The proton elastic form factor ratio $\mu_p G_E^p/G_M^p$ at low momentum transfer

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High-precision measurements of the proton elastic form factor ratio, $\mu_p G_E^p/G_M^p$, have been made at four-momentum transfer, $Q^2$, values between 0.2 and 0.5 GeV$^2$. The new data, while consistent with previous results, clearly show a ratio less than unity and significant differences from the central values of several recent phenomenological fits. By combining the new form-factor ratio data with an existing cross-section measurement, one finds that in this $Q^2$ range the deviation from unity is primarily due to $G_E^p$ being smaller than expected.

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Elastic scattering of electrons from protons reveals information about the distribution of charge and magnetism.
in the nucleon via the electromagnetic form factors. For decades, these form factors were determined by making Rosenbluth separations of cross-section results, as done for example in the reanalysis by Arrington. Recently, however, high-quality polarized electron beams have allowed polarization techniques to be used. The new techniques revealed that the electric to magnetic proton form-factor ratio, which was long thought to be nearly unity for all four-momentum transfers, $Q^2$, becomes significantly less than unity at $Q^2 > 1$ GeV$^2$. This observation has led to a renewed experimental focus on the proton electromagnetic form factors and the extraction of the Zemach radius.

A recent suggestion from a modern form-factor fit that there is structure in each of the four nucleon electromagnetic form factors for even $Q^2 < 1$ GeV$^2$ is intriguing and has been discussed in recent review articles. The interest stems from the fact that changes of just a few percent in the nucleon form factors at low $Q^2$ have direct implications on our understanding of nucleon structure. These include, but are not limited to, the weak form factors of the nucleon, generalized parton distributions accessed in DVCS, generalized polarizabilities accessed in VCS near threshold, and the extraction of the Zemach radius.

The highest precision data set of the ratio $\mu_p G_E^p / G_M^p$ at low $Q^2$, prior to the results reported herein, is from Bates BLAST. This set has two out of eight points 2σ (statistical) below unity with the average of the eight points equal to 0.99 ± 0.01. However, when systematic uncertainties are included, no point is significantly lower than 1σ from unity and thus it was concluded that the data were consistent with unity.

In this work we present new, high precision measurements of $\mu_p G_E^p / G_M^p$ at $Q^2$ between 0.2 and 0.5 GeV$^2$ via the polarization transfer reaction $^1\text{H}(e', e'p)$. In the Born approximation the ratio of the transferred transverse to longitudinal polarization relates to the electromagnetic form factors by the equation:

$$R \equiv \mu_p \frac{G_E^p}{G_M^p} = -\mu_p \frac{E_e + E'_e}{2M} \tan \left( \frac{\theta_e}{2} \right) \frac{P_T}{P_L},$$

(1)

where $\mu_p$ is the proton magnetic moment, $M$ is the mass of the proton, $E_e$ ($E'_e$) is the incident (scattered) electron energy, $\theta_e$ is the electron scattering angle and $P_T$ ($P_L$) is the recoil proton polarization transverse (longitudinal) to the proton momentum. In this approximation the third or normal polarization component is zero.

The experiment was performed in Hall A of the Thomas Jefferson National Accelerator Facility. The polarized electrons, $e'$, were produced from a strained-superlattice GaAs crystal from the photoelectron gun and were accelerated to either 362 or 687 MeV. The beam helicity state was flipped pseudo-randomly at 30 Hz; beam charge asymmetries between the two helicity states were negligible. Due to multi-hall running the degree of longitudinal polarization in Hall A was limited to 40% rather than the full 80%. Note from Eq. 1 that $R$ is independent of the beam polarization, though the uncertainties do increase as a result of the lower beam polarization.

The polarized beam was incident on a 15 cm long, liquid hydrogen target. The kinematics of the measurements are given in Table 1. In all cases, the elastically scattered protons were detected in the left High Resolution Spectrometer, HRS, which contains a Focal Plane Polarimeter, FPP. Six of the eight measurements were done as single-arm proton measurements, since obstructions in the Hall prevented detecting electrons at angles larger than 60°. In the two measurements where it was possible, the coincident scattered electrons were detected in the right HRS. Details of the standard Hall A equipment can be found in [26].

