Medium-Modified Form Factors, Relativistic Dynamics, and the $(e,e'p)$ Reaction

T. D. Cohen and J. W. Van Orden
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

A. Picklesimer
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 22 June 1987)

We examine the effects of relativistic dynamics and medium-modified electromagnetic form factors on the ratio of transverse to longitudinal response in $(e,e'p)$. Calculations performed in the distorted-wave impulse approximation show that the effects of Dirac dynamics and medium-modified form factors are small. We also show that current data seem consistent with our distorted-wave-impulse approximation calculations.

PACS numbers: 25.30.Fj

The observed suppression of the longitudinal response function relative to theoretically predicted values[1] has proved to be a persistent and difficult problem for intermediate-energy nuclear physics. Simple calculations with use of traditional nuclear physics have been unable to explain this suppression. Accordingly, the efforts to account for this discrepancy have been extended to encompass more exotic explanations. These are relativistic dynamical effects[2-4] and modification of the effective nucleon size in the nuclear medium.[5-7] Both effects are often referred to as medium modifications of the nucleon current.

The relativistic dynamical effect is due to the presence of large scalar and vector potentials which occur in Dirac models.[8-10] In the Dirac distorted-wave impulse-approximation (DWIA) description of the inclusive (e,e')[3,4] and exclusive $(e,e'p)$[11] reactions, the reduction of the longitudinal response is the result of a suppression of the scattering wave functions in the interior of the nucleus due to coupling to virtual negative-energy states.

It has been observed that the data can be accounted for by a modification of the nucleon electromagnetic form factors in the nuclear medium.[5-7] This modification can be characterized as an increase of the nucleon size in the medium, producing a more rapid falloff of the form factors with increasing four-momentum transfer and an increase in nucleon magnetic moments.

The widely held view that the quasielastic $(e,e'p)$ reaction provides a means of examining the properties of individual protons[12] in the nucleus has motivated further experimental studies of this reaction with the objective of detecting medium modifications of the nuclear electromagnetic current, as described above. Thus far, reported results have been interpreted to indicate a quantitative failure of the usual DWIA to describe the $(e,e'p)$ reaction.[13,14]

In this Letter we examine the effects of Dirac dynamics and of density-dependent nucleon form factors in a DWIA analysis of the $(e,e'p)$ reaction. We present both Dirac and Schrödinger calculations of this reaction, with and without density-dependent form factors. Our results show that, in the region of current interest, both Dirac dynamical and medium-modified form-factor effects are small. We find that the currently available data seem entirely consistent with the effects of final-state interactions and do not appear to require the inclusion of any exotic effects.

The results presented here represent an extension of the methods detailed in Ref. 11 to allow for a wider variety of Dirac and Schrödinger optical potentials and to accommodate density-dependent form factors. We restrict ourselves to the parallel-antiparallel kinematics used in the experimental work of Refs. 13 and 14. Results are shown for three optical potentials: a relativistic impulse-approximation potential[10] as used in Ref. 11, a phenomenological Dirac potential,[15] and a Schrödinger folding-model potential with Pauli-blocking corrections handled in the local-density approximation (LDA).[16] The Dirac potential produces an excellent fit to 200-MeV elastic proton-scattering cross sections and spin observables up to scattering angles of 80°. The LDA potential also provides an excellent description of elastic proton scattering over the range of proton energies considered here. The impulse-approximation potential represents an extreme case of large scalar and vector potentials in the energy region shown here. It therefore gives some measure of the sensitivity of the results to uncertainties in the details of the optical potential.

The density dependence of the nucleon form factors is taken from Ref. 6. In that work, the density dependence of the nucleon form factors is calculated with a nontopological soliton model of the nucleon. The electromagnetic current operator for the nucleons which we use is given by

$$J^\mu(q,\rho(r))=F_1(Q^2,\rho(r))\gamma^\mu+\frac{F_2(Q^2,\rho(r))}{2m}i\sigma^{\mu\alpha}q_\alpha, \quad (1)$$

which is the usual Dirac single-nucleon current operator except that the form factors F_1 and F_2 are taken to depend on the local nucleon density $\rho(r)$, as well $Q^2 = -q^2 = \mathbf{q}^2 - \omega^2$. For convenience, the form factors of Ref. 6 at fixed density have been fitted by a dipole form for the Sachs electric and magnetic form factors given by

$$G_E(Q^2,\rho) = \left[\frac{1}{1+Q^2/\alpha_E^2(\rho)}\right]^2, \tag{2a}$$

and

$$G_M(Q^2,\rho) = \mu_p \left[\frac{\beta(\rho)}{1+Q^2/\alpha_M^2(\rho)}\right]^2, \tag{2b}$$

where μ_p is the magnetic moment of the proton.

