The Super Rosenbluth Experiment
(The E01-001 collaboration)

Jefferson Lab
April 16, 2004
Magnetic moments

Dirac

point particle: $\mu_B = \frac{q\hbar}{2mc}$

electron: $\mu_e = gs\mu_B = g(1/2)\mu_B; \quad g = 2$

Experiment

electron: $\mu = \frac{q\hbar}{2mc} \times 1.002; \quad (g = 2.004)$

proton $\mu = 2.793 \mu_N = \frac{q\hbar}{2m_p c} \times 2.793$

neutron $\mu = -1.913 \mu_N = \frac{q\hbar}{2m_n c} \times \infty$
Scattering from point (heavy) nucleus (Rutherford):

\[
\frac{d\sigma}{d\omega} = \frac{(Z_1 Z_2 e^2)^2}{16E^2 \sin^4 \frac{\theta}{2}} = \frac{4m^2 (Z_1 Z_2 e^2)^2}{q^4}
\]

where \( q = p_i - p_f = 2\sin \theta/2 \) (elastic scattering)

extended nucleus:

\[
\frac{d\sigma}{d\omega} = \left( \frac{d\sigma}{d\omega} \right)_{\text{point}} |F(q^2)|^2
\]

\( F = \) form factor

\[
= 1 - \frac{1}{6} q^2 <r^2> + \ldots
\]

Electron \((s = \frac{1}{2})\) scattering from point nucleus:

\[
\left( \frac{d\sigma}{d\sigma} \right)_{\text{Mott}} = \frac{4(Z e^2)^2 E^2}{q^4} \left( 1 - \beta^2 \sin^2 \frac{\theta}{2} \right)
\]

\[
\approx \frac{4Z^2 e^4 E^2}{q^4} \cos^2 \frac{\theta}{2}
\]
Rosenbluth separation

\[ \frac{d\sigma}{d\omega}(E,\theta) = \left( \frac{d\sigma}{d\omega} \right)_{\text{Mott}} \left( G_E^2 + \varepsilon^{-1} \left( \frac{1}{2m_p} \right)^2 Q^2 G_M^2 \right) \]

\[ = \left( \frac{d\sigma}{d\omega} \right)_{\text{Mott}} \frac{1}{\varepsilon} \left( \varepsilon G_E^2 + \left( \frac{1}{2m_p} \right)^2 Q^2 G_M^2 \right) \]

\[ \varepsilon = (1 + 2(1 + \tau) \tan^2 \frac{\theta}{2})^{-1}; \quad \tau = \frac{|q|^2}{Q^2} - 1 \]

\[ \varepsilon = \text{virtual polarization parameter} \]

\[ G_E \equiv G_E(Q^2) \rightarrow 1 \quad \text{as} \quad Q^2 \rightarrow 0 \]

\[ G_M \equiv G_m(Q^2) \rightarrow \mu_p \quad \text{as} \quad Q^2 \rightarrow 0 \]
$\epsilon = 4.702$

$\epsilon = 3.772$

$\epsilon = 2.842$

$\epsilon = 2.262$

$\epsilon = 1.912$
Rosenbluth extractions of $G_E$ and $G_M$

\[ \sigma_R = \frac{d\sigma}{d\Omega} \frac{\varepsilon(1+\tau)}{\sigma_{\text{Mott}}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2) \]

First Rosenbluth separations-1961
Bumiller, Croisiaux, Dally, and Hofstadter, Phys. Rev. 124, 144

Olson, Schopper, and Wilson, PRL 6, 286

Initial Rosenbluth measurement (up to $Q^2=1$ GeV$^2$) consistent with form factor scaling
$G_M(Q^2) \equiv \mu_\rho G_E(Q^2)$

For large $Q^2$ values, $\tau G_M^2$ dominates and $G_E^2$ becomes difficult to extract

---

Janssens et al., 1966
$Q^2=0.39$ GeV$^2$
$\mu_\rho G_E/G_M = 1.061 +/- 0.058$
Form factors (old Rosenbluth)

\[ \frac{1}{(1+Q^2/0.71)^2} \] "dipole"
Rosenbluth separation

\[
\frac{d\sigma}{d\omega}(E, \theta) = \left( \frac{d\sigma}{d\omega} \right)_{\text{Mott}} \left( G_E^2 + \varepsilon^{-1} \left( \frac{1}{2m_p} \right)^2 Q^2 G_M^2 \right)
\]

\[
= \left( \frac{d\sigma}{d\omega} \right)_{\text{Mott}} \frac{1}{\varepsilon} \left( \varepsilon G_E^2 + \left( \frac{1}{2m_p} \right)^2 Q^2 G_M^2 \right)
\]

\[
\varepsilon = (1 + 2(1 + \tau) \tan^2 \frac{\theta}{2})^{-1}; \quad \tau = \frac{|q|^2}{Q^2} - 1
\]