Table 1: Kinematics and FPP parameters for the measured data points. The central spin precession angle is $\chi$. $\theta^p_{lab}$ and $T_p$ are the proton lab angle and proton kinetic energy, respectively. S(C) denotes a single-arm (coincidence) measurement. The analyzer material was carbon with a density $\approx 1.7$ g/cm$^3$.

| $Q^2$ (GeV$^2$) | $E_e$ (GeV) | $\theta^p_{lab}$ (deg) | $T_p$ (GeV) | Analyzer Thickness (inches) | $\chi$ (deg) | S/C |
|----------------|-------------|------------------------|-------------|-----------------------------|--------------|-----|
| 0.225          | 0.362       | 28.3                   | 0.120       | 0.75                        | 91.0         | S   |
| 0.244          | 0.362       | 23.9                   | 0.130       | 0.75                        | 91.9         | S   |
| 0.263          | 0.362       | 18.8                   | 0.140       | 0.75                        | 92.7         | S   |
| 0.277          | 0.362       | 14.1                   | 0.148       | 0.75                        | 93.4         | S   |
| 0.319          | 0.687       | 47.0                   | 0.170       | 2.25                        | 95.3         | C   |
| 0.356          | 0.687       | 44.2                   | 0.190       | 3.75                        | 97.0         | C   |
| 0.413          | 0.687       | 40.0                   | 0.220       | 3.75                        | 99.6         | S   |
| 0.488          | 0.687       | 34.4                   | 0.260       | 3.75                        | 103.0        | S   |

For the singles data, it was necessary to apply cuts on the target interaction position, and to subtract residual end-cap events using spectra taken on an aluminum dummy target. The two coincidence points were essentially background free, due to the large $ep$ cross section. Quasi-elastic events from the target end-caps, through the Al($e, e'p$) reaction, were suppressed by requiring hydrogen elastic kinematics. For the scattered protons, the polarization precesses as the particle is transported through the spectrometer. At the FPP, the transverse polarization components lead to azimuthal asymmetries in the re-scattering material due to spin-orbit interactions. The alignment of the FPP chambers was determined with straight-through trajectories, with the analyzing material removed. While misalignments and detector inefficiencies lead to false asymmetries, these false asymmetries largely cancel in forming the helicity differences which determine the polarization-transfer observables. The transferred polarization was determined by a maximum likelihood method using the difference of the azimuthal distributions corresponding to the two beam helicity states. The spin transport in the spectrometer was taken into account us-
ing a magnetic model calculation. Previous Hall A measures-
ments of the form-factor ratio used the same proce-
dures \[6, 7, 9, 11, 27, 28\].

The form-factor ratio is determined from the ratio of po-
larization transfer components, and thus from the phase
shift of the azimuthal scattering distribution in the FPP an-
alyzer. The analyzing power, efficiency, and beam polar-
ization cancel out in the calculation of the form-factor ra-
tio – although they affect the size of the uncertainty; thus,
the main issue for systematic uncertainties is spin transport
in the spectrometer. The spin transport systematic uncer-
tainties are determined by studying how the form factor
ratio changes when parameters such as reconstructed an-
gles and the spectrometer bend angle are changed by their
uncertainties. Detailed optical studies were performed to
constrain the spin transport for the first Hall A \(G_E^P\) ex-
periment \[6\], which had the FPP mounted in HRS-right.
The FPP was moved to HRS-left for the second \(G_E^P\) ex-
periment \[9\] and has remained there for subsequent exper-
iments, but no similarly detailed optical studies have been
performed. As the spectrometers are nearly identical, it is
expected that the limiting systematic uncertainties in this
measurement are similar, though since we lack the optical
studies for HRS-left, our estimated systematic uncertain-
ties are twice as large

To control the systematics in this experiment, each polar-
ization point was measured at three different spectrometer
momentum settings, spaced 2 – 3% apart. In all cases, the
polarization values extracted were consistent for the three
settings. The uncertainties resulting from the subtraction
of residual Al end-cap events were negligible compared
with the other systematic uncertainties. The kinematics of
the reaction are well determined by the recoil proton, thus
there is no discernible improvement in the uncertainties
when performing a coincidence measurement. The benefit
of the coincidence trigger is the suppression of background
events, which for a fixed data-acquisition rate allowed for
higher statistics within a shorter time.

The experimental results are summarized in Table II. The
average FPP analyzing power \((A_E)\) and efficiency \(\varepsilon_{FPP}\)
are consistent with parameterizations of earlier FPP
results \[29\]. The Hall A FPP design allows a much broader
angular acceptance than many previous devices, usually
limited to about 20\(^\circ\), which leads to a slightly larger ef-
ciciency. Also, at the lowest energies, the analyzing power
increases at angles beyond 20\(^\circ\), leading to a somewhat
larger average analyzing power. The analyzing power
quoted is the r.m.s. result, so that the FPP figure of merit,
FOM, is given by \(\varepsilon_{FPP}(A_E)^2\).

