Recoil Polarization Measurements of the Proton Electromagnetic Form Factor Ratio to $Q^2 = 8.5 \text{ GeV}^2$

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Abstract

Among the most fundamental observables of nucleon structure, electromagnetic form factors are a crucial benchmark for modern calculations describing the strong interaction dynamics of the nucleon’s quark constituents; indeed, recent proton data have attracted intense theoretical interest. In this letter, we report new measurements of the proton electromagnetic form factor ratio using the recoil polarization method, at momentum transfers $Q^2 = 5.2, 6.7, \text{ and } 8.5 \text{ GeV}^2$. By extending the range of $Q^2$ for which $G_E^p$ is accurately determined by more than 50%, these measurements will provide significant constraints on models of nucleon structure in the non-perturbative regime.
The measurement of nucleon electromagnetic form factors, pioneered at Stanford in the 1950s, has again become the subject of intense investigation. Precise recoil polarization experiments [1] established conclusively that the proton electric form factor $G_E^p$ falls faster than the magnetic form factor $G_M^p$ for momentum transfers $Q^2 \geq 1 \text{ GeV}^2$, in disagreement with results obtained from cross section measurements [2–5]. Precise data to the highest possible $Q^2$ are needed, for example, to test the onset of validity of perturbative QCD (pQCD) predictions for asymptotic form factor behavior [6], constrain Generalized Parton Distributions (GPDs) [7], and to determine the nucleon’s model-independent impact parameter-space charge and magnetization densities [8].

The effect of nucleon structure on elastic electron-nucleon scattering at a spacelike momentum transfer $q^2 = -Q^2 < 0$ is described in the one-photon-exchange approximation by the helicity-conserving and helicity-flip form factors $F_1(q^2)$ (Dirac) and $F_2(q^2)$ (Pauli), or alternatively the Sachs form factors, defined as the linear combinations $G_E = F_1 - \tau F_2$ (electric) and $G_M = F_1 + F_2$ (magnetic), where $\tau \equiv Q^2/4M^2$ and $M$ is the nucleon mass. Polarization observables, such as the beam-target double-spin asymmetry [9] and polarization transfer [10, 11] provide enhanced sensitivity to the electric form factor at large $Q^2$ compared to cross section measurements, for which $G_M$ becomes the dominant contribution. The polarization of the recoil proton in the elastic scattering of longitudinally polarized electrons from unpolarized protons has longitudinal ($P_l$) and transverse ($P_t$) components with respect to the momentum transfer in the scattering plane [11]. The ratio $P_t/P_l$ is proportional to $G_E^p/G_M^p$:

$$R \equiv \mu_p \frac{G_E^p}{G_M^p} = -\mu_p \frac{P_t E_e + E'_e}{P_l} \frac{E_e}{2M_p} \tan \frac{\theta_e}{2}$$

where $\mu_p$ is the proton magnetic moment, $E_e$ is the beam energy, $E'_e$ is the scattered $e^-$ energy, $\theta_e$ is the $e^-$ scattering angle and $M_p$ is the proton mass. Because the extraction of $G_E^p$ from the ratio [11] is much less sensitive than the Rosenbluth method [12] to higher-order corrections beyond the standard radiative corrections [13], it is generally believed that polarization measurements provide the correct determination of $G_E^p$ in the $Q^2$ range where the two methods disagree. Previously neglected two-photon-exchange effects have been shown to partially resolve the discrepancy [14], and are a highly active area of theoretical and experimental investigation.

The new measurements of $G_E^p/G_M^p$ were carried out in experimental Hall C at Jefferson
Lab. A continuous polarized electron beam was scattered from a 20 cm liquid hydrogen target, and elastically scattered electrons and protons were detected in coincidence. Typical beam currents ranged from 60-100 $\mu$A. The beam helicity was reversed pseudorandomly at 30 Hz. The beam polarization of typically 80-85% was monitored periodically using Möller polarimetry [15].