\(\varepsilon = \) virtual polarization parameter

\(G_E \equiv G_E(Q^2) \rightarrow 1 \quad \text{as} \quad Q^2 \rightarrow 0\)

\(G_M \equiv G_m(Q^2) \rightarrow \mu_p \quad \text{as} \quad Q^2 \rightarrow 0\)
When longitudinally polarized electrons scatter from unpolarized protons polarization is transferred to the recoil proton with:

$$P_t = \frac{2 \sqrt{\tau (1 + \tau)} G_E G_M \tan \frac{\theta}{2}}{G_E^2 + \frac{\tau}{\varepsilon} G_M^2}$$

and

$$P_l = \frac{(E_e + E_e) \sqrt{\tau (1 + \tau)} G_M^2 \tan^2 \frac{\theta}{2}}{m_p (G_E^2 + \frac{\tau}{\varepsilon} G_M^2)}$$

where $P_t$ = proton polarization in the plane of the reaction perpendicular to the proton momentum

$P_l$ = proton polarization parallel to the proton momentum

Jefferson Lab experiments E93-027 and E99-007 measured $P_e/P_1$ to determine:

$$\frac{G_E}{G_M} = \frac{P_t}{P_l} \frac{(E_e + E_e) \tan \left( \frac{\theta}{2} \right)}{2m_p}$$
Incoming $e^-$ 4600 MeV

$P_e = 70\%$
$I = 60 \mu A$

Distance from target of 17, 12.4 and 9 m

15 x 15 x 40 cm lead glass blocks, 9 columns by 17 rows
\[
\chi = \gamma_p \theta_B (\mu_p - 1)
\]

\[
P_{fpp} = P_t
\]

\[
P_{n}^{fpp} = P_l \sin \chi
\]
\[ \mu E/G_M \]

**Graph Title:**

**Axes:**
- **Y-axis:** \( \mu E/G_M \)
- **X-axis:** \( Q^2 \)

**Legend:**
- Litt SLAC 70
- Price CEA 71
- Bartel DESY 71
- Walker SLAC 94
- Andivhis SLAC 94
- Christy JLAB 03
- Green: polarization transfer

**Data Points:**
Each data point represents measurements from different experiments and collaborations, plotted against their respective \( Q^2 \) values.
E01-001: New Measurement of (GeV/G_{M}) for the Proton

R. E. Segel (Spokesperson), L. Jisonna, I. Qattan
Northwestern University, Evanston, IL

J. Arrington (Spokesperson), K. Hashid, R. J. Holt, E. C. Schulte, K. Wijesooriya, B. Zeidman
Argonne National Laboratory, Argonne, IL

K. Aniol, D. Margaziotis
California State University, Los Angeles, CA

O. Gayou, L. Pentchev, C. Perdrisat, V. Sulcany
College of William and Mary, Williamsburg, VA

J. Reinhold
Florida International University, Miami, FL

O. K. Baker, M. E. Christy, C. E. Keppel
Hampton University, Hampton, VA

S. Frullani
INFN-Gruppo Sanita' and Physics Laboratory, Istituto Superiore di Sanita', Rome, Italy

P. Moussiegt
ISN Grenoble

Jefferson Laboratory, Newport News, VA

K. McCormack
Kent State University, Kent, OH

D. Dutta, P. Monaghan
Massachusetts Institute of Technology, Cambridge, MA

V. Punjabi
Norfolk State University, Norfolk, VA

W. Hinton, H. Ibrahim
Old Dominion University, Norfolk, VA

R. Gilman, C. Ghabousser, G. J. Kambartaki, R. Ransome
Rutgers University, New Brunswick, NJ

A. Sarty
Saint Mary's University, Halifax, Nova Scotia, Canada

K. Sifer, P. Solvignon
Temple University, Philadelphia, PA

A. Casamass
Universite Blaise Pascal / LPC, Clermont-Ferrand, France

D. Gaskell, E. Kimney
University of Colorado, Boulder, CO

J. Calarco
University of New Hampshire, Durham, NH

E. J. Braw, G. Huber
University of Regina, Saskatchewan

N. L. Laman
University of Virginia, Charlottesville, VA
Major Players

Ralph Segel  Northwestern  spokesperson

John Arrington  Argonne  spokesperson

Issam Qattan  Northwestern  PhD student

Dave Gaskell  Jefferson Lab  period coordinator

Dave Meekins  Jefferson Lab  period coordinator

Xiaochao Zheng  Argonne  simulations
Reducing uncertainties

1. Better facility.

2. Concentrated on \((G_E/G_M)\)

3. Detected protons (not electrons).

4. Luminosity monitor.
\[
\frac{d\sigma}{d\omega}(E, \theta) = \left(\frac{d\sigma}{d\omega}\right)_{\text{Mott}} \frac{1}{\varepsilon} \left( \varepsilon G_E^2 + \left(\frac{1}{2m_p}\right)^2 Q^2 G_M^2 \right)
\]