![FIG. 1: (Color online) The proton form factor ratio as a function
of four-momentum transfer \(Q^2\) shown with world data with to-
tal uncertainties below 3% \[6, 13\]. The dotted and dash-dotted
lines are fits \[2, 14, 30, 31\], while the dashed and solid lines
are from a vector-meson dominance calculation \[32\], light-front
cloudy-bag model calculation \[33\], a light-front quark model
calculation \[34\], and a point-form chiral constituent quark model
calculation \[35\].](image)

The new data, along with other high precision results, are
shown in Fig. 1 with the four data points taken at 362 MeV
beam energy having been combined into a single point for
plotting. Included in the figure are a representative sample
of the numerous modern calculations and fits that are avail-
able. The high statistical precision points at \(Q^2 = 0.356\)
and 0.413 GeV\(^2\) clearly indicate that \(R < 1\). While the
BLAST data alone were consistent with unity \[13\], usually
at the upper end of the uncertainty, the BLAST data are
also consistent with the new measurements, and the com-
bination of the two data sets is clearly not consistent with
unity. The point at 0.356 GeV\(^2\) is 5\(\sigma\) (stat. + syst.) be-
low unity and the point at 0.413 GeV\(^2\) is 3.4\(\sigma\) below unity;
previous data were within \(\sim 2\sigma\) (stat.) of unity.

| \(Q^2 (\text{GeV}^2)\) | \((A_E)\) | \(\varepsilon_{FPP}\) | FOM | \(R \pm \text{stat.} \pm \text{sys.}\) |
|------------------|--------|----------|-----|----------------------------------|
| 0.225            | 0.16   | 1.17     | 0.03| 0.9570 \pm 0.0857 \pm 0.0036       |
| 0.244            | 0.22   | 1.03     | 0.05| 0.9549 \pm 0.0500 \pm 0.0037       |
| 0.263            | 0.24   | 1.04     | 0.06| 1.0173 \pm 0.0495 \pm 0.0035       |
| 0.277            | 0.30   | 1.00     | 0.09| 1.0060 \pm 0.0504 \pm 0.0030       |
| 0.319            | 0.34   | 6.05     | 0.70| 0.9691 \pm 0.0143 \pm 0.0058       |
| 0.356            | 0.36   | 6.94     | 0.90| 0.9441 \pm 0.0099 \pm 0.0050       |
| 0.413            | 0.46   | 4.73     | 1.00| 0.9491 \pm 0.0138 \pm 0.0053       |
| 0.488            | 0.46   | 4.73     | 1.00| 0.9861 \pm 0.0189 \pm 0.0094       |
Although a smooth fall-off of $\mu_p G_E^p/G_M^p$ with $Q^2$ is not ruled out, the new data hint at a local minimum in the form-factor ratio at about $0.35 - 0.4$ GeV$^2$. Assuming uncorrelated uncertainties, in the range $Q^2 = 0.3 - 0.45$ GeV$^2$, we find the world data including the current work average to $0.960 \pm 0.005 \pm 0.005$. This is $3\sigma$ lower than the neighboring $Q^2$ range $0.45 - 0.55$ GeV$^2$, where $R = 0.987 \pm 0.005 \pm 0.006$. In this latter range, the form-factor ratio is only $1.6\sigma$ below unity. Calculations which tend to agree with the new ratio results, such as the light-front cloudy bag model calculation by G.A. Miller [33], however, show a monotonic decrease of the form-factor ratio. Additional calculations may be found in [11].

By combining the present measurement with previous cross-section results, it is possible to extract the individual form factors. This was done by combining the highest precision existing cross-section data in the vicinity of the measured ratio [36] at $Q^2 = 0.389$ GeV$^2$ with the average of our form-factor ratios from $Q^2 = 0.36$ GeV$^2$ and 0.41 GeV$^2$. Figure 2, which uses the same codes as Fig. 1, shows that the form-factor extraction is essentially independent of $\varepsilon$, the virtual photon polarization, over the extracted range. Interestingly, the deviation from unity in the ratio seems to be dominated by the electric form factor. Our data suggest a lower value of the ratio and electric form factor than many modern fits. No fit or calculation adequately represents the ratio correctly. Some calculations, which were not shown, such as the light-front constituent quark model by the Cardarelli et al. [37] are in good agreement with the form-factor ratio data in this $Q^2$ range, but the individual form factors are significantly overestimated by present quark potential models [38].

The comparison of fits with the new data suggests that a critical reexamination is needed of experiments (e.g. [20, 30, 39]) that require a knowledge of low $Q^2$ form factors to a precision of better than $\sim$3%. For example, for the HAPPEX measurement of the weak form factors [40] the new data adjust the measured asymmetry by about 0.5 ppm, corresponding to a smaller effect from strange quarks, on data with a statistical uncertainty of $\approx 1$ ppm. More significantly, this new result would shift the expected HAPPEX-III result [41] by one standard deviation.

In summary, we made polarization-transfer measurements to precisely determine the proton form-factor ratio at low $Q^2$. We showed that the form-factor ratio differs from unity at low $Q^2$ and that the deviation is most likely dominated by the electric form factor. Our data suggest a lower value of the ratio and electric form factor than many modern fits. No fit or calculation adequately represents the ratio and extracted form factor data over the entire range.

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