Scattered protons were detected in the Hall C High Momentum Spectrometer (HMS) [16], a superconducting magnetic spectrometer with three focusing quadrupole magnets followed by a 25° vertical bend dipole magnet, operated in a point-to-point tune. Charged particle trajectories at the focal plane were measured using drift chambers, and their momenta, scattering angles, and vertex coordinates were reconstructed using the transport matrix of the HMS. For this experiment, the HMS trigger was defined by a coincidence between the pair of scintillator planes just behind the drift chambers and an additional scintillator paddle placed at the exit of the dipole. The size of this new paddle matched the acceptance of elastically scattered protons.

To measure the polarization of scattered protons, a double Focal Plane Polarimeter (FPP) was installed in the HMS detector hut, replacing the standard Čerenkov detector and rear scintillators. The FPP consists of two retractable 50 g cm$^{-2}$ CH$_2$ analyzer doors, each followed by a pair of large-acceptance drift chambers with an active area 164 $\times$ 132 cm$^2$. The tracks of protons scattered in the analyzer material were reconstructed with an angular resolution of approximately 1 mrad.

Scattered electrons were detected in a large-acceptance electromagnetic calorimeter (Big-Cal) positioned for each $Q^2$ to cover a solid angle kinematically matched to the $\approx$ 7 msr proton acceptance of the HMS, up to 143 msr at $Q^2 = 8.5$ GeV$^2$. BigCal was assembled from 1,744 lead-glass bars stacked in a rectangular array with a frontal area of 1.2 $\times$ 2.2 m$^2$ and a thickness of approximately 15 radiation lengths. The trigger for BigCal was formed from analog sums of up to 64 channels, grouped with overlap to maximize the efficiency for electrons at high thresholds of nearly half the elastic $e^-$ energy, used to suppress charged pions and low-energy backgrounds. The over-determined elastic ep kinematics allowed for continuous in situ calibration and gain matching. The primary trigger for the experiment was a time coincidence between BigCal and the HMS within a ±50 ns window.

Elastic events were selected by applying cuts to enforce two-body reaction kinematics. The electron scattering angle $\theta_e$ was predicted from the proton momentum $p_p$ and the
beam energy, and the azimuthal angle $\phi_e$ was predicted from $\phi_p$ assuming coplanarity of the electron and the proton. The predicted electron trajectory was projected from the interaction vertex to the surface of BigCal and compared to the measured shower coordinates. The small area of each cell relative to the transverse shower size resulted in coordinate resolution of 5-10 mm, corresponding to an angular resolution of 1-3 mrad, which matched or exceeded the resolution of the predicted angles from elastic kinematics of the reconstructed proton.

An elliptical cut $(\Delta x/x_{\text{max}})^2 + (\Delta y/y_{\text{max}})^2 \leq 1$ was applied to the horizontal and vertical coordinate differences $(\Delta x, \Delta y)$, where $(x_{\text{max}}, y_{\text{max}})$ are the $Q^2$-dependent, $3\sigma$ cut widths used for the final analysis. An additional cut was applied to the proton angle-momentum correlation $p_p - p_p(\theta_p)$ which further suppressed the inelastic background. No cut was applied to the measured $e^-$ energy, because the BigCal energy resolution was insufficient to provide additional separation between elastic and inelastic events. Figure 1 illustrates the separation of the elastic peak in the $p_p - p_p(\theta_p)$ spectrum using BigCal.

![Figure 1](image.png)

**FIG. 1.** (Color online) Elastic event selection for $Q^2 = 8.5$ GeV$^2$. The momentum difference $(p_p - p_p(\theta_p))/p_0$, where $p_0$ is the HMS central momentum, plotted for all events (black dashed), events passing the $3\sigma$ elliptical cut (blue solid), and events failing the cut (green dotted). The estimated background (red dot-dashed) integrated over the final cut region (black vertical lines) is approximately 5.9%.

