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We report the first precision measurement of the proton electric to magnetic form factor ratio from spin-dependent elastic scattering of longitudinally polarized electron beam from a polarized hydrogen internal gas target at the MIT-Bates South Hall Storage Ring in a $Q^2$ range of 0.1 to 0.65 (GeV/c)$^2$. In combination with world cross-section data on elastic electron-proton scattering in the same momentum transfer squared region, significantly improved results on proton electric and magnetic form factors are obtained.

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The electromagnetic form factors of the nucleon are fundamental quantities describing the distribution of charge and magnetization within the nucleon. At low momentum transfer squared $Q^2$, they probe the structure of the pion cloud [1], and provide tests of predictions of effective field theories of QCD [2]. Lattice QCD has made considerable progress in describing the form factors at low $Q^2$ [3–5], and with future advances in technique and computing power will require precision data to test against. Precision data on nucleon electromagnetic form factors at low $Q^2$ is also important to parity-violation electron scattering experiments [6], which probe the strange quark contribution to the nucleon electromagnetic structure. Knowledge of the internal structure of protons and neutrons in terms of quark and gluon degrees of freedom of QCD 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 over a wide range of $Q^2$ from unpolarized electron-proton (e-p) elastic scattering using the Rosenbluth separation technique [7]. The electric form factor has been mapped out very precisely at $Q^2 < 0.1$ (GeV/c)$^2$ in an effort to determine the RMS charge radius of the proton [8], and the magnetic form factor has been measured out to $Q^2 = 31.2$ (GeV/c)$^2$ [9]. While precise information on $G_E^p$ and $G_M^p$ is important for understanding the underlying electromagnetic structure of the nucleon, it is also very interesting to study the ratio $\frac{G_E^p}{G_M^p}$ as a function of $Q^2$, where $\mu_p$ is the proton magnetic moment in the units of the nuclear magneton. The observation of $Q^2$ dependence of the form factor ratio would suggest different charge and current spatial distributions inside the proton.

Recent advances in polarized beams, targets, and polarimetry have allowed for a new class of experiments extracting $\frac{G_E^p}{G_M^p}$ from spin degrees of freedom. Extraction of the form factor ratio from polarization observables has two substantial advantages over unpolarized cross section measurements. First the spin-dependent cross section has an interference term between $G_E$ and $G_M$, allowing for a direct determination of the proton electric to magnetic form factor ratio, from either the spin-dependent asymmetry [10] or the recoil polarization measurement [11] while the unpolarized cross section only depends on $G_E^2$ and $G_M^2$. Second, spin degrees of freedom can be varied instead of the beam energy and scattering angle as done in the Rosenbluth separation, greatly reducing the systematic errors. New
data from polarization transfer experiments [12, 13] show a very intriguing behavior at higher $Q^2$: starting at $Q^2 = 1(\text{GeV}/c)^2$, $\frac{G_F^p}{G_M}$ drops linearly from approximately 1 down to 0.28 at the highest measured $Q^2$ value ($\sim 5.54$ (GeV/c$^2$)). No such dramatic departure from $\frac{G_F^p}{G_M} \sim 1$ ratio had been observed from unpolarized cross section measurements [14]. Recent Jefferson Lab data [15] from Rosenbluth separations are in good agreement with previous SLAC results. They are also consistent with results from a new “Super-Rosenbluth” experiment [16], in which the recoil proton instead of electron was detected to avoid systematic uncertainties associated with large variation in momentum of the scattered electron.

The new recoil polarization data [12, 13] suggest that the proton Dirac ($F_1(Q^2)$) and Pauli ($F_2(Q^2)$) form factors scale as $Q^2 F_1 \sim \text{constant}$ at large values of $Q^2$ [13] instead of $Q^2 F_2 \sim \text{constant}$, as was implied by the unpolarized data. The latter scaling was thought to hold because contributions from nonzero parton orbital angular momentum are power suppressed, as shown by Lepage and Brodsky [17]. However, more detailed calculations have shown these contributions still lead to asymptotic scaling of the proton form factor ratio: $F_2(Q^2)/F_1(Q^2) \sim (\log Q^2/\Lambda^2)/Q^2$ with 0.2 GeV$\leq\Lambda\leq0.4$ GeV based on an explicit pQCD calculation [18] or $F_2(Q^2)/F_1(Q^2) \sim 1/\sqrt{Q^2}$ [21, 22] that agrees with the JLab proton form factor data [12, 13]. A generalized counting rule along the same lines as [18] derived by Ji et al. was shown to provide a better description [20] of the proton-proton elastic scattering data. A recent nonperturbative analysis [23] of the hadronic form factors based on light-front wave functions also describes the JLab proton form factor data [12, 13] well.

