Proton electric to magnetic form factor ratio from spin-dependent electron scattering from polarized internal hydrogen gas target

Haiyan Gao

Department of Physics and Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708, U.S.A.

Christopher Crawford

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.

and the BLAST Collaboration

Recently a new measurement of proton electric to magnetic form factor ratio, $\frac{G_E^p}{G_M^p}$ at Q^2= 0.1 - 0.9 $(\mathrm{GeV}/c)^2$ in the South Hall Ring of the MIT-Bates Linear Accelerator Facility from polarized electron-proton elastic scattering was completed. This experiment used a polarized electron beam, a pure hydrogen internal polarized target, and the symmetric Bates Large Acceptance Spectrometer Toroid (BLAST) detector. By measuring the spin-dependent elastic *ep* elastic scattering asymmetry in both sectors simultaneously, we can extract the form factor ratio independent of beam and target polarization. This is the first experiment to measure $\frac{G_E^p}{G_M^p}$ using a polarized proton target, which is complementary to recoil polarimetry experiments. Preliminary results are presented which are based on a subset of the data.

PACS: 25.30.Bf, 24.70.+s
Key words: polarized electron scattering, proton form factors

1 Introduction

The electromagnetic form factors of the nucleon are fundamental quantities describing the distribution of charge and magnetization within nucleons. Quantum Chromodynamics (QCD) is the theory of strong interaction in terms of quark and gluon degrees of freedom. While QCD has been extremely well tested in the high energy regime, where perturbative QCD is applicable, understanding confinement and hadron structure in the non-perturbative region of QCD remains challenging. Knowledge of the internal structure of protons and neutrons in terms of quark and gluon degrees of freedom is not only essential for testing QCD in the confinement regime, but it also provides a basis for understanding more complex, strongly interacting matter at the level of quarks and gluons.

The proton electric (G_E^p) and magnetic (G_M^p) form factors have been studied extensively in the past from unpolarized electron-proton (*ep*) elastic scattering using the Rosenbluth separation technique [1]. Recent advances in polarized beams, targets, and polarimetry have allowed for a new class of experiments extracting $\mu G_E^p/G_M^p$ from spin degrees of freedom. Recent data from polarization transfer experiments [2, 3], which measure this ratio directly with unprecedented precision, show very intriguing behavior at higher Q^2. The form factor ratio, $\frac{\mu G_E^p}{G_M^p}$ drops to approximately 0.5 at a Q^2 value above 3 (GeV/c)^2, and to approximately 0.3 at the highest measured Q^2 value ($\sim$ 5.5 (GeV/c)^2). No such dramatic behavior in this ratio had been observed from unpolarized cross section measurements.

Fig. 1 shows the proton electric to magnetic form factor ratio as a function of Q^2 from recoil proton polarization measurements at Jefferson Lab [2, 3], together with data from SLAC using Rosenbluth separation technique [4]. These new data [2, 3] suggest that the proton Dirac ($F_1(Q^2)$) and Pauli form factors ($F_2(Q^2)$) scale as $Q\frac{F_1}{F_2} \sim$ constant at large values of Q^2, instead of $Q^2\frac{F_1}{F_2} \sim$ constant, as suggested by the previous unpolarized data. The Q^2 scaling was believed to occur because contributions from nonzero parton orbital angular momentum were power suppressed, as shown by Lepage and Brodsky [6]. However, these contributions have been shown to lead to asymptotic scaling of the proton form factor ratio: $F_2(Q^2)/F_1(Q^2) \sim (\log^2 Q^2/\Lambda^2)/Q^2$ with 0.2 GeV$\leq \Lambda \leq$0.4 GeV based on an explicit pQCD calculation [7]. In the same approach, Ji, Ma and Yuan [8] derived a generalized counting rule for exclusive processes at fixed angles involving parton orbital angular momentum and hadron helicity flip. A new analysis [9] based on the generalized quark counting was able to provide a better description of the proton-proton elastic scattering data. $F_2(Q^2)/F_1(Q^2) \sim 1/\sqrt{Q^2}$ scaling behavior was obtained by Ralston [10] and Miller [11] using calculations involving parton orbital angular momentum. A recent nonperturbative analysis [12] of the hadronic form factors based on light-front wave functions was also carried out. All these approaches [7, 10, 11, 12] describe the JLab proton form factor data [2, 3] well.

