Results from the Hall A GMp Experiment (E12-07-108)

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Hampton University / Jefferson Lab

on behalf of the GMp collaboration

2019 Hall A/C Summer Workshop
June 28, 2019
Proton magnetic form factor

- Form factors encode electric and magnetic structure of the nucleon

- Form factors characterize the spatial distribution of the electric charge and the magnetization current in the nucleon

\[
|\text{Form Factor}|^2 = \frac{\sigma\left(\text{Structured object}\right)}{\sigma\left(\text{Point like object}\right)}
\]

- In one photon exchange approximation the cross section in ep scattering when written in terms of \( G_E^p \) and \( G_M^p \) takes the following form:

\[
\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \frac{\epsilon \left(G_E^p\right)^2 + \tau \left(G_M^p\right)^2}{\epsilon \left(1 + \tau\right)}, \quad \sigma_{\text{Mott}} = \frac{\alpha^2 \cos^2 \theta}{4 E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E}
\]

Where,

\[
\tau = \frac{Q^2}{4 M^2}, \quad \epsilon = \left[1 + 2 \left(1 + \tau\right) \tan^2 \left(\frac{\theta}{2}\right)\right]^{-1}
\]

\[
J_{\text{proton}} = e\bar{N}(p') \left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(Q^2)\right] N(p)
\]

\[
G_E = F_1 - \tau F_2 \quad G_M = F_1 + F_2
\]
Methods of measurements

- **Rosenbluth separation method:**
  - This method uses different beam energies and angle at fixed $Q^2$.
  $$\sigma_R = \frac{d\sigma}{d\Omega} \frac{\varepsilon (1+\tau)}{\tau \sigma_{\text{Mott}}} = \frac{\varepsilon}{\tau} \left( G^p_E \right)^2 + \left( G^p_M \right)^2,$$

  The slope of $\sigma_R(\varepsilon)$ is directly related to $G^p_E$ and the intercept to $G^p_M$.

- **Recoil polarization technique:**

  Polarized electron transfers longitudinal polarization to $G^p_E$, but transverse polarization to $G^p_M$.

  $$\frac{G_E}{G_M} = -\frac{P_t}{P_l} \frac{E_e + E_e'}{2M} \tan\left( \frac{\theta_e}{2} \right)$$

  Polarization transfer cannot determine the values of $G_E$ and $G_M$ but can determine the form factor ratio.
→ Discrepancy in $G_E/G_M$ P-T and Rosenbluth ($\varepsilon$) separations

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Leading explanation is hard 2-$\gamma$ exchange, not included in standard radiative corrections of Mo-Tsai, etc.


Resolving the Rosenbluth vs P-T discrepancy

→ Expected to be relatively small for P-T method
2-γ contributions from e+P / e-P ratios

Hard 2-γ contribution comes in with different signs for e+P and e-P =>

\[ \frac{\sigma^+}{\sigma^-} = R_{2\gamma} \sim 1 - 2\delta_{2\gamma} \]

Conclusions from combined analysis of A. Afanasev, P. G. Blunden, D. Hasell, and B. A. Raue:

→ CLAS and VEPP-3 and OLYMPUS data exclude no TPE hypothesis at >95% confidence level

→ Data of insufficient precision to distinguish calculations of 2-γ contributions

→ Renormalization of OLYMPUS results required at twice the estimated uncertainty

New data from

- VEPP-3
- CLAS
- OLYMPUS

OLYMPUS
PRL 118, 092501 (2017)
Non-linearities in existing Rosenbluth data

→ Existing data indicate *no significant* non-linearities vs $\varepsilon$

Fit of elastic data to quadratic form

$$\sigma_r = P_0 + P_1 (\varepsilon - 0.5) + P_2 (\varepsilon - 0.5)^2$$

$$<P_2> = 0.019 \pm 0.027$$

Super-Rosenbluth data also consistent with linear $\varepsilon$ dependence of $\sigma_r$
Precision GMp is part of the 12 GeV Form Factor Program

→ Precision $G_M$ required to study approach of QCD scaling in Dirac $F_1$

$$F_1 = \frac{G_F + Q^2/4M_N^2 \times G_M}{1 + Q^2/4M_N^2}$$

→ $F_2$ provides constraint on $E(x,t)$ GPD at high-$x$, high-$t$ via sum rules

→ Precision $G_M$ up to $Q^2 \sim 12$ GeV$^2$

complementary to 12 GeV polarization Transfer measurements of $G_E/G_M$

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GMp and other High $Q^2$ data