Two-photon exchange contributions [24] are suggested to contribute to the observed discrepancy between the polarization method and the Rosenbluth technique. Currently, there are intensive efforts both in theory [25] and in experiment [26] aiming at understanding the two-photon exchange contributions to electron scattering in general, particularly to the aforementioned discrepancy in the proton form factor ratio.

In this letter, we report the first measurement of $\frac{G_F^p}{G_M}$ using both polarized beam and polarized target in the intermediate $Q^2$ region between unpolarized proton radius data and the FPP Jlab data. This experiment uses a completely different technique than the recoil polarimeter with different sources of systematic error, but benefits from some of the same cancellations in systematic error.

The spin-dependent asymmetry for elastic e-p scattering has the following form [10]:

$$A = \frac{\Delta}{\Sigma} = -\frac{2\tau v_{TT'} \cos \theta^* G^p_M}{\Sigma} - \frac{2\sqrt{2\tau(1+\tau)} v_{T'L'} \sin \phi^* G^p_M G^p_E}{1+\tau} v_{LT'} G^p_E + 2\tau v_{TT'} G^p_E,$$

(1)

where $\theta^*$, $\phi^*$ 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 Eq. 1 by the relation $A_{exp} = P_b P_t A$, where $P_b$ and $P_t$ are the beam and target polarizations, respectively. A determination of the ratio $\frac{G_F^p}{G_M}$, independent of the knowledge of the beam and target polarization, can be precisely obtained by forming the so-called super ratio [29]:

$$R = \frac{A_{left}}{A_{right}} = \frac{2\tau v_{TT'} \cos \theta_1^* G^p_M}{2\tau v_{TT'} \cos \theta_2^* G^p_M} \frac{2\tau v_{T'L'} \sin \theta_1^* \cos \phi_1^* G^p_M G^p_E}{2\tau v_{T'L'} \sin \theta_2^* \cos \phi_2^* G^p_M G^p_E},$$

(2)

where $A_{left}$ and $A_{right}$ 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., $(\theta_1^*, \phi_1^*)$ and $(\theta_2^*, \phi_2^*)$, respectively. For a detector configuration that is symmetric with respect to the incident electron momentum direction, $A_{left}$ and $A_{right}$ 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.

The experiment (BLAST) was carried out in the South Hall Ring of the MIT Bates Linear Accelerator Center, which stores an intense polarized beam with a beam cur-
rent of up to 300 mA and longitudinal electron polarization of 0.65. A Siberian Snake in the ring opposite of the interaction point preserves the electron polarization, which was continuously monitored with a Compton polarimeter installed upstream of the internal target region. The electrons scattered from polarized protons in a cylindrical, windowless aluminum target tube 60 cm long by 15 mm in diameter of an Atomic Beam Source (ABS) internal target based on the Stern-Gerlach technique. The background was minimized with a tungsten collimator in front of the target cell. The ABS provided a highly polarized \( P_L \approx 0.80 \) isotopically pure target without windows in the beam line, and with fast spin reversal to reduce systematic errors. The spin state was alternated every five minutes by switching the final RF transition immediately before the target to ensure equal target intensities for both states. The ring was filled with alternating electron polarizations every half hour. Details of the BLAST ABS target can be found in [27].

The relatively low luminosity \( L = 1.6 \times 10^{31} \text{cm}^{-2}\text{s}^{-1} \) of the internal gas target was compensated by a large acceptance spectrometer. The symmetric detector package was built around eight copper coils which provided a 0.4 Tesla toroidal magnetic field. Two of the eight sectors were instrumented with three drift chambers each for momentum, angular, and positional resolution, plastic 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 \( Q^2 = 0.85 \text{(GeV/c)}^2 \). Details of the BLAST detector can be found in [28].

We accumulated 89.8 pb\(^{-1} \) of integrated luminosity, corresponding to 291 kC of integrated charge on the target. The elastic events were detected in coincidence with a hardware trigger requirement of TOF signals for both the electron and proton. A second level trigger also required signals in the wire chambers to reduce background rates and to decrease the computer deadtime. The beam current was measured by a parametric DC current transformer in the ring, calibrated periodically with a DC current supply. The output voltage was converted to a frequency signal and integrated in a scaler channel, gated by the DAQ deadtime.

