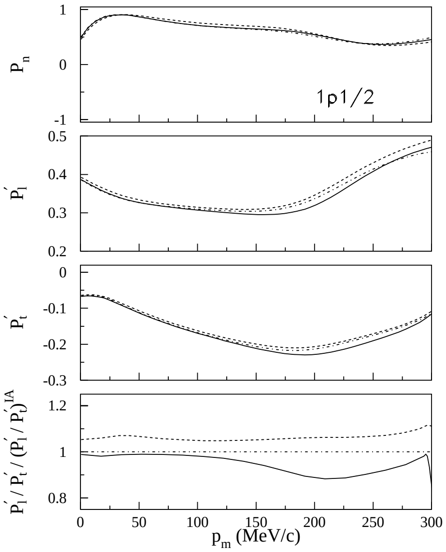

Figure 3. Effects of two-body currents on the polarization transfer observables predicted by Ryckebusch for the $p_{1/2}$ state in ^{16}O. The dot-dashed curves show the IA results. MEC effects have been included for the dashed curves. The solid curves show the full results including also IC.[11]

The curves in these figures represent theoretical calculations based on one-body currents and the free electromagnetic form factors of the proton. Non-relativistic (NR) calculations carried out with the code LEA of J.J. Kelly[5] include final state interactions using the EDAD1 optical potential of Cooper *et al.*[12] Also shown are relativistic (R) and non-relativistic distorted wave calculations by Van Orden.[7] All three calculations are in good agreement with the measured data. Only the value of P_l' for the $s_{1/2}$ state at 85 MeV/c disagrees with the predictions by more than one standard deviation. Because of the substantial continuum beneath this state, it is surprising that the predictions are so good here.

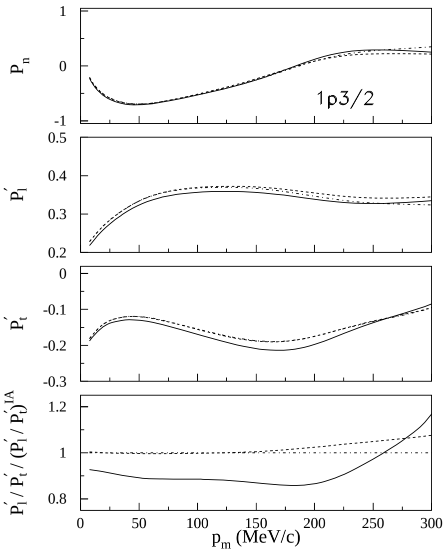

Figure 4. Effects of two-body currents on the polarization transfer observables predicted by Ryckebusch[11] for the $p_{3/2}$ state in ^{16}O, as in the preceding figure.

An important virtue of the recoil polarization technique for examining the nucleon form factors in the nuclear medium is that both the experimental polarization results and the theoretical predictions appear robust.

As discussed above, the systematic errors on the polarization measurements are much smaller than the present statistical errors. Predictions based on the PWIA are distinguishable from the DWIA curves in Fig. 2 only at very large values of the missing momentum. Results obtained with a wide variety of reasonable variations in the optical potentials generally differ by only a few percent from those shown. Previous calculations, verified for the present kinematics, have shown that the non-relativistic predictions are also insensitive to the choice of gauge and one-body current operator.[5] Calculations of the effects of relativistic dynamics, including the modification of the lower components of the nucleon wave function in the medium, have been carried out for the present kinematics by Moya de Guerra and Udias,[13] and more recently by Kelly.[14] Typical effects on the ratios of P'_t/P'_l are ±5%. The contributions of meson exchange currents and isobar excitations have recently been calculated

