

Comparison of Polarization Observables in Electron Scattering from the Proton and Deuteron

B. D. Milbrath,^{1,*} J. I. McIntyre,^{2,†} C. S. Armstrong,² D. H. Barkhuff,^{1,‡} W. Bertozzi,³ J. P. Chen,^{3,§} D. Dale,^{3,||} G. Dodson,³ K. A. Dow,³ M. B. Epstein,⁴ M. Farkhondeh,³ J. M. Finn,² S. Gilad,³ M. K. Jones,² K. Joo,^{3,¶} J. J. Kelly,⁵ S. Kowalski,³ R. W. Lourie,^{1,**} R. Madey,⁶ D. J. Margaziotis,⁴ P. Markowitz,^{5,††} C. Mertz,⁷ J. Mitchell,⁸ C. F. Perdrisat,² V. Punjabi,⁹ L. Qin,¹⁰ P. M. Rutt,¹¹ A. J. Sarty,^{3,‡‡} D. Tieger,³ C. Tschalær,³ W. Turchinets,³ P. E. Ulmer,¹⁰ S. P. Van Verst,^{1,3,§§} G. A. Warren,^{3,|||} L. B. Weinstein,¹⁰ and R. J. Woo^{2,¶¶}

(Bates FPP Collaboration)

¹University of Virginia, Charlottesville, Virginia 22901

²College of William & Mary, Williamsburg, Virginia 23185

³Massachusetts Institute of Technology and Bates Linear Accelerator Center, Cambridge, Massachusetts 02139

⁴California State University, Los Angeles, Los Angeles, California 90032

⁵University of Maryland, College Park, Maryland 20742

⁶Kent State University, Kent, Ohio 44242

⁷Arizona State University, Tempe, Arizona 85287

⁸Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

⁹Norfolk State University, Norfolk, Virginia 23504

¹⁰Old Dominion University, Norfolk, Virginia 23529

¹¹Rutgers University, Piscataway, New Jersey 08855

(Received 8 August 1997)

Recoil proton polarization observables were measured for both the $p(\vec{e}, e'\vec{p})$ and $d(\vec{e}, e'\vec{p})n$ reactions at two values of Q^2 using a newly commissioned proton focal plane polarimeter at the MIT-Bates Linear Accelerator Center. The hydrogen and deuterium spin-dependent observables $D_{\ell\ell}$ and $D_{\ell t}$, the induced polarization P_n , and the form factor ratio G_E^p/G_M^p were measured under identical kinematics. The deuterium and hydrogen results are in good agreement with each other and with the plane-wave impulse approximation (PWIA). [S0031-9007(97)04964-8]

PACS numbers: 25.30.Dh, 13.40.Gp, 13.88.+e, 14.20.Dh

For many years, a major effort of nuclear physics has been the determination of the nucleon electromagnetic form factors. In the Breit frame, the Sachs representation of the elastic form factors G_E and G_M represent Fourier transforms of the charge and magnetization densities of the nucleon; the same interpretation is also obtained at low Q^2 in the nucleon rest frame. Precise experimental determination of these form factors imposes stringent constraints on models of baryon structure.

In the past, the Q^2 dependence of the proton form factors [1–6] has been measured using the Rosenbluth separation technique. Extracting the form factors requires performing a set of measurements at fixed Q^2 while varying the electron scattering angle θ_e and the incident electron beam energy E . Because the technique relies on absolute cross section measurements, it is sensitive to systematic errors in E , E' (the scattered electron energy), and θ_e .

The Rosenbluth separation technique has also been used to determine the Q^2 dependence of the neutron form factors via quasielastic electron-deuteron scattering [7–10]. Consequently, the extraction of the neutron information is sensitive to deuteron wave function models. It appears possible, however, using polarization techniques [such as $d(\vec{e}, e'\vec{n})p$ [11]] to determine the neutron form factors in a nearly model-independent fashion. This requires that polarization observables measured on the deuteron for quasifree kinematics be insensitive to specifi-

cally nuclear mechanisms such as final state interactions (FSI), meson exchange currents (MEC), and isobar configurations (IC). Since recoil polarimetry can be used for both neutrons and protons, it is possible to test these assumptions using the complementary reaction $d(\vec{e}, e'\vec{p})n$ and directly compare the results to those obtained using recoil polarization in elastic proton scattering.