The dominant background was hard-Bremsstrahlung-induced $\pi^0$ photoproduction, $\gamma + p \to \pi^0 + p$, in the 2.3% radiation length cryotarget, with the proton detected in the HMS and one or two $\pi^0$ decay photons detected in BigCal. The kinematics of this reaction overlap with elastic $ep$ scattering within experimental resolution for near-endpoint photons. The contribution of quasi-elastic Al$(e, e'p)$ scattering from the cryocell windows was also
measured and found to be negligible after cuts. The total background including inelastic reactions and random coincidences was estimated as a function of $p_{\text{p}} - p_{\text{p}}(\theta_{\text{p}})$, as shown in figure 1, using a two-dimensional Gaussian extrapolation of the $(\Delta x, \Delta y)$ distribution of the background into the cut region under the elastic peak. A Monte Carlo simulation of elastic $ep$ scattering and $\pi^0$ photoproduction was performed as a check on the background estimation procedure. The two methods agreed at the 10% (relative) level for wide variations of the cuts.

The angular distribution of protons scattered in the CH$_2$ analyzers measures the polarization components at the focal plane. The polar and azimuthal scattering angles $(\vartheta, \varphi)$ of tracks in the FPP drift chambers were calculated relative to the incident track defined by the focal plane drift chambers. The measured angular distribution can be expressed in the general form,

$$N^\pm(p, \vartheta, \varphi) = N_0^\pm \frac{\varepsilon(p, \vartheta)}{2\pi} \left[ 1 + (c_1 \pm A_y P_{fpp}^y) \cos \varphi + (s_1 \mp A_y P_{fpp}^y) \sin \varphi + c_2 \cos(2\varphi) + s_2 \sin(2\varphi) + \ldots \right]$$

(2)

where $N_0^\pm$ is the number of incident protons in the $\pm$ beam helicity state, $\varepsilon(p, \vartheta)$ is the fraction of protons of momentum $p$ scattered by an angle $\vartheta$, $A_y(p, \vartheta)$ is the analyzing power of the $p^+\text{CH}_2$ reaction, and $P_{fpp}^x$ and $P_{fpp}^y$ are the transverse components of the proton polarization at the focal plane. $c_1, s_1, c_2, s_2, \ldots$ are the Fourier coefficients of helicity-independent instrumental asymmetries, which are cancelled to first order by the helicity reversal. Figure 2 shows the measured helicity-dependent azimuthal asymmetry $f_+ - f_- = 2\pi \frac{N_+(\varphi) - N_-(\varphi)}{N_0} \approx \bar{A}_y [P_{fpp}^y \cos \varphi - P_{fpp}^x \sin \varphi]$, where $\Delta \varphi$ is the bin width, summed over all $p$ and the $\vartheta$ range $0.5^\circ \leq \vartheta \leq 14^\circ$ outside which $A_y \approx 0$.

The extraction of $P_t$, $P_l$, and $P_t/P_l$ from the measured asymmetry at the focal plane involves the precession of the proton polarization in the HMS magnetic field, governed by the Thomas-BMT equation [17]. The rotation of longitudinal $P_l$ into normal $P_{fpp}^x$ allows the simultaneous measurement of $P_l$ and $P_t$ in the FPP, which is insensitive to longitudinal polarization. The unique spin transport matrix for each proton trajectory was calculated as a function of its angles, momentum, and vertex coordinates from a detailed model of the HMS using the differential-algebra based COSY software [18]. The polarization components
FIG. 2. (Color online) Helicity difference distribution $f_+ - f_-$ for $Q^2 = 8.5$ GeV$^2$, $0.5^\circ \leq \vartheta \leq 14.0^\circ$. The data are fitted with $f_+ - f_- = a \cos \varphi + b \sin \varphi$ (solid curve), resulting in $a = (0.16 \pm 1.19) \times 10^{-3}$ and $b = (-3.99 \pm 0.12) \times 10^{-2}$ ($\chi^2$/n.d.f. = 0.67).

at the target were then extracted by maximizing the likelihood function defined as:

$$\mathcal{L}(P_t, P_l) = \prod_{i=1}^{N_{\text{event}}} \left[ 1 + h \epsilon_i A_y^{(i)} (S_{yt}^{(i)} P_t + S_{yl}^{(i)} P_l) \cos \varphi_i - h \epsilon_i A_y^{(i)} (S_{xt}^{(i)} P_t + S_{xl}^{(i)} P_l) \sin \varphi_i + \lambda_0^{(i)} \right]$$

where $h$ is the beam polarization, $S_{jk}^{(i)}$ are the spin transport matrix elements, $\epsilon_i = \pm 1$ is the beam helicity, and $\lambda_0$ is the false asymmetry.