While the intriguing Q^2 dependence of the proton form factor ratio can be described [7, 10, 11, 12], it is important to understand the discrepancy between results obtained from recoil proton polarization measurements and those from the Rosenbluth method. New Jefferson Lab data [13] from Rosenbluth separations are in good agreement with previous SLAC results. Recently, a new "Super-Rosenbluth" experiment was carried out at Jefferson Lab [14], in which the struck protons were detected instead of the electron to minimize systematic uncertainties associated the large variation of energy of the scattered electron. These new results (solid circles in Fig. 1) agree with previous Rosenbluth experiments, suggesting some fundamental difference in the formalism of polarized and unpolarized extractions of the form factor ratio. Two-photon exchange contributions [15] are believed to contribute to the observed discrepancy between the polarization method and the Rosenbluth technique. Currently, there are intensive efforts both in theory [16] and in experiment [17] aiming at understanding the two-photon exchange contributions to electron scattering in general, particularly with respect to the aforementioned discrepancy in the proton form factor ratio.

As an independent extraction of the proton form factor ratio from polarized electron scattering, we recently completed a new experiment [18] in which longitudinally polarized electrons were scattered from a polarized proton target at the MIT-Bates accelerator Laboratory. The proton electric to magnetic form factor ratio can be extracted from the spin-dependent asymmetry with high precision up to a Q^2 value of about 0.6 (GeV/c)^2. Such a double-polarization experiment is important because it employs a completely different experimental technique with different systematic uncertainties than recoil proton polarization measurements.

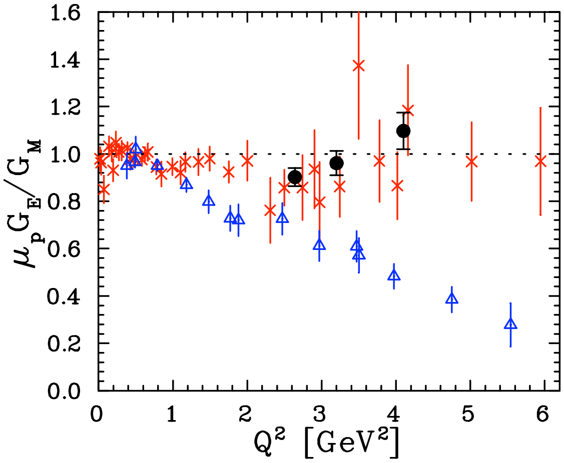

Fig. 1. *Proton electric to magnetic form factor ratio as a function of Q^2. Data from the JLab recoil proton polarization measurements [2, 3] are shown as open triangles, and the new Jefferson Lab data from Super-Rosenbluth separation [14] are shown as solid circles. A global analysis of the previous cross section data (Fig. 2 of Ref. [5]) is shown as crosses.*

2 Spin-dependent electron-proton elastic scattering

The spin-dependent asymmetry for elastic e-p scattering has the following form [19]:

$$A = \frac{\Delta}{\Sigma} = -\frac{2\tau v_{T'} \cos\theta^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2} , \quad (1)$$

where θ^*, ϕ^* are the target spin polar and azimuthal angles defined relative to the three-momentum transfer vector of the virtual photon. The experimental asymmetry A_{exp}, is related to the spin-dependent asymmetry of Eqn. 1 by the relation

$$A_{exp} = P_b P_t A , \quad (2)$$

where P_b and P_t are the beam and target polarizations, respectively. A determination of the ratio $\frac{G_E^p}{G_M^p}$, independent of the knowledge of the beam and target polarization, can be precisely obtained by forming the so-called super ratio [20]:

$$R = \frac{A_1}{A_2} = \frac{2\tau v_{T'} \cos\theta_1^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta_1^* \cos\phi_1^* G_M^p G_E^p}{2\tau v_{T'} \cos\theta_2^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta_2^* \cos\phi_2^* G_M^p G_E^p}\,, \qquad (3)$$

where A_1 and A_2 are elastic electron-proton scattering asymmetries measured at the same Q^2 value, but two different proton spin orientations relative to the corresponding three-momentum transfer vector, i.e., (θ_1^*, ϕ_1^*) and (θ_2^*, ϕ_2^*), respectively. For a detector configuration that is symmetric with respect to the incident electron momentum direction, and a polarized target with the spin vector alligned at approximately 45° with respect to the beamline, A_1 and A_2 can be measured simultaneously by forming two independent asymmetries with respect to either the electron beam helicity or the target spin orientation in the beam-left and beam-right sector of the detector system, respectively.