In Ref. 13, a specific quantity was introduced as a measure of the medium modification of the proton magnetic moment in the $(e,e'p)$ reaction. This quantity, R_G, expressed with use of the response functions $W_{L,T}$ of Ref. 13 or $R_{L,T}$ of Ref. 11, is

$$R_G = \left[\frac{4m^2 W_T}{Q^2 W_L}\right]^{1/2} = \left[\frac{2m^2 \mathbf{q}^2 R_T}{Q^4 R_L}\right]^{1/2}. \tag{3}$$

This choice is motivated by a prescription for describing the off-shell single nucleon current due to de Forest.[17] Evaluation of this expression for R_G in the density-independent plane-wave impulse approximation (PWIA) yields the ratio G_M/G_E, which is approximately equal to the magnetic moment of the free proton. If this prescription is used and if the effects of final-state interactions are small, then R_G represents a measure of the magnetic moment of the proton in the nuclear medium.

Figure 1 shows various calculations of R_G for the ejection of a 200-MeV proton from the $1p_{3/2}$ shell of ^{16}O as a function of Q^2. For reference, a horizontal line is drawn at $R_G = \mu_p = 2.79$. The long-short-dashed line represents a Dirac PWIA calculation. Clearly, our use of the free Dirac current operator deviates from the off-shell prescription of de Forest. The long–two-short–dashed line results from the inclusion of the density-dependent form factors in the Dirac PWIA calculation.

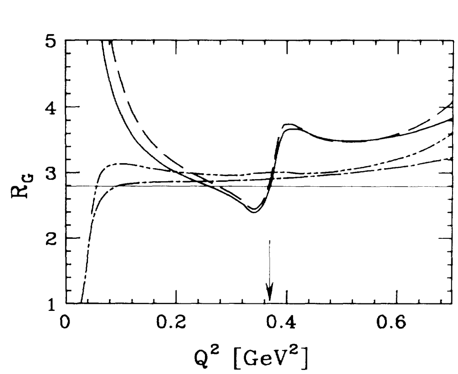

FIG. 1. R_G for the ejection of 200-MeV protons from the $1p_{3/2}$ shell of ^{16}O.

Although the two PWIA calculations differ by the greatest amounts at the extreme values of Q^2, the overall effect of the introduction of the medium-modified form factors is an increase in R_G of roughly 10%. A calculation of R_G in DWIA with the phenomenological Dirac optical potential is represented by the solid line. The effects of the final-state interactions are clearly dominant. The large size of R_G near the photon point $Q^2=0$ is, in large part, due to the presence of the factor of Q^4 in the denominator of (3). An interesting feature is the rapid variation of R_G near $Q^2 = 0.368$ GeV^2 which, under these kinematical conditions, corresponds to the point where the recoil momentum becomes zero. This point is indicated by the arrow in this figure. In PWIA, the response functions are proportional to the momentum-density distribution of the state from which the proton is ejected as a function of the magnitude of the recoil momentum. In the case where the initial state is a p state, the momentum distribution vanishes when the recoil momentum is zero. Thus, the response functions are relatively small in the vicinity of this point. In momentum space, the inclusion of the distortions can be viewed (in part) as a redistribution of the plane-wave response over the dispersion of the proton's scattering wave. This folding over of two momentum profiles can result in large modifications to the values of the response function in regions where the underlying momentum distribution is changing rapidly, such as in the region where it is falling rapidly toward zero. Given the difference in form of the charge and current-density operators, it is possible that such changes will be different for the longitudinal and transverse response functions. It should, therefore, be expected that the ratio R_G can be very sensitive to the presence of final-state interactions in the region of zero recoil momentum. The analogous distorted-wave calculation with density-dependent form factors is represented by the dashed line. The effect of these form factors is smaller than in the plane-wave case since the absorption associated with the optical potential damps the scattering wave function in the interior of the nucleus, decreasing contributions to the cross section from the region of largest density.

The sensitivity of R_G to the choice of optical potential is gauged in Fig. 2. Distorted-wave calculations using the phenomenological Dirac potential (solid line), impulse-approximation Dirac potential (dashed line), and LDA Schrödinger potential (dash-dotted line) are exhibited. All three calculations have the same qualitative features. The results of the Dirac potentials differ from those of the Schrödinger potential only at the largest values of Q^2. The qualitative features of this ratio are not appreciably affected by relativistic dynamics.

In Fig. 3, R_G is shown for the ejection of 70-MeV protons from the $1p_{3/2}$ shell of ^{16}O. Calculations are shown for Dirac PWIA (dashed line), and DWIA with Dirac impulse-approximation (solid line) and Schrödinger LDA optical potentials (dash-dotted line). The value of

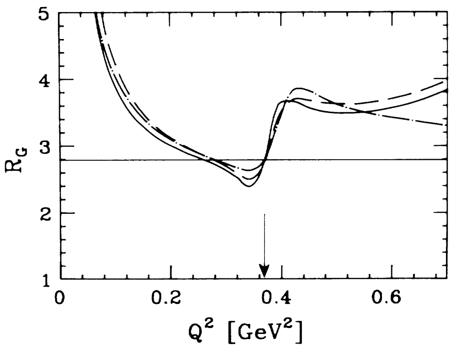

FIG. 2. R_G under the same conditions as Fig. 1 with use of three different optical potentials.