The polarization of the residual inelastic background passing “elasticity” cuts was obtained from the rejected events using the same procedure, and used to correct the polarization of elastic events. The acceptance-averaged fractional inelastic backgrounds for $Q^2 = 5.2$, 6.7, and 8.5 GeV$^2$ were $N_{\text{inel}}/(N_{\text{inel}} + N_{\text{el}}) = (1.12 \pm 0.16)\%$, (0.77 $\pm 0.12)\%$, and (5.9 $\pm 0.9)\%$, respectively. The resulting absolute corrections to $R$ were $\Delta R = (8.4 \pm 1.5) \times 10^{-3}$, $(7.5 \pm 1.3) \times 10^{-3}$, and $(6.0 \pm 1.3) \times 10^{-2}$.

Since the beam polarization and the $p^+\text{CH}_2$ analyzing power cancel in the ratio, there are few significant sources of systematic uncertainty in the results of this experiment. The most important contribution comes from the precession calculation. An excellent approximation to the full COSY calculation used for the final analysis is obtained from the product of simple rotations relative to the proton trajectory by angles $\chi_\phi$ in the non-dispersive plane and $\chi_\theta$ in the dispersive plane. $\chi_\phi = \gamma \kappa_p \phi_{\text{bend}}$ and $\chi_\theta = \gamma \kappa_p \theta_{\text{bend}}$ are proportional to the trajectory bend angles $\phi_{\text{bend}}$ and $\theta_{\text{bend}}$ by a factor equal to the product of the proton’s boost factor $\gamma$ and anomalous magnetic moment $\kappa_p$. The relevant matrix elements in this approximation
are \( S_{yt} = \cos \chi \phi \), \( S_{yt} = \sin \chi \phi \), \( S_{xt} = \sin \chi \phi \sin \chi \theta \), and \( S_{xt} = -\cos \chi \phi \sin \chi \theta \). These simple matrix elements were used to study the effects of systematic errors in the reconstructed kinematics.

The error \( \Delta \phi_{\text{bend}} \) due to unknown misalignments of the quadrupoles relative to the HMS optical axis leads to an error \( \gamma \kappa_p \Delta \phi_{\text{bend}} \) on \( P_t/P_l \). This uncertainty was minimized through a dedicated study of the non-dispersive optics of the HMS following the method of [19], setting a conservative upper limit of \(|\Delta \phi| \leq 0.5 \text{ mrad}\), which is the single largest contribution to the systematic uncertainty in \( R \). The contribution of uncertainties in the absolute central momentum of the HMS and the dispersive bend angle \( \theta_{\text{bend}} \) is small by comparison. The extracted form factor ratio showed no statistically significant dependence on any of the variables involved in the precession calculation, providing a strong test of its quality.

Uncertainties in \( E_e \), \( E'_e \) and \( \theta_e \) make an even smaller contribution. Uncertainties in the scattering angles in the FPP were minimized by a software alignment procedure using “straight-through” data obtained with the CH\(_2\) doors open. False asymmetry coefficients obtained from Fourier analysis of the helicity sum distribution \( f_+ + f_- \) were used to correct the small, second-order contributions to the extracted polarization components. The resulting correction to \( R \) was small (\(|\Delta R| \leq 0.007\)) and negative for each \( Q^2 \). The correction procedure was verified using a Monte Carlo simulation.

| \( E_e, \text{GeV} \) | \( \theta_e, ^\circ \) | \( \langle Q^2 \rangle \pm \Delta Q^2, \text{GeV}^2 \) | \( R \pm \Delta R_{\text{stat.}} \pm \Delta R_{\text{syst.}} \) |
|------------------|------------------|------------------|------------------|
| 4.05 | 60.3 | 5.17 ± 0.123 | 0.443 ± 0.066 ± 0.018 |
| 5.71 | 44.2 | 6.70 ± 0.190 | 0.327 ± 0.105 ± 0.022 |
| 5.71 | 69.0 | 8.49 ± 0.167 | 0.138 ± 0.179 ± 0.043 |

**TABLE I.** Results for \( R = \mu_p G_E^0/G_M^0 \), with statistical and systematic uncertainties. \( E_e \) is the beam energy, \( \theta_e \) is the central electron scattering angle, \( \langle Q^2 \rangle \) is the acceptance-averaged \( Q^2 \), and \( \Delta Q^2 \) is the r.m.s. \( Q^2 \) acceptance.