In the $p(\vec{e}, e'\vec{p})$ reaction, there are, assuming one-photon exchange, two helicity-dependent polarization observables [12–14]:

$$P_t = hD_{\ell t} = \frac{h}{I_0} \left(-2\sqrt{\tau(1+\tau)} G_M^p G_E^p \tan \frac{\theta_e}{2} \right),$$

$$P_\ell = hD_{\ell\ell} = \frac{h(E+E')}{I_0 M_p} \sqrt{\tau(1+\tau)} (G_M^p)^2 \tan^2 \frac{\theta_e}{2}. \quad (1)$$

The subscripts t and ℓ refer to the recoil proton's polarization components in the electron scattering plane, either transverse or longitudinal to its momentum. The first subscript in the polarization transfer coefficients $D_{\ell t}$ and $D_{\ell\ell}$ refers to the electron's longitudinal polarization. The electron beam helicity is denoted by h , I_0 is the unpolarized cross section (excluding σ_{Mott}), and $\tau = Q^2/4M^2$.

The measurement of polarization observables is of interest because they result from the interference between amplitudes and, thus, may be linear in small, interesting quantities rather than quadratic (as in cross section

measurements). An example of this is G_E^p in P_t . It is increasingly difficult to measure G_E^p as Q^2 becomes large [≥ 1 (GeV/c)²] using Rosenbluth separation because the cross section is kinematically dominated by G_M^p . Note that the ratio of P_t/P_ℓ gives the ratio of the form factors G_E^p/G_M^p independent of the beam helicity:

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_\ell} \frac{(E + E') \tan(\theta_e/2)}{2M_p}. \quad (2)$$

Because these two polarization observables are measured simultaneously, this technique avoids a major systematic uncertainty of the Rosenbluth method.

A recoil polarization component normal to the (e, e') plane, P_n , may, for example, be induced by FSI. Such a polarization is helicity independent, unlike the above longitudinal and transverse polarizations. For elastic scattering from a proton, P_n vanishes in one-photon exchange. Comparing the measured polarization observables in both $p(\vec{e}, e'\vec{p})$ and $d(\vec{e}, e'\vec{p})n$ scattering allows a sensitive, model-independent test of the impulse approximation for the deuteron.

The experiment [15–17] was performed at the MIT-Bates Linear Accelerator Center during the winter of 1995. A longitudinally polarized electron beam of 580 MeV with a current ranging from 5–15 μ A and a 1% duty factor was incident on a cryogenic target. The target had cells for both liquid hydrogen and deuterium. The hydrogen and deuterium target cells were 5 and 3 cm in diameter, respectively. They were alternated in the beam every 8–12 h. The scattered electrons were detected in the Medium Energy Pion Spectrometer (MEPS) while the scattered protons were detected in the One-Hundred Inch Proton Spectrometer (OHIPS). Both spectrometers contain two focusing quadrupoles followed by a vertically bending dipole. MEPS had a 14 msr solid angle acceptance while OHIPS had a 7.0 msr solid angle acceptance. The momentum acceptances were $\pm 10\%$ and $\pm 5\%$, respectively. A focal plane polarimeter (FPP) built by the experimenters was installed on OHIPS, allowing the polarization of the outgoing protons to be measured. Data were acquired at two different electron scattering angles, 82.7° and 113° corresponding to four-momentum transfers squared of 0.38 and 0.50 (GeV/c)².

The FPP consists of four two-plane multiwire proportional chambers, two each before and after a graphite analyzer, allowing the proton trajectory to be determined both before and after it scatters in the graphite. The analyzer thickness [7 and 9.5 cm for the 0.38 and 0.50 (GeV/c)² Q^2 measurements, respectively] was chosen to optimize the figure of merit. Scattering angles θ in the graphite could be resolved to $\leq 1^\circ$ and the FPP provided complete azimuthal coverage for $\theta \leq 20^\circ$. The device was calibrated in a direct beam of polarized protons at the Indiana University Cyclotron Facility (IUCF) in February of 1993 [18].

The angular distribution of the $^{12}\text{C}(p, p')$ scattering in the analyzer, in terms of focal plane polarizations, is [19]

$$I(\theta, \phi) = I_0(\theta) [1 - P_n^{\text{fp}} A_c(\theta) \sin \phi + P_t^{\text{fp}} A_c(\theta) \cos \phi], \quad (3)$$

where $I_0(\theta)$ is the unpolarized angular distribution, ϕ is the second scattering azimuthal angle, and A_c is the analyzing power of the $^{12}\text{C}(p, p')$ reaction. A_c depends on the second scattering polar angle θ and the proton kinetic energy T_p . A_c peaks between 10°–20° and goes to zero as θ goes to zero because the small-angle scatterings are predominantly spin-independent multiple Coulomb scatterings; however, the $^{12}\text{C}(p, p')$ elastic cross section is dominated by these small-angle ($\leq 3.5^\circ$) events. To eliminate such events, the readout electronics was equipped with a fast, small-angle rejection system described elsewhere [20].