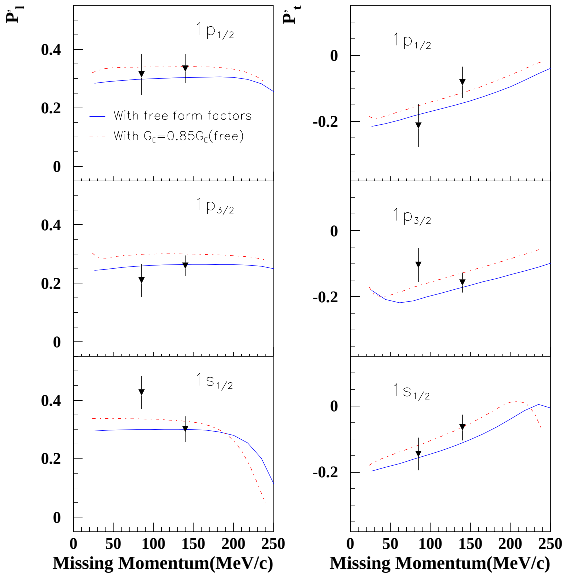

Figure 5. The preliminary polarization transfer data are compared with LEA calculations based on the free form factors and on the free form factor ratio reduced by 15%.

by J. Ryckebusch *et al.*[11] for the present kinematics. Their results for the two p states are shown in Figs. 3 and 4. The effects are again small on the scale of the errors in this experiment, though they can be significant in a future high precision experiment. It is interesting to note the state dependence in these predictions. Meson exchange currents contribute almost nothing to the super-ratio of polarizations for the $p_{3/2}$ state, but isobar currents yield a 10% reduction even at low missing momentum p_m. On the other hand, for the $p_{1/2}$ state, the effects of isobar currents cancel the effects of MEC at low p_m, and the impulse approximation is good to about 2%. Early calculations of MEC and IC effects on polarization observables were carried out by the Pavia group.[4] Preliminary calculations by M. Radici[15] of this group for the present kinematics suggest essentially no contribution from MEC, and a very small effect of IC in the super-ratio.

Because the theoretical corrections to the predictions shown in Fig. 2 are small, the data shown there represent a new measurement of possible medium effects on the form factors. The same data are plotted in Fig. 5 where they are compared with LEA predictions based on either the free form-factor ratio or the form-factor ratio decreased by 15%. The good agreement with the prediction based on the free ratio suggests that changes in the form factor ratio are not very large in these kinematics. The present results are not, however, inconsistent with the predictions of the Adelaide group,[2] since they are also in good agreement with the curve in Fig. 5 based on a modified form factor ratio. If the experimental ratio P'_t/P'_l is calculated for each p state, and divided by the theoretical ratio for that state, the result is the experimental determination of the super-ratio for that state. Deviations from unity indicate modifications of the form factor in the medium. For the present (preliminary) results, the value of the super-ratio summed over the data for the two states is 0.97±0.18.

3 Prospects

Much tighter constraints on possible changes in the form factors can now be obtained from FPP experiments over a range in Q^2 from about 0.3 GeV^2 to about 3 GeV^2. The error bars on the experimental polarizations can be reduced dramatically simply by running longer. Recent experience with the polarized beam at Jefferson Lab shows a marked improvement in intensity, lifetime, and polarization relative to the situation during the commissioning experiment. Conditions at the MAMI accelerator at Mainz are also appropriate for a high precision measurement at low Q^2. Uncertainties in the measurement of the polarization of the beam and in the analyzing power of the FPP make it hard to reduce the systematic errors in P'_l or P'_t much below about 5%, but a significantly smaller systematic error in their ratio is possible. An experiment on ^{4}He has already begun at Mainz;[16] JLab experiment E93-049,[17] tentatively scheduled for Spring, 2000, will extend the Q^2 range to about 3 GeV^2.

The theoretical interpretation of such precise data will require a unified treatment of the reaction model and of the changes in the properties of the nucleon. Modifications of the quark structure of the nucleon come about from exchanges with the surrounding medium–a unified treatment can avoid double counting. Corrections to the PWIA can be minimized by choosing parallel kinematics, by choosing a light target, and (perhaps) by investigating large momentum transfers. We should soon be able to learn whether the nucleon in nuclei is really so amazingly robust as it presently seems.

Acknowledgments

We are grateful to the entire technical staff at TJNAF for their dedicated expert support of the commissioning experiment. This work is supported in part by the National Science Foundation and the Departmentt of Energy (U.S.), the Institute for Nuclear Research (Italy), the Atomic Energy Commission and the National Center for Scientific Research (France), the Natural Sciences and Engineering Research Council (Canada) and the Fund for Scientific Research-Flanders (Belgium).

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