Studies of Nucleon Form Factors with 12 GeV CEBAF and the Super Bigbite Spectrometer

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Jefferson Lab

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Nucleon Elastic Form Factors — Formalism

**Nucleon hadronic current**

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

- Dirac FF
- Pauli FF

**Sachs form factors**

\[ G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2 \]

with

\[ \tau = \frac{Q^2}{4M_{\text{nucleon}}^2} \]
Second-generation data on $G_E^p/G_M^p$ from JLab

Sharp drop completely unexpected
Second-generation data on $G^p_E/G^p_M$ from JLab

Sharp drop completely unexpected

Data between 10–15 GeV$^2$ will cleanly distinguish some models
World data on $G^n_E$

Difficult measurement as neutron has no electric charge
World data on $G^n_E$

Difficult measurement as neutron has no electric charge
### Current Best Measurement Techniques

#### $G_E^n / G_M^n$

**polarized target:** $^3\text{He}(\bar{e}, e' n)$

F.o.M. $\propto \sigma \cdot \Omega \cdot P_t^2 \cdot \mathcal{L} \propto \frac{E^2}{Q^{12}} \cdot \Omega \cdot P_t^2 \cdot \mathcal{L}$

#### $G_E^p / G_M^p$

Recoil polarization asymmetry: $p(\bar{e}, e' p)$

F.o.M. $\propto \sigma \cdot A_y^2 \cdot \Omega \cdot \mathcal{L} \propto \frac{E^2}{Q^{16}} \cdot \Omega \cdot \mathcal{L}$

(Polarized proton targets cannot tolerate high $\mathcal{L}$)

#### $G_M^n / G_M^p$

**cross section ratio:** $d(e, e' n) / d(e, e' p)$
## Current Best Measurement Techniques

### $G^n_E / G^n_M$
- Polarized target: $^3\text{He}(\vec{e}, e'n)$

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Extra factor $A_y^2 \propto 1/Q^4$

### $G^n_M / G^p_M$
- Cross section ratio: $d(e, e'n) / d(e, e'p)$
Current Best Measurement Techniques

$G^n_E / G^n_M$

polarized target: $^3\text{He}(\vec{e}, e'n)$

$$F.o.M. \propto \sigma \cdot \Omega \cdot P_t^2 \cdot L \propto \frac{E^2}{Q^{12}} \cdot \Omega \cdot P_t^2 \cdot L$$

$G^p_E / G^p_M$

Recoil polarization asymmetry: $p(\vec{e}, e'\vec{p})$

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(Polarized proton targets cannot tolerate high $L$)

Challenge!

$G^n_M / G^p_M$

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### Current Best Measurement Techniques

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#### $G^p_E / G^p_M$

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Need absolute measurement

(Polarized proton targets cannot tolerate high $\mathcal{L}$)

#### $G^n_M / G^p_M$

**Cross Section Ratio:** $d(e, e' n) / d(e, e' p)$

![Diagram](image-url)
6 GeV electron accelerator, $I_{\text{max}} \approx 200 \mu\text{A}$, $P_{\text{beam}} = 85\%$
Jefferson Lab

6 GeV electron accelerator, $I_{\text{max}} \approx 200 \mu\text{A}, \ P_{\text{beam}} = 85\%$
JLab 12 GeV Upgrade

- Double beam energy (6 → 12 GeV)
- 11 GeV max to Halls A, B, C
- 12 GeV to new Hall D
- Maintain ability to deliver lower-pass energies to Halls (1.1, 2.2, ... GeV)
- Re-use vast majority of existing equipment
- Major upgrades to existing Halls
- First physics in 2014
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Super BigBite

- New equipment in Hall A, to be constructed
- Set of components for **flexible** spectrometer configuration
  - Dipole magnet
  - GEM trackers
  - Calorimeter
  - CH\(_2\) analyzers (for p polarimeter)
  - Dual-radiator RICH (for SIDIS program)
- Use in combination with existing apparatuses, *e.g.* BigBite
SBS Magnet

- Simple dipole, vertical bending
- 46 cm gap, 2.5 T-m
- Provides large acceptance

<table>
<thead>
<tr>
<th>$\theta_{\text{centr}}$ (deg)</th>
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<tr>
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<td>±12.2</td>
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<tr>
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<td>76</td>
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- Momentum resolution

\[
\frac{\Delta p}{p} = (0.03p[\text{GeV}] + 0.29)[\%]
\]

- Angular resolution $\approx 0.3$ mrad
- Vertex resolution $\approx 1 \ldots 2$ mm
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Gas Electron Multiplier (GEM) Trackers

- F. Sauli, NIM A386, 531 (1997)
- Very high rate capability
- Successfully used in COMPASS
- Gain $O(10^4)$
- $\leq 70\mu m$ position resolution
- $40 \times 50$ cm$^2$ prototype sections being tested

**Gain vs. rate**

- Ar/CO$_2$/CF$_4$ (60/20/20) mixture
- 500 KHz /cm$^2$
- SBS

**Ar/CO$_2$/CF$_4$ (60/20/20) mixture**

- 500 KHz /cm$^2$
SBS for Gep5

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<th>quantity</th>
<th>resolution</th>
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<tr>
<td>$\delta, %$</td>
<td>$0.03_p+0.20$</td>
</tr>
<tr>
<td>$x'_{tor}, \text{mrad}$</td>
<td>$0.09 \pm 0.59/p$</td>
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<tr>
<td>$y_{tar}, \text{mm}$</td>
<td>$0.53 + 4.49/p$</td>
</tr>
<tr>
<td>$y'_{tor}, \text{mrad}$</td>
<td>$0.14+1.34/p$</td>
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GEp(5) experiment

**Reaction**

\[ p(\vec{e}, e'\vec{p}) \]

- 40 cm LH2 target
- \( \mathcal{L} = 8 \cdot 10^{38} \text{cm}^{-2}\text{s}^{-1} \)
- High calorimeter thresholds to reject background
- Coincidence rate \( \leq 5 \text{ kHz} \)
- 45 days of beam approved

<table>
<thead>
<tr>
<th>( Q^2 ) (GeV)</th>
<th>( E_{\text{beam}} ) (GeV)</th>
<th>( p_p ) (GeV)</th>
<th>( \theta_{\text{SBS}} ) (deg)</th>
<th>( E' ) (GeV)</th>
<th>( \theta_{\text{BigCal}} ) (deg)</th>
<th>( \Delta[G_E/G_M] ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>6.6</td>
<td>3.5</td>
<td>28.0</td>
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<td>2.3</td>
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<td>16.7</td>
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<td>6.5</td>
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<td>11</td>
<td>7.4</td>
<td>16.9</td>
<td>4.45</td>
<td>29</td>
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GEp(5) Tracking Monte Carlo

Front tracker GEM strip occupancy

- Raw occupancy
- With Λ and D cuts

Tracking Efficiency

- No search region (Max missing planes 2)
- With search region (Max missing planes 3)

Track reconstruction accuracy

- Realistic digitization of GEM & electronics response
- Huge photon background rate, $\mathcal{O}(100)$ MHz
- > 90% tracking efficiency despite > 70% raw occupancy!
- $\approx 40 \mu$m reconstruction accuracy
GEp(5) Expected Precision

\[ \frac{G_E^p}{G_M^p} \]

- **VMD - E. Lomon (2002)**
- **VMD - Bijker and Iachello (2004)**
- **RCQM - G. Miller (2002)**
- **DSE - C. Roberts (2009)**

\[ F_2/F_1 \propto \ln^2(Q^2/\Lambda^2)/Q^2, \Lambda = 300 \text{ MeV} \]

**Legend:**
- **GEp(1)**
- **GEp(2)**
- **GEp(3) (prelim, stat only)**
- **GEp(5) E12-07-109, SBS**
Neutron FF Experiments

\[ G^n_E \text{ measurement} \]

\[ \overrightarrow{^3\text{He}}(\overrightarrow{e}, \overrightarrow{e'}n) \]

\[ A \propto \frac{G^n_E G^n_M \sin \theta^* \cos \phi^*}{a(G^n_M)^2} + b \]

- 60 cm high-pressure \(^3\text{He}\) target (effective polarized neutron)
- \(P_t \geq 65\%\) at \(I = 40\ \mu\text{A}\)
- \(\mathcal{L} = 6 \cdot 10^{36}\text{cm}^{-2}\text{s}^{-1}\)
- BigBite with GEM trackers for precise electron kinematics
- SBS magnet deflects protons
- 50 days of beam approved
Optically-pumped spin-exchange target
Extensive R&D over last decade (UVa)
New convection method very promising
$P \geq 65\%$
Fast spin rotation (seconds)

New target cell design gains $\times 15$ in luminosity
$G_M^n$ Ratio Method Measurement

$G_M^n$ measurement

$$\frac{d(e, e'n)}{d(e, e'p)}$$

- 10 cm LD2 target
- $\mathcal{L} = 3 \cdot 10^{37} \text{cm}^{-2}\text{s}^{-1}$
- Magnet separates QE protons and neutrons
- 25 days of beam approved
$G_M^n$ Expected Precision

![Graph showing $G_M^n/G_D$ vs $Q^2$ for different experiments and models.]

- Rock
- Lachniet
- E12-07-104, CLAS12
- E12-09-019, SBS
Summary

- The Super BigBite program in JLab’s Hall A will measure the nucleon elastic form factors at the highest $Q^2$ to date.
- The measurements represent the current state of the art, offering the highest figure of merit in each case.
- Results will provide crucial input for theory in a previously-unexplored kinematical regime.