Asymmetry Measurement of the Electric Form Factor of the Neutron at $Q^2 = 1.16$ GeV$^2$

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Hall A Collaboration Meeting 2018

January 23, 2018
INTRODUCTION

- A brief introduction to the physics goals of E02-013, otherwise known as $G_E^n$
- Overview of the experimental apparatus
- Summary of the analysis
- Preliminary results of $G_E^n/G_M^n$ at $Q^2 = 1.16$ GeV$^2$
Nucleon Form Factors

- Nucleon form factors arise by generalizing the typical vertex factor $-ie\gamma^\mu$ in OPEX:

$$\Gamma^\nu = \gamma^\nu F_1(q^2) + \frac{i\sigma^{\nu\alpha}q_\alpha}{2M} F_2(q^2)$$

- An unpolarized calculation incorporating the nucleon structure results in the Rosenbluth formula:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{LAB}} = \frac{\alpha^2 \cos^2 \frac{\theta_e}{2}}{4E_e^2 \sin^4 \frac{\theta_e}{2}} \frac{E'_e}{E_e} \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \frac{\theta_e}{2} \right],$$

where $\tau = \frac{Q^2}{4M^2}$, $G_E = F_1 - \tau F_2$ and $G_M = F_1 + F_2$. 
**Beam-Target Asymmetry**

Polarize beam and target, and an asymmetry arises by flipping the beam helicity \( h = \pm 1 \):

\[
A_{\text{phys}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{2\sqrt{\tau(1+\tau)} \tan\frac{\theta_e}{2}}{\frac{\tau}{\epsilon} + \Lambda^2} \left\{ P_x\Lambda + \sqrt{\tau \left[ 1 + (1+\tau) \tan^2\frac{\theta_e}{2} \right]} P_z \right\},
\]

\[
= \frac{\mathcal{B}\Lambda + \mathcal{C}}{\mathcal{D} + \Lambda^2}.
\]

- \( \Lambda \equiv G_E/G_M, P_x = \sin\theta^* \cos\phi^* \) and \( P_z = \cos\theta^* \)
- At leading order, \( A_{\text{phys}} \propto \Lambda \) if \( \theta^* = \pi/2 \) and \( \phi^* = 0 \) or \( 180^\circ \)
INTRODUCTION TO E02-013

- Extract $G^n_E$ via a beam-target helicity asymmetry measurement using the semi-exclusive reaction $^3\text{He}(\vec{e}, e'n)pp$
- The double-arm coincidence experiment took data at four $Q^2$ configurations:

<table>
<thead>
<tr>
<th>$Q^2$ [GeV$^2$]</th>
<th>Days</th>
<th>$E_b$ [GeV]</th>
<th>$\theta_{BB}$ [deg]</th>
<th>$\theta_{NA}$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.16</td>
<td>8</td>
<td>1.519</td>
<td>-56.3</td>
<td>35.74</td>
</tr>
<tr>
<td>1.72</td>
<td>9</td>
<td>2.079</td>
<td>-51.6</td>
<td>35.74</td>
</tr>
<tr>
<td>2.48</td>
<td>19</td>
<td>2.640</td>
<td>-51.6</td>
<td>30.25</td>
</tr>
<tr>
<td>3.41</td>
<td>33</td>
<td>3.291</td>
<td>-51.6</td>
<td>25.63</td>
</tr>
</tbody>
</table>

Table: Kinematic configurations of E02-013, red is unpublished.
Measurements of the Electric Form Factor of the Neutron up to $Q^2 = 3.4$ GeV$^2$

Using the Reaction $^3$He($e, e' n$)$pp$


Spokespeople:

- Gordon