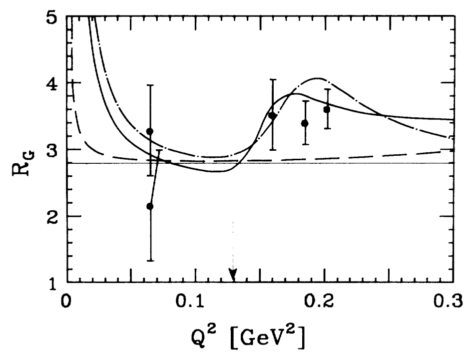

FIG. 3. R_G for the ejection of 70-MeV protons from the $1p_{3/2}$ shell of ^{16}O.

Q^2 at which the recoil momentum vanishes is again indicated by an arrow. The data from Ref. 13 for the ejection of a 70-MeV proton from the $1p_{3/2}$ shell of ^{12}C are shown for purposes of comparison. Although some allowance must be made for differences in the bound-state wave functions and optical potentials for ^{16}O and ^{12}C, the DWIA calculations are in qualitative agreement with the data. We have chosen to perform the calculation for ^{16}O rather than ^{12}C because of the lack of good quality relativistic wave functions and optical potentials for ^{12}C. Clearly, our results are in disagreement with those reported in Ref. 13, where the effects on R_G due to final-state distortion were found to be less than 2%. The origin of this discrepancy is being investigated.

The results presented above indicate that the effects of an increase in effective nucleon size on the ratio R_G are small for the ejection of protons from the outer shells of light nuclei. Furthermore, there is nothing in the currently available data for R_G which gives an unambiguous signature for relativistic dynamical effects. The ratio R_G is sensitive to final-state interactions and is particularly sensitive in the vicinity of the zero in recoil momentum for the ejection of protons from p states. Because the effects of final-state interactions on R_G are substantially larger than density-dependent form-factor effects, R_G cannot be reasonably used as a direct measure of the nucleon magnetic moment in the medium. Finally, the qualitative features of the DWIA calculations presented here are consistent with the currently available $(e,e'p)$ data for R_G.

The authors would like to acknowledge the assistance of A. Rosenthal, J. J. Kelly, and C. R. Chinn in providing some of the ingredients necessary to the calculations presented in this Letter. The support of the U.S. Department of Energy and the University of Maryland Computer Science Center for this research is gratefully acknowledged.

[1]R. Altemus *et al.*, Phys. Rev. Lett. **44**, 965 (1980); R. Barreau *et al.*, Nucl. Phys. **A402**, 515 (1983); M. Deady *et al.*, Phys. Rev. C **28**, 631 (1983), and **33**, 1897 (1986); C. Marchand *et al.*, Phys. Lett. **153B**, 29 (1985); Z.-E. Meziani *et al.*, Phys. Rev. Lett. **52**, 2130 (1982), and **54**, 1233 (1985).

[2]T. de Forest, Jr., Phys. Rev. Lett. **53**, 895 (1984).

[3]G. Do Dang and N. Van Giai, Phys. Rev. C **30**, 731 (1984).

[4]C. R. Chinn and J. W. Van Orden, Bull. Am. Phys. Soc. **32**, 1030 (1987).

[5]J. V. Nobel, Phys. Rev. Lett. **46**, 412 (1981), and Phys. Lett. B **178**, 285 (1986).

[6]L. S. Celenza, A. Rosenthal, and C. M. Shakin, Phys. Rev. Lett. **53**, 892 (1984), and Phys. Rev. C **31**, 232 (1985).

[7]P. J. Mulders, Phys. Rev. Lett. **54**, 2560 (1985), and Nucl. Phys. **A459**, 525 (1986).

[8]C. J. Horowitz and B. D. Serot, Nucl. Phys. **A368**, 503 (1981).

[9]J. A. McNeil, J. R. Shepard, and S. J. Wallace, Phys. Rev. Lett. **50**, 1439 (1983); J. R. Shepard, J. A. McNeil, and S. J. Wallace, Phys. Rev. Lett. **50**, 1443 (1983); B. C. Clark, S. Hama, R. L. Mercer, L. Ray, and B. D. Serot, Phys. Rev. Lett. **50**, 1644 (1983).

[10]M. V. Hynes, A. Picklesimer, P. C. Tandy, and R. M. Thaler, Phys. Rev. Lett. **52**, 978 (1984), and Phys. Rev. C **31**, 1438 (1985).

[11]A. Picklesimer, J. W. Van Orden, and S. J. Wallace, Phys. Rev. C **32**, 1312 (1985).

[12]S. Frullani and J. Mougey, Adv. Nucl. Phys. **14**, 1 (1984).

[13]G. van der Steenhoven *et al.*, Phys. Rev. Lett. **57**, 182 (1986).

[14]G. van der Steenhoven *et al.*, Phys. Rev. Lett. **58**, 1727 (1987).

[15]A. M. Kobos, E. D. Cooper, J. I. Johansson, and H. S. Sherif, Nucl. Phys. **A445**, 605 (1985).

[16]J. J. Kelly, University of Maryland Report No. 87-126.

[17]T. de Forest, Jr., Nucl. Phys. **A392**, 232 (1983).