The small-angle rejection system implemented a box cut on the second scattering coordinates x and y , resulting in azimuthally biased small-angle data. This bias was removed by a software cut that excluded events scattering through less than 7°. Events with $\theta > 20^\circ$ were also excluded since A_c is not well known at larger angles. Instrumental asymmetries of the FPP were separated from the physical asymmetries by elastically scattering unpolarized electrons from hydrogen. Any P_n component to this data could only result from two or more photon exchanges and would, thus, be negligible in comparison to instrumental effects; therefore, we treated any such component as an instrumental asymmetry and subtracted it from the P_n component of the deuterium data.

The A_c values used to extract the physical asymmetries were 0.514 and 0.537 for the 0.38 and 0.50 (GeV/c)² Q^2 measurement, respectively. These were determined using a fit of the form developed by Aprile-Giboni *et al.* [19] on a database that included our IUCF calibration measurement and other similar measurements [19,21]. The uncertainty in the measured proton polarization due to the analyzing power was 1.4% for the lower Q^2 measurement and 1.9% for the higher Q^2 measurement.

The electron beam polarization was measured on a daily basis using a Møller polarimeter. It could also be determined from the hydrogen data using the G_E^p/G_M^p ratio as determined from the FPP. This ratio was used in Eq. (1) to determine a value of $D_{\ell t}$. By then taking the ratio $P_t/D_{\ell t}$, the helicity was determined. These results agreed with the Møller data to within 2.0% and are shown in Table I. The first error bars are statistical while the second are systematic.

TABLE I. Summary of beam helicity measurements.

Device	h	
	$[Q^2 = 0.38 \text{ (GeV/c)}^2]$	$[Q^2 = 0.50 \text{ (GeV/c)}^2]$
FPP	$0.281 \pm 0.014 \pm 0.004$	$0.275 \pm 0.013 \pm 0.006$
Møller	$0.287 \pm 0.002 \pm 0.012$	$0.280 \pm 0.002 \pm 0.011$

TABLE II. Summary of $\mu_p G_E^p/G_M^p$ measurements.

Reaction	$Q^2 = 0.38 \text{ (GeV/c)}^2$	$Q^2 = 0.50 \text{ (GeV/c)}^2$
$p(\vec{e}, e'\vec{p})$	$1.016 \pm 0.052 \pm 0.016$	$0.970 \pm 0.047 \pm 0.020$
$d(\vec{e}, e'\vec{p})n$	$1.024 \pm 0.103 \pm 0.016$	$1.005 \pm 0.064 \pm 0.021$

The FPP measures only the two polarization components perpendicular to the proton momentum vector; however, they are each determined for both helicity states (+ and -) so that there are four observables at the focal plane: two helicity sums and two helicity differences $[(P_{fp}^+ \pm P_{fp}^-)_{i=1,2}]$. Because P_ℓ and P_t are helicity dependent while P_n is not, all three polarization components at the target can then be extracted by exploiting the spin mixing in the spectrometer magnets.

In order to extract the polarization components at the target from the focal plane polarizations, it was necessary to model the spin precession in OHIPS. This was done utilizing the optics code COSY [22] which generated a trajectory- and energy-dependent spin precession matrix \mathbf{M} such that $\mathbf{P}_{fp} = \mathbf{M}\mathbf{P}_{tgt}$. To the extent that $\overline{\mathbf{M}} \cdot \mathbf{P}_{tgt} \approx \overline{\mathbf{M}} \cdot \mathbf{P}_{tgt}$ (found to differ by less than 1% in a Monte Carlo simulation using a realistic model of the deuteron), the method of least squares can be used to give the maximum likelihood estimate of the three polarization components at the target in terms of the four focal plane observables [23]. In a separate analysis, the Monte Carlo program MCEEP [24] was coupled with several physics models [25,26] to generate polarized scattering events appropriately weighted by their production cross section over the full experimental acceptance. Using M , the polarization vector for each of these events was transported to the focal plane and their ensemble average then compared to the experimental data. Recoil polarizations at the target extracted using these two different methods were consistent with one another to better than 0.6%.

To facilitate the comparison between the hydrogen and deuterium data, the recoil momentum of the residual neutron for the deuterium data was restricted to the range 0–60 MeV/c. A precise subtraction of the polarization of accidental events was made for the deuterium data.