GMp12 data at much smaller $\epsilon$ than Sill data

Less sensitivity to $G_E$ in extracting $G_M$

Lever arm in $\epsilon$ provides sensitivity to:
- $2\gamma$ from global fit utilizing $G_E / G_M$ from polarization transfer

$$\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \frac{\epsilon \left( G_E^p \right)^2 + \tau \left( G_M^p \right)^2}{\epsilon (1 + \tau)}.$$
E12-07-108 Experiment Overview

- Precision measurement of the elastic $ep$ cross-section over the wide range of the $Q^2$ and extraction of proton magnetic form factor

➢ To improve the precision of cross section at high $Q^2$ by a factor of 3

➢ To provide insight into scaling behavior of the form factors at high $Q^2$

GMp Uncertainties:

**Statistical:** Significant improvement over existing data for $Q^2 > 6$

**Systematic Goals:**
- Point to point: 0.8-1.1%
- Normalization: 1.3%

Need a good control on:
- Beam charge
- Beam position
- Scattering angle
- target density, ...

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Experimental setup

Jefferson Lab at Newport News Virginia

CEBAF: Continuous Electron Beam Accelerator Facility

Experimental Hall A

High resolution spectrometers
Jefferson Lab Hall A

HRS Parameters:

Acceptance: $-4.5\% < \Delta p/p < 4.5\%$, 6 msr

Resolution: $\frac{\delta p}{p} \leq 2 \times 10^{-4}$
- $\Delta x'_\text{tar} = 0.5$ mrad (Horizontal)
- $\Delta y'_\text{tar} = 1.0$ mrad (Vertical)
Data collected during GMp

### Spring 2015:

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (GeV)</th>
<th>HRS</th>
<th>$P_0$ (GeV/c)</th>
<th>$\Theta_{\text{HRS}}$ (deg)</th>
<th>$Q^2$ (GeV/c)$^2$</th>
<th>Events (k)</th>
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</thead>
<tbody>
<tr>
<td>2.06</td>
<td>R</td>
<td>1.15</td>
<td>48.7</td>
<td>1.65</td>
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<td>25.0 *</td>
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### Spring 2016:

* Surveyed angles

<table>
<thead>
<tr>
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<th>HRS</th>
<th>$P_0$ (GeV/c)</th>
<th>$\Theta_{\text{HRS}}$ (deg)</th>
<th>$Q^2$ (GeV/c)$^2$</th>
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<tbody>
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<td>8.84</td>
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<td>8.84</td>
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<td>2.50</td>
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<td>11.02</td>
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<td>2.20</td>
<td>48.8*</td>
<td>16.5</td>
<td>0.7</td>
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</table>

### Fall 2016:

*Most complete systematic studies during this period

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (GeV)</th>
<th>HRS</th>
<th>$P_0$ (GeV/c)</th>
<th>$\Theta_{\text{HRS}}$ (deg)</th>
<th>$Q^2$ (GeV/c)$^2$</th>
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<td>R</td>
<td>2.17</td>
<td>48.8*</td>
<td>15.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Extraction of Elastic $ep$ Cross Section

\[
\frac{d\sigma^{\text{data}}}{d\Omega} (\theta) = \int dE' \frac{N^{\text{data}}(E', \theta) - N_{BG}(E', \theta)}{L^{\text{data}}.\epsilon.LT} \frac{RC^{\text{data}}}{A^{\text{data}}(E', \theta)}
\]

\[
\frac{d\sigma^{\text{mod}}}{d\Omega} (\theta) = \int dE' \frac{N^{MC}(E', \theta)}{L^{MC}} \cdot \frac{RC^{MC}}{A^{MC}(E', \theta)}
\]

\[
\frac{d\sigma^{\text{data}}}{d\Omega} (\theta) / \frac{d\sigma^{\text{mod}}}{d\Omega} (\theta) = \frac{\int^{E_{\text{max}}} (N^{\text{data}}(E', \theta) - N_{BG}(E', \theta)) dE'}{\int^{E_{\text{max}}} N^{MC} dE'} \cdot \frac{A^{MC}(E', \theta)}{A^{\text{data}}(E', \theta)} \cdot \frac{RC^{\text{data}}}{RC^{MC}}
\]

Assuming acceptance and radiative contributions are correctly modeled:

\[
\frac{d\sigma^{\text{data}}}{d\Omega} (\theta) = \frac{d\sigma^{\text{mod}}}{d\Omega} (\theta) \cdot \frac{Y^{\text{data}}}{Y^{MC}}
\]

→ Results were cross checked with acceptance correction method (eq 1) using Rad Cor based on code utilized for later SLAC experiments.