The elastic events were selected with a cut on the invariant mass of the virtual photon and the target proton system, 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 charge on the same target cell without hydrogen flowing. The beam halo effect was shown to be negligible by comparing the \( H(e,e'n) \) background rates between hydrogen and empty targets.

The data were divided into 8 \( Q^2 \) bins ranging from 0.025 \( \text{(GeV/c)}^2 \) to 0.01 \( \text{(GeV/c)}^2 \) in width. The value of \( Q^2 \) determined from the electron scattering angle agreed with \( Q^2 \) determined from the proton angle to 0.007 \( \text{(GeV/c)}^2 \), and agreed with that from the time-of-flight of the proton to 0.015 \( \text{(GeV/c)}^2 \). The yields were in good agreement with results from a Monte Carlo simulation, including all detector efficiencies measured from the real data. The thickness of the ABS target was determined by comparison of luminosity with an unpolarized buffer gas system, where the flow rate was calculated from the volume and rate of decrease of pressure in the buffer.

Separate yields were measured for each combination of electron helicity and target spin orientation. The experimental physics asymmetry was formed from \( (\sigma_{++} - \sigma_{+-+-} - \sigma_{--} - \sigma_{-+-})/\Sigma_{ij} \). The beam and target single-asymmetries were also measured, monitoring for false asymmetry. The physics asymmetry was corrected for background dilution, including the beam halo effect. Radiative corrections were also applied using MASCARAD [30], but were less than 0.43% for \( A_{L\text{eft}} \) and 0.16% for \( A_{L\text{eft}} \). The asymmetries are shown in Fig. 1.

![FIG. 1: Experimental \( H(e,e'p) \) asymmetry.](image)

The form factors were extracted by fitting Eq. 1 to the experimental asymmetries in both sectors for \( P_L P_l \) and an independent form factor ratio \( \frac{\mu e G^p_{eff}}{G^n_{eff}} \) in each \( Q^2 \) bin. The asymmetry in the left and right sector in each \( Q^2 \) bin were interpolated to the average \( Q^2 \) value of the two sectors. As a check, \( P_L P_l \) was also extracted independently in each \( Q^2 \) bin using Eq. 2, but a single value \( P_L P_l \) was fit for all \( Q^2 \) values in the final analysis for optimal extraction of the form factor ratio. The two major sources of systematic uncertainty are in the determination of \( \langle Q^2 \rangle \) in each bin and in the determination of the target spin angle. The measurement of \( Q^2 \) in the drift chambers was compared between that from the electron and that from the proton. Also, the \( Q^2 \) was independently calculated from the time of flight information of the proton, a method which is insensitive to both the geometry of the drift chambers and the BLAST magnetic field. The
timing offsets were calibrated absolutely using the timing of the cosmic rays which passed through both sectors of the detector. The spin angle of the target was measured to 1° in a magnetic field map of the target region. This measurement agreed well with extractions of the spin angle from the analysis of e-p elastic scattering and also of the $T_{20}$ tensor polarization in elastic scattering from deuterium. The systematic effect of the spin angle is reduced because extraction of the polarization partially compensates for errors in the spin angle. The overall systematic uncertainties are 2% in the proton form factor ratio.

The results are shown in Fig. 2 with the inner error bars being the statistical errors and the outer error bars being the statistical and systematic errors in quadrature. Also shown in Fig. 2 are published recoil polarization data [12, 13, 31–34]. A few models were selected [29] which gave good descriptions of the high $Q^2$ recoil polarization data [12, 13] on the proton form factor ratio. These are the Soliton model [35], the extended vector meson dominance model [36], the relativistic CQM model [37], and the relativistic CQM [38] with SU(6) symmetry breaking and a constituent quark form factor. Also shown is the Höhler parameterization, which seems to describe our data the best.

In combination with the world cross-section data on e-p elastic scattering in the same $Q^2$ values, the proton electric and magnetic form factors can be re-extracted. Fig. 3 shows the extracted proton electric and magnetic form factors. The extracted form factors using the BLAST form factor ratio results are shown as red solid dots. The precision has been significantly improved compared with results (shown in all other plotting symbols) obtained using the Rosenbluth separation technique. The proton electric form factor suggests a rather interesting $Q^2$ dependence around $Q^2 = 0.2$ to 0.3 (GeV/c)$^2$. Similar interesting behavior has been observed in the neutron electric [40] and magnetic form factor [41] data as well. A possible explanation for this interesting behavior could be due to the effect of the pion cloud at low momentum transfers as suggested by Friedrich and Walcher [42], though a more detailed understanding of such structure requires new precision results from lattice QCD.

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[27] ABS NIM paper
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