Table II summarizes the experimental results for the hydrogen and deuterium targets. The first error bars are statistical while the second are uncorrelated systematic

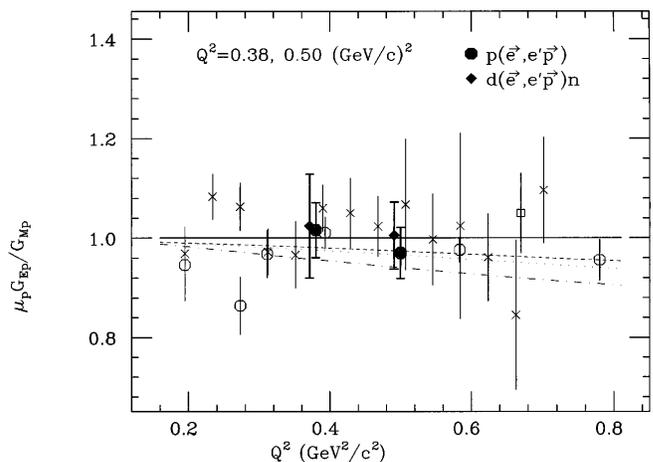


FIG. 1. The ratio $\mu_p G_E/G_M$ for both the proton (solid circles) and deuteron (solid diamonds) vs Q^2 . The error bars represent the statistical and systematic errors added in quadrature. The fits and other (Rosenbluth) data are listed in the text. The deuterium data are offset slightly for the sake of clarity.

errors due to kinematic uncertainties and also uncertainties in the positions of the spectrometer magnets which affect the spin precession. Figure 1 compares these results with previous Rosenbluth separation measurements. The error bars represent the statistical and systematic errors added in quadrature. Our deuterium (solid diamonds) results are slightly offset in Q^2 from our hydrogen (solid circles) measurements to allow comparison. The data are in good agreement with previous Rosenbluth measurements. The previous measurements shown in the figure are from Höhler *et al.* [2] (open circles), Bartel *et al.* [4] (open square), and Janssens *et al.* [5] (\times s). The dot-dashed [27] and short-dashed [28] curves are based on vector dominance models, while the long-dashed curve [29] is based on an extended vector dominance model. Table III shows the measured polarization observables $D_{\ell\ell}$, $D_{\ell t}$, and P_n for the proton and deuteron. Their systematic errors include, in addition to the previously mentioned kinematic and magnet position uncertainties, larger correlated errors due to uncertainties in the beam polarization (4%, which does not affect P_n) and the analyzing power.

The hydrogen and deuterium data agree with each other, which precisely confirms the validity of the impulse

TABLE III. Summary of polarization transfer coefficients. The theoretical calculations are by Arenhövel.

Reaction	$Q^2 \text{ [(GeV/c)}^2]$	$D_{\ell\ell}$	$D_{\ell t}$	P_n
$p(\vec{e}, e'\vec{p})$	0.38	$0.627 \pm 0.031 \pm 0.027$	$-0.510 \pm 0.007 \pm 0.022$	$0.0000 \pm 0.0022 \pm 0.0000$
$d(\vec{e}, e'\vec{p})$	0.38	$0.624 \pm 0.060 \pm 0.027$	$-0.513 \pm 0.016 \pm 0.022$	$-0.0014 \pm 0.0042 \pm 0.0000$
$d(\vec{e}, e'\vec{p})_{\text{theory}}$	0.38	0.649	-0.508	-0.0033
$p(\vec{e}, e'\vec{p})$	0.50	$0.858 \pm 0.030 \pm 0.038$	$-0.410 \pm 0.014 \pm 0.019$	$0.0002 \pm 0.0042 \pm 0.0000$
$d(\vec{e}, e'\vec{p})$	0.50	$0.825 \pm 0.038 \pm 0.037$	$-0.408 \pm 0.018 \pm 0.019$	$-0.0045 \pm 0.0052 \pm 0.0001$
$d(\vec{e}, e'\vec{p})_{\text{theory}}$	0.50	0.866	-0.422	-0.0024

approximation at these kinematics. The deuteron data are consistent with theoretical calculations by Arenhövel assuming a dipole parametrization of the form factors that predicts negligible influence from FSI, MEC, and IC at our kinematics [25]. We have demonstrated that recoil polarization observables may be precisely determined at intermediate energies and, as these observables are inherently much more sensitive than spin-averaged ones to the presence of small amplitudes, this technique shows great promise for future measurements of, for example, G_E^n [30] and G_E^p at higher Q^2 [31].

We thank the staff at the Bates Linear Accelerator Center for their assistance in carrying out this experiment, as well as H. Arenhövel for his calculations of the deuteron polarization observables. One of us (B. D. M.) acknowledges the support of the Air Force Office of Sponsored Research. This work was supported in part by the Department of Energy under Grants No. DE-FG05-90ER40570 and No. DE-FG05-89ER40525, and by the National Science Foundation under Grants No. PHY-89-13959, No. PHY-91-12816, No. PHY-93-11119, No. PHY-94-11620, No. PHY-94-09265, and No. PHY-94-05315. One of us (R. W. L.) acknowledges the support of a NSF Young Investigator Award.