\[
= \left(\frac{d\sigma}{d\omega}\right)_{\text{Mott}} \frac{G_M^2}{\mu_p^2 \varepsilon} \left( \varepsilon \left(\frac{\mu_p G_E}{G_M}\right)^2 + \left(\frac{\mu_p}{2m_p}\right)^2 Q^2 \right)
\]

\[
= \left(\frac{d\sigma}{d\omega}\right)_{\text{Mott}} \frac{G_M^2}{4m_p^2 \varepsilon} Q^2 \left( 1 + \left(\frac{2m_p}{\mu_p}\right)^2 \left(\frac{\mu_p G_E}{G_M}\right)^2 \frac{\varepsilon}{Q^2} \right)
\]

\[
= K(E, \theta) \left( 1 + \frac{0.452}{Q^2} \left(\frac{\mu_p G_E}{G_M}\right)^2 \varepsilon \right)
\]
$Q^2 = 2.64$

The graph shows the relationship between $\sigma_r$ and $\varepsilon$ for polarization transfer and scaling, with $Q^2 = 2.64$. The data points for polarization transfer are represented by blue circles, and the data points for scaling are represented by pink squares. The error bars indicate the uncertainty in the measurements.
Particle momentum ($Q^2 = 2.64$)

- Electrons
- Protons
sensitivity to angle ($Q^2 = 2.64$)

$d\sigma/d\theta$ (%/degree)

- **electrons**
- **protons**
sensitivity to incident energy ($Q^2 = 2.64$)

- % for electrons
- % for protons

Graph showing the relationship between $\varepsilon$ and % for electrons and protons.
(lab) cross section ($Q^2 = 2.64$)

$d\sigma/d\theta$ (fm$^2$/sr)

- Electrons
- Protons

$\epsilon$
2.262 2.64 coincidence
Radiative corrections \( (Q^2 = 2.64) \)
Radiative Corrections \( Q^2 = 2.64 \)

<table>
<thead>
<tr>
<th>( \varepsilon )</th>
<th>protons</th>
<th>electrons (to ( \pi ) threshold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.117 )</td>
<td>1.178</td>
<td>1.113</td>
</tr>
<tr>
<td>( 0.356 )</td>
<td>1.160</td>
<td>1.107</td>
</tr>
<tr>
<td>( 0.597 )</td>
<td>1.134</td>
<td>1.098</td>
</tr>
<tr>
<td>( 0.782 )</td>
<td>1.121</td>
<td>1.087</td>
</tr>
<tr>
<td>( 0.865 )</td>
<td>1.105</td>
<td>1.078</td>
</tr>
<tr>
<td>( \Delta \varepsilon = 1/\varepsilon = 0 )</td>
<td>-0.080</td>
<td>-0.040</td>
</tr>
</tbody>
</table>
$E_e = 2.262$ GeV  \( \theta_p = 12.526 \) deg  \( Q^2 = 3.20 \)
Spectrum Components

\( e^-p \rightarrow e^-p \) physics

reactions in end caps, primarily take data with empty (dummy) target
quasi-elastic scattering

\( \gamma p \rightarrow \pi^0 p \) simulate with bremsstrahlung spectrum,
s-7 cross section dependence -
some data available

\( \gamma p \rightarrow \gamma p \) (“Compton”) \(~2\% \text{ of } \pi^0 \text{ production – some data available}\)
$Q^2 = 3.20 \ \varepsilon = .131$

- LH2
- endcaps
- pi0 p (+compton)
- ep elastic scattering
- sum
$E_e = 4.702$ GeV  \( \theta_p = 34.139 \) deg  \( Q^2 = 3.20 \)
sensitivity of proton momentum to proton angle

MeV/degree vs. θ
$E=2842, \varphi=29.4859, P_0=2149.23, Q_2=2.64, \text{kin}=i$
Backgrounds: $Q^2=2.64$ GeV$^2$