The results of the experiment are presented in table II. Standard radiative corrections to \( P_t/P_l \) were calculated using the code MASCARAD [13], found to be no greater than 0.13% (relative) for any of the three \( Q^2 \) values, and were not applied. Figure 3 presents the new results with recent Rosenbluth and polarization data and selected theoretical predictions.
FIG. 3. (Color online) Upper panel: The proton form factor ratio $\mu_p G_E^p/G_M^p$ from this experiment (filled black triangles), with statistical error bars and systematic error band below the data. Previous experiments are [1] (Jones, Punjabi, Gayou), [3] (Andivahis), [4] (Christy), and [5] (Qat-tan). Theory curves are [20] (Lomon), [21] (de Melo), [22] (Gross), [23] (Cloët), [24] (Guidal), and [25] (Belitsky). Lower panel: The same data and theory curves as the upper panel, expressed as $Q^2 F_2^p/F_1^p$.

Theoretical descriptions of nucleon form factors emphasize the importance of both baryo-meson and quark-gluon dynamics, with the former (latter) generally presumed to dominate in the low (high) energy limit. Recent Vector Meson Dominance (VMD) model fits by Lomon [20] include $\rho'(1450)$ and $\omega'(1420)$ mesons in addition to the usual $\rho$, $\omega$, and $\phi$, and a “direct coupling” term enforcing pQCD-like behavior as $Q^2 \to \infty$. de Melo et al. [21] considered the non-valence components of the nucleon state in a light-front framework, using
Ansätze for the nucleon Bethe-Salpeter amplitude and a microscopic version of the VMD model. Gross and Agbakpe [22] modeled the nucleon as a bound state of three dressed valence constituent quarks in a covariant spectator theory. Cloët et al. [23] calculated a dressed-quark core contribution to the nucleon form factors in an approach based on Dyson-Schwinger equations (DSE) in QCD. The disagreement between this calculation and the data at lower $Q^2$ is attributed to the omission of meson cloud effects.

The Dirac and Pauli form factors are related to the vector ($H$) and tensor ($E$) GPDs through sum rules [7]. Guidal et al. [24] fit a model of the valence quark GPDs based on Regge phenomenology to form factor data. In this model, the ratio $F_2^p/F_1^p$ constrains the $x \to 1$ behavior of $E$, where $x$ is the light-cone parton momentum fraction. When combined with the forward limit of $H$ determined by parton distribution functions, the new information on $E$ obtained from precise form factor data allowed an evaluation of Ji’s sum rule [7] for the total angular momentum carried by quarks in the nucleon.

The data do not yet satisfy the leading-twist, leading order pQCD “dimensional scaling” relation $F_2^p \propto F_1^p/Q^2$ [6]. The modified scaling $Q^2F_2^p/F_1^p \propto \ln^2(Q^2/\Lambda^2)$ obtained by considering the subleading twist components of the light-cone nucleon wavefunction [25], with $\Lambda = 300$ MeV as shown in figure 3, describes the polarization data rather well. This “precocious scaling” of $F_2^p/F_1^p$ is a necessary, but not sufficient condition for the validity of a pQCD description of nucleon form factors. Despite progress in calculations based on light cone QCD sum rules [26], pQCD form factor predictions have not yet reached the level of accuracy of phenomenological models such as [20–22, 24] when applied to all four form factors ($F_1^{p,n}$), underscoring both the difficulty of predicting observables of hard exclusive reactions directly from QCD, and the strong guidance to theory provided by high quality data such as the results reported in this letter.

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