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Detector efficiencies

\[ E_{\text{beam}} = 2.222, \theta = 42 \]

Detector efficiencies

- \( \epsilon_{\text{cal}} > 99.8\% \)
- \( \epsilon_{\text{cer}} > 99.9\% \)
- \( \epsilon_{\text{cut}} > 99.9\% \)

\[ \frac{\delta \epsilon}{\epsilon} < 0.1\% \]
VDC Track Reconstruction Efficiency

- Standard Tracking for HRS VDCs utilizes single cluster only in each chamber
- GMp utilized additional Straw Chamber to perform precise checks on efficiency determination

A “coarse” track was formed using scintillator hit and straw chamber. This method enables us to estimate the track intercept at the focal plane without using VDC hits.

Barak Schmookler (MIT)
Bashar Aljawrneh (NC A&T)

### Elastic events were reconstructed with:

1. single cluster in both VDCs
2. single cluster in 1 VDC + SC

<table>
<thead>
<tr>
<th>Kinematic</th>
<th>K3-4</th>
<th>K3-6</th>
<th>K3-7</th>
<th>K3-8</th>
<th>K4-9</th>
<th>K4-10</th>
<th>K4-11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Yield ratio</td>
<td>1.0016</td>
<td>0.9994</td>
<td>0.9993</td>
<td>0.9985</td>
<td>1.0007</td>
<td>1.0021</td>
<td>0.9997</td>
</tr>
</tbody>
</table>

Corrected yields agree to better than 0.2%
Significant Effort to Improve Optics Calibration

**Angle and vertex calibration**: used deep inelastic electrons from multi-foil carbon target

A 9-foil carbon target covers a total length of 20 cm along the beam direction

A 1-inch-thick tungsten sieve slit with high density holes at the spectrometer entrance selects scattered electrons in specific directions

**Algorithm**: Minimization of $\chi^2$ by varying the optics coefficients

$$\chi^2(y_{tg}) = \sum_{\text{events}} (Y_{ijkl} x_f^i \theta_f^j y_f^k \phi_{fp} - y_{tg}^{\text{survey}})^2$$

**Momentum calibration**: used elastic electrons from liquid hydrogen target
Example Data to Monte Carlo Comparison: LHRS

- Excellent comparison after subtraction of target cell endcaps via dummy (~3%)
- Small offsets in W consistent with estimated kinematic uncertainties

Data to MC ratio: 1.0102
$P_0$: 2.6720 GeV/c
Beam energy = 6.427 GeV
Scattering angle = 37.01 deg
$Q^2 = 6.99$ (GeV/c)$^2$
Cross section = 2.89e-06 ub/sr
## Error Budget (LHRS Fall 2016)

<table>
<thead>
<tr>
<th>Source</th>
<th>$d\sigma/\sigma$ (%) (pt-pt)</th>
<th>$d\sigma/\sigma$ (%) (Norm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam charge ($\Delta I = 0.06 \mu A$)</td>
<td>0.6(at 10 $\mu A$) - 0.1(at 65 $\mu A$)</td>
<td>0.1</td>
</tr>
<tr>
<td>Scattering angle ($\Delta \theta = 0.2$ mrad)</td>
<td>0.1 - 0.4</td>
<td>0.1 - 0.4</td>
</tr>
<tr>
<td>Beam energy ($\Delta E = 5 \times 10^{-4}$)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Boiling</td>
<td>&lt;0.35 (at 10 $\mu A$) - 0 (at 60 $\mu A$)</td>
<td>0.35 (at 60 $\mu A$)</td>
</tr>
<tr>
<td>Optics</td>
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<td>0.3</td>
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<tr>
<td>Track Reco</td>
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<td>PID</td>
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<tr>
<td>Trigger</td>
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<td>Target Length</td>
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<tr>
<td>Spectrometer acceptance</td>
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<td>0.8</td>
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<tr>
<td>Radiative correction</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Background subtraction</td>
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<td>0.2</td>
</tr>
<tr>
<td>Cross section model</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.2 - 1.3%</strong></td>
<td><strong>1.4 - 1.6%</strong></td>
</tr>
</tbody>
</table>
Cross section relative to 1-$\gamma$ cross section calculated with $G_E = G_M/\mu = G_{\text{dip}}$.

Significant improvement in precision for $Q^2 > 6$.

Systematic uncertainties on Fall 2016 LHRS data ~1.3% (pt-pt), 1.5% (norm)

RHRS (additional 2% from optics)
Sample GMp Global Rosenbluth separations

- Utilize all available data
- $\sigma_r$ centered to common $Q^2$ utilizing Cross section fit.

Relative normalization not yet applied
Impact of E12-07-108 data on $G_E/G_M$ at large $Q^2$

Lab Hall A GMp12 data significantly reduce uncertainties on $G_E/G_M$ at largest $Q^2$

=> further highlights discrepancy with P-T data up to $Q^2 > 9$

Full data set provides significantly more sensitivity than shown in select L/T separations
2-$\gamma$ form factors


\[
\sigma_r = G_M^2 + 2 G_M \Re(\delta \tilde{G}_M) + \frac{\epsilon}{\frac{\epsilon}{\tau} G_E^2 + 2 G_M \Re(\delta \tilde{G}_M) + \epsilon \left[ \frac{2}{\tau} G_E \Re(\delta \tilde{G}_E) + \frac{4 \tau^2}{M^2} \Re(\tilde{F}_3)(G_M + \frac{1}{\tau} G_E) \right]}
\]

Rosenbluth intercept

\[
\sigma_r \approx G_M^2 + 2 G_M \Re(\delta \tilde{G}_M) + \frac{\epsilon}{\frac{\epsilon}{\tau} G_E^2 + 2 G_M \Re(\delta \tilde{G}_M) + \epsilon \left[ \frac{r^2}{\mu^2} G_M^2 + \frac{4 \tau^2}{M^2} \Re(\tilde{F}_3)(G_M + \frac{1}{\tau} G_E) \right]}
\]

Assuming $2 G_E \Re(\tilde{G}_E)$ is negligible

\[
r = \frac{\mu G_E}{G_M}
\]

\[
\rightarrow r \text{ constrained by fit to P-T data}
\]

\[
\rightarrow \text{global fit to cross section data provides access to }
\]

\[
G_M^2(Q^2) \quad \Re(\delta \tilde{G}_M)(Q^2) \quad \text{And} \quad \Re(\tilde{F}_3)(Q^2)
\]

\[\epsilon \text{ average}\]
GMp data provides enhanced access to Gmp 2-γ Form Factors
Summary

- 12 GeV era GMp experiment in Jefferson Lab Hall A measured e-p elastic cross sections for 21 kinematics with
  \[ 1 < Q^2 < 16.5 \text{ GeV}^2 \]

- Final Cross sections for Fall2016 data to be published soon with uncertainties of
  - 1.2 - 2\% pt-pt
  - 1.5\% normalization

- Data:
  - important for JLab 12 GeV Form Factor and GPD program
  - provides precision normalization for upcoming 12 GeV experiments at JLab

- \( \epsilon \) coverage complementary to existing data and provides enhanced sensitivity to proton
  \( G_M \) and 2-\( \gamma \) Form Factors
  - full power of data through global fits.
GMp (E12-07-108) Analysis Team

- Spokesperson:
  - John Arrington
  - Eric Christy
  - Shalev Gilad
  - Vincent Sulkosky
  - Bogdan Wojtsekhowski

- Postdoc:
  - Kalyan Allada

- Ph.D students (all have defended):
  - Bashar Aljawrneh (NCA&T)
  - Thir Gautam (Hampton U.)
  - Longwu Ou (MIT)
  - Barak Schmookler (MIT)
  - Yang Wang (William & Mary)

Thanks to JLab accelerator team, Hall A target group, and all shift takers for their tremendous effort to make the GMp run successful!

Thanks!

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Measurement of Elastic Cross Section

- Cross section:

\[
\frac{d\sigma}{d\Omega}(\theta) = \int dE' \frac{N_{\text{det}}(E', \theta) - N_{\text{BG}}(E', \theta)}{\mathcal{L} \cdot \epsilon_{\text{eff}} \cdot \text{LT}} \cdot A(E', \theta) \cdot \text{RC}
\]

- Reduced cross section:

\[
\sigma_{\text{red}} = \frac{d\sigma}{d\Omega} \cdot \frac{\epsilon(1 + \tau)}{\sigma_{\text{Mott}}} = \frac{4E^2 \sin^4 \frac{\theta}{2}}{\alpha^2 \cos^2 \frac{\theta}{2} E'} \frac{E}{E'} \epsilon(1 + \tau) \frac{d\sigma}{d\Omega}
\]

- Parameters:
  - \(N_{\text{det}}\): number of scattered elastic electrons detected
  - \(N_{\text{BG}}\): events from background processes
  - \(\mathcal{L}\): Integrated luminosity
  - \(\epsilon\): Corrections for efficiencies
  - \(\text{LT}\): live time correction
  - \(A(E', \theta)\): spectrometer acceptance
  - \(\text{RC}\): radiative correction factor
  - \(E\): beam energy
  - \(\theta\): Scattering angle

A thorough understanding of all these parameters is crucial for a precision cross section measurement.