3 The BLAST experiment on spin-dependent electron-proton elastic scatting

The experiment was carried out in the South Hall Ring of the MIT Bates Linear Accelerator Center, which stored an intense polarized beam with a beam current of up to 300 mA and longitudinal electron polarization of 0.65. A Siberian Snake in the ring opposite of the interaction point preserved the electron polarization, which was continuously monitored with a Compton polarimeter installed upstream of the internal target region. The background was minimized with a tungsten collimator in front of the target cell.

The electrons scattered off of polarized protons from an Atomic Beam Source (ABS) internal target, in a cylindrical target cell 60 cm long by 15 mm in diameter. The ABS provided a highly polarized ($P_t \sim 0.8$) isotopically pure target without windows in the beam line, and with fast spin reversal to reduce systematic errors. The ABS was operated in single state mode in order to avoid depolarization due to hyperfine interactions. The ABS switched between states every five minutes and the ring was filled with alternating electron polarizations every half hour.

The relatively low luminosity $L = 1.6 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ of the internal gas target is compensated by the large acceptance spectrometer. The symmetric detector package was built around eight copper coils which provided the 0.4 Tesla BLAST toroidal magnetic field. Two of the sectors were instrumented with three drift chambers each for momentum, angular, and positional resolution, scintillators for triggering and time-of-flight, and Čerenkov detectors for pion rejection. Additional scintillators at backward angles beyond the drift chambers extended the acceptance to $Q^2 = 0.85(\mathrm{GeV/c})^2$.

The elastic events were selected with a cut on the invariant mass of the scattered electron, and a vertex cut, and fiducial cuts on the acceptance. These cuts were also consistent with kinematic cuts on the 3-momentum of the recoil proton, and timing and co-planarity cuts on the scintillators. These cuts were sufficient to reduce the background to less than 1%. The background was measured with 14.9 kC of integrated beam current on the same target cell without hydrogen flowing.

4 Preliminary results

The first production run in December 2003 accumulated 3.4 pb^{-1} of integrated luminosity with the target polarization $P_t = 0.48 \pm 0.04$ and the BLAST field reversed to extend to lower values of Q^2. The second run in April 2004 accumulated 9.6 pb^{-1} with $P_t = 0.42 \pm 0.04$ and the nominal BLAST field. Another 98 pb^{-1} have been accumulated in the third run completed in December 2004, with target polarization improved to $P_t = 0.80$.

Preliminary results are shown in Fig. 2 with statistical errors only. These results do not include the December 2004 run, which will increase our effective statistics by a factor of 13. We have also taken 76 pb^{-1} of elastic $D(e,e'p)$ data of target vector polarization $P_z \sim 0.72$ with BLAST which may be used to extract $\frac{G_E}{G_M}$ from the deuteron.

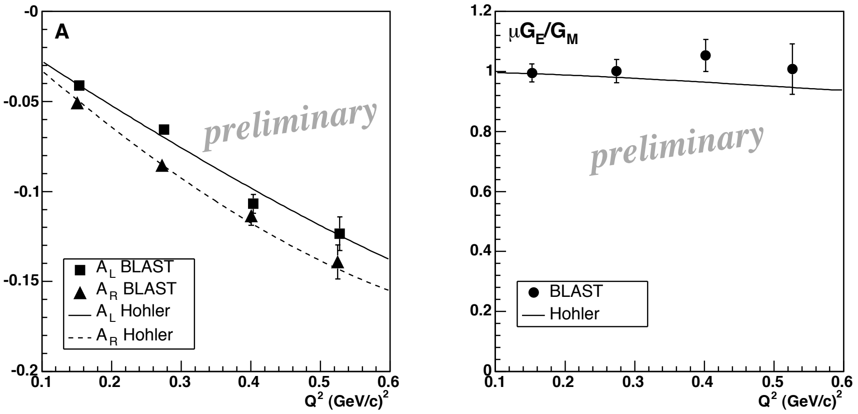

Fig. 2. Left: the *ep* elastic asymmetry in the left and right sectors of BLAST, compared to the asymmetry from the Höhler[21] parametrization of G_E^p and G_M^p. Right: preliminary results of $\frac{\mu_p G_E^p}{G_M^p}$ from the partial dataset also compared to Höhler.