*Present address: Eastern Kentucky University, Richmond, Kentucky 40475.

†Present address: Rutgers University, Piscataway, New Jersey 08855.

‡Present address: Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

§Present address: Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606.

||Present address: University of Kentucky, Lexington, Kentucky 40506.

¶Present address: Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606.

**Present address: State University of New York at Stony Brook, Stony Brook, New York 11794.

††Present address: Florida International University, Miami, Florida 33199.

‡‡Present address: Florida State University, Tallahassee, Florida 32306.

§§Present address: Washington Dept. of Health, Division of Radiation Protection, Olympia, Washington 98504.

|||Present address: Universität Basel, CH-4056 Basel, Switzerland.

¶¶Present address: University of Manitoba, Winnipeg, Canada R3T 2N2.

- [1] L. Andivahis *et al.*, Phys. Rev. D **50**, 5491 (1994); P. E. Bosted *et al.*, Phys. Rev. Lett. **68**, 3841 (1992).
- [2] G. Höhler *et al.*, Nucl. Phys. **B114**, 505 (1976).
- [3] R. C. Walker *et al.*, Phys. Rev. D **49**, 5671 (1994).
- [4] W. Bartel *et al.*, Nucl. Phys. **B58**, 429 (1973).
- [5] T. Janssens *et al.*, Phys. Rev. **142**, 922 (1966).
- [6] R. G. Arnold *et al.*, Phys. Rev. Lett. **57**, 174 (1986); A. F. Sill *et al.*, Phys. Rev. D **48**, 29 (1993).
- [7] E. B. Hughes *et al.*, Phys. Rev. **139**, B458 (1965); **146**, 973 (1966).
- [8] B. Grossetête, S. Julian, and P. Lehmann, Phys. Rev. **141**, 1435 (1966).
- [9] D. Braess, D. Hasselmann, and G. Kramer, Z. Phys. **198**, 527 (1967).
- [10] S. Platchkov *et al.*, Nucl. Phys. **A508**, 343 (1990); **A510**, 740 (1990).
- [11] T. Eden *et al.*, Phys. Rev. C **50**, R1749 (1994).
- [12] R. G. Arnold, C. E. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981).
- [13] A. I. Akhiezer and M. P. Rekalov, Fiz. Elem. Chastits. At. Yadra **4**, 662 (1973) [Sov. J. Part. Nucl. **4**, 277 (1974)].
- [14] N. Dombey, Rev. Mod. Phys. **41**, 236 (1969).
- [15] J. M. Finn, R. W. Lourie, C. F. Perdrisat, and P. E. Ulmer, Bates Proposal No. E88-21, 1988.
- [16] J. I. McIntyre, Ph.D. dissertation, College of William & Mary, 1996 (unpublished).
- [17] B. D. Milbrath, Ph.D. dissertation, University of Virginia, 1996 (unpublished).
- [18] R. W. Lourie *et al.*, IUCF Scientific and Technical Report (1993), p. 135.
- [19] E. Aprile-Giboni *et al.*, Nucl. Instrum. Methods **215**, 147 (1983).
- [20] R. W. Lourie *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **306**, 83 (1991).
- [21] M. W. McNaughton *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **241**, 435 (1985).
- [22] M. Berz, Nucl. Instrum. Methods Phys. Res., Sect. A **298**, 473 (1990).
- [23] D. H. Barkhuff, Bates/Internal Report 97-01, 1997.
- [24] P. E. Ulmer, MCEEP, TJNAF-TN-91-101, 1991.
- [25] H. Arenhövel *et al.*, Z. Phys. A **331**, 123 (1988).
- [26] A. Picklesimer and J. W. Van Orden, Phys. Rev. C **40**, 290 (1989); **35**, 266 (1987).
- [27] P. Mergell, U-G. Meißner, and D. Drechsel, Nucl. Phys. **A596**, 367 (1996).
- [28] G. G. Simon *et al.*, Nucl. Phys. **A333**, 381 (1980).
- [29] M. Gari and W. Krümpelmann, Z. Phys. A **322**, 689 (1985).
- [30] R. Madey *et al.*, TJNAF Proposal No. 93-038, 1993; Bates Proposal No. E89-04, 1989.
- [31] C. F. Perdrisat, V. Punjabi, and M. Jones, TJNAF Proposal No. E93-027, 1993.