**Forward angles:**
- Background large
- Resolution is good
- $\pi$ threshold is low

**Back angles:**
- Resolution is worse
- $\pi$ threshold close to elastic
- Background small
\[
\frac{d\sigma}{d\omega}(E, \theta) = \left(\frac{d\sigma}{d\omega}\right)_{\text{Mott}} \frac{1}{\varepsilon} \left( \varepsilon G_E^2 + \left(\frac{1}{2m_p}\right)^2 Q^2 G_M^2 \right)
\]

\[
= \left(\frac{d\sigma}{d\omega}\right)_{\text{Mott}} \frac{G_M^2}{\mu_p^2 \varepsilon} \left( \varepsilon \left(\frac{\mu_p G_E}{G_M}\right)^2 + \left(\frac{\mu_p}{2m_p}\right)^2 Q^2 \right)
\]

\[
= \left(\frac{d\sigma}{d\omega}\right)_{\text{Mott}} \frac{G_M^2}{4m_p^2 \varepsilon} Q^2 \left( 1 + \left(\frac{2m_p}{\mu_p}\right)^2 \left(\frac{\mu_p G_E}{G_M}\right)^2 \frac{\varepsilon}{Q^2} \right)
\]

\[
= K(E, \theta) \left( 1 + \frac{0.452}{Q^2} \left(\frac{\mu_p G_E}{G_M}\right)^2 \varepsilon \right)
\]
Sensitivity of cross section to proton angle (%/degree)

<table>
<thead>
<tr>
<th>$EE\sqrt{Q^2}$</th>
<th>0.500</th>
<th>2.640</th>
<th>3.200</th>
<th>4.100</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.912</td>
<td>17.403</td>
<td>5.023</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.262</td>
<td>18.573</td>
<td>9.449</td>
<td>5.559</td>
<td></td>
</tr>
<tr>
<td>2.842</td>
<td>19.999</td>
<td>13.393</td>
<td>11.302</td>
<td>6.533</td>
</tr>
</tbody>
</table>
# Angles in degrees

<table>
<thead>
<tr>
<th>pointing angle</th>
<th>survey angle</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.170</td>
<td>22.155</td>
<td>0.015</td>
</tr>
<tr>
<td>12.692</td>
<td>12.674</td>
<td>0.018</td>
</tr>
<tr>
<td>28.384</td>
<td>28.368</td>
<td>0.016</td>
</tr>
<tr>
<td>12.642</td>
<td>12.624</td>
<td>0.018</td>
</tr>
<tr>
<td>23.670</td>
<td>23.652</td>
<td>0.017</td>
</tr>
</tbody>
</table>
$E_e = 2.842$ $Q^2=0.500$

![Graph showing the distribution of events per MeV versus delta p (MeV).](image)
$E_e = 1.912 \quad Q^2 = 0.50$
$E_e = 4.702 \quad Q^2 = 0.500$
Q^2=0.500 (luminosity monitor)

<table>
<thead>
<tr>
<th>incident electron energy</th>
<th>ratio peak to simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.912</td>
<td>0.962</td>
</tr>
<tr>
<td>2.262</td>
<td>0.950</td>
</tr>
<tr>
<td>2.262</td>
<td>0.959</td>
</tr>
<tr>
<td>2.842</td>
<td>0.956</td>
</tr>
<tr>
<td>2.842</td>
<td>0.955</td>
</tr>
<tr>
<td>2.842</td>
<td>0.956</td>
</tr>
<tr>
<td>3.772</td>
<td>0.957</td>
</tr>
<tr>
<td>3.772</td>
<td>0.958</td>
</tr>
<tr>
<td>3.772</td>
<td>0.955</td>
</tr>
<tr>
<td>4.702</td>
<td>0.963</td>
</tr>
<tr>
<td>4.702</td>
<td>0.956</td>
</tr>
<tr>
<td>4.702</td>
<td>0.955</td>
</tr>
</tbody>
</table>
$Q^2 = 3.2$
E01-001 preliminary results: Reduced cross sections

Extraction from single arm without luminosity monitor

Not the "SuperRosenbluth" extraction

$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

$$= \tau G_M^2 \left[ 1 + \epsilon \frac{G_E^2}{\tau G_M^2} \right]$$

Points show statistical plus uncorrelated systematic uncertainties (typically 0.5%)

$\epsilon$-dependent uncertainties applied to extracted ratio ($\sim 0.7\% \epsilon$-dependence)

Large scale uncertainty ($\sim 5\%$) applies to $G_E$ and $G_M$, but not the ratio

---

Graphs show data points for different $Q^2$ values:

- $Q^2 = 2.64$ GeV$^2$
- $Q^2 = 3.20$ GeV$^2$
- $Q^2 = 4.10$ GeV$^2$

Slopes based on polarization data and Rosenbluth data.


\[ \mu_{pGE/GM} \]

- **polarization transfer**
- **Super Rosenbluth**
- **fit to old Rosenbluths**

\[ Q^2 (\text{GeV}^2) \]

- Vertical axis: \( \mu_{pGE/GM} \)
- Horizontal axis: \( Q^2 (\text{GeV}^2) \)
• Rosenbluth experiments are wrong.

• Polarization transfer experiment is is wrong.

• Data are being misinterpreted.
Possible checks on polarization transfer experiments

• Continuation of Hall A experiments in Hall C with a different magnet and new polarimeter. Approved. Runs in 2006.
• Scatter longitudinally polarized electrons from polarized protons.
• Measure transverse polarization transfer in scattering longitudinally polarized electrons from unpolarized protons.
\[ A = \frac{\frac{\tau}{1+\tau} \tan \frac{\theta}{2} \left( \sqrt{\frac{\tau(1+(1+\tau)\tan^2\frac{\theta}{2}) \cos \theta^* + \sin \theta^* \cos \phi^* (G_E / G_M)}{\sqrt{(G_E / G_M)^2 + \frac{\tau}{1+\tau} + 2\tau \tan^2\frac{\theta}{2}}} \right)}{1+(1+\tau)\tan^2\frac{\theta}{2}} \]
When longitudinally polarized electrons scatter from unpolarized protons polarization is transferred to the recoil proton with:

\[ P_t = \frac{2 \sqrt{\tau(1 + \tau)} G_E G_M \tan \frac{\theta}{2}}{G_E^2 + \frac{\tau}{\varepsilon} G_M^2} \]

and

\[ P_i = \frac{(E_e + E_\gamma) \sqrt{\tau(1 + \tau)} G_M^2 \tan^2 \frac{\theta}{2}}{m_p (G_E^2 + \frac{\tau}{\varepsilon} G_M^2)} \]

where \( P_t \) = proton polarization in the plane of the reaction perpendicular to the proton momentum

\( P_i \) = proton polarization parallel to the proton momentum

Jefferson Lab experiments E93-027 and E99-007 measured \( P_i/P_t \) to determine:

\[ \frac{G_E}{G_M} = \frac{P_i}{P_t} \frac{(E_e + E_\gamma) \tan \left( \frac{\theta}{2} \right)}{2m_p} \]
Manifestations of two-photon exchange

- non-linearity in Rosenbluth plot
- epsilon dependence in polarization transfer
- induced normal polarization in unpolarized e-p scattering
- $e^-p$ and $e^+p$ cross sections unequal
$Q^2 = 2.64$

Graph showing $\sigma_r$ vs. $\varepsilon$ with data points and a fit line.

Symbols:
- Red circles with error bars: data
- Black line: fit
- Green line: polarization transfer
Figure 8: Schematic of the polarimeter. The hatched rectangles represent tracking detectors. $S_1$ is a scintillating trigger hodoscope, $T_2$ is the $CH_2$ analyzing target (polyethylene), and $2\pi$ is a rear cylindrical barrel of scintillator.
Studies of two-photon effects ('50s and '60s)

Definitive test: Positron-proton scattering vs. electron-proton scattering

\[ R \equiv \frac{\sigma_{e^+}}{\sigma_{e^-}} = \frac{(A_{1\gamma} + A_{2\gamma})^2}{(A_{1\gamma} - A_{2\gamma})^2} \approx 1 + 4 \text{Re}(A_{2\gamma} / A_{1\gamma}) \]

\[ e^+/e^- \]
\[ <R> = 1.003 \pm 0.005 \]
\[ J. \text{Mar et al., PRL 21, 482 (1968)} \]
\[ \text{and refs therein} \]

\[ \mu^+/\mu^- \]
\[ <R> = 0.993 \pm 0.006 \]
\[ L. \text{Camilleri et al., PRL 23, 149 (1969)} \]
\[ (Q^2 < 1 \text{ GeV}^2) \]

\[ \text{Re}\{A_{2\gamma} / A_{1\gamma}\} \approx (0.0 +/− 0.1)\% \]

One-photon approximation assumed to be good to \( \sim 1\% \)
Conclusions

• Super-Rosenbluth experiment verifies previous Rosenbluth data on proton form factors

• Polarization transfer and Rosenbluth separation give divergent proton electric form factors for $Q^2>\sim 1.5 \ (\text{GeV})^2$.

• Calculations (very difficult) say two-photon exchange corrections may resolve discrepancy. Experiments in planning stage.