There are two important systematic errors which are currently being addressed. The first is in the uncertainty of $\theta^* = \beta - \theta_q$. The target spin angle β can be measured from tensor polarized *ed* elastic scattering in BLAST, and the momentum transfer angle θ_q is overdetermined in elastic kinematics from both the momentum and scattering angle of the electron and proton. The second main contribution comes from the two detectors not being exactly symmetric, and we must account for the difference in Q^2 between the left and right sectors. The experimental asymmetry can be formed in four different ways from our experiment by reversing both the beam helicity and the target polarization directions in order to minimize the experimental false asymmetry. The final results from the complete data set will be available in several months.

5 Acknowledgment

We thank the staff at the MIT-Bates Linear Accelerator Center for the delivering of high quality electron beam and for the their technical support which made this experiment an success. We thanks T.W. Donnelly for stimulating discussions and J. Arrington for providing Figure 1. This work is supported by the U.S. Department of Energy under contract number DE-FC02-94ER40818 and DE-FG02-03ER41231.

References

[1] M.N. Rosenbluth, Phys. Rev. **79**, 615 (1950).

[2] M. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000).

[3] O. Gayou *et al.*, Phys. Rev. Lett. **88**, 092301 (2002).

[4] R.C. Walker *et al.*, Phys. Rev. D **49**, 5671 (1994).

[5] J. Arrington, Phys. Rev. C **69**, 022201(R) (2004).

[6] G. P. Lepage and S. J. Brodsky, Phys. Rev. D **22**, 2157 (1980).

[7] A. V. Belitsky, X. Ji, and F. Yuan, Phys. Rev. Lett.**91**, 092003 (2003).

[8] X. Ji, J.-P. Ma, F. Yuan, Phys. Rev. Letts. **90**, 241601 (2003).

[9] D. Dutta, H. Gao, Phys. Rev. C **71**, 032201 (2005).

[10] J. P. Ralston and P. Jain, hep-ph/0207129, (2002); J. P. Ralston, R. V. Buniy and P. Jain, hep-ph/0206063, (2002)

[11] G. A. Miller and M. R. Frank, Phys. Rev. C **65**, 065205 (2002).

[12] S.J. Brodsky, J.R. Hiller, D.S. Hwang, V.A. Karmanov, Phys. Rev. D **69**, 076001 (2004), also hep-ph/0311218.

[13] M.E. Christy *et al.*, Phys. Rev. C **70**, 015206 (2004).

[14] I.A. Qattan *et al.*, Phys. Rev. Letts. **94**, 142301 (2005).

[15] P.A.M. Guichon and M. Vanderhaeghen, Phys. Rev. Lett. **91**, 142303 (2003). P.G. Blunden, W. Melnitchouk, J.A. Tjon, Phys. Rev. Lett. **91**, 142304 (2003); M.P. Rekalo and E. Tomasi-Gustafsson, nucl-th/0307066.

[16] Y.C. Chen, A.V. Afanasev, S.J. Brodsky, C.E. Carlson and M. Vanderhaeghen, hep-ph/0403058; A.V. Afanasev and N.P. Merenkov, hep-ph/0406127.

[17] Jefferson Lab experiment E04-116, contact person W. Brooks; J. Arrington *et al.*, nucl-ex/0408020; Jefferson Lab experiment E04-019, contact person: R. Suleiman; Jefferson Lab experiment E05-015, contact person: T. Averett.

[18] MIT-Bates Experiment E01-01, Spokespersons: H. Gao, J. Calarco, H. Kolster; C. Crawford, Ph.D thesis, 2005, MIT (unpublished).

[19] T.W. Donnelly and A.S. Raskin, Ann. Phys. **169**, 247 (1986).

[20] H. Gao, Int. J. of Mod. Phys. E **12**, 1-40 (2003).

[21] G. Höhler , *Nucl. Phys.* **B114**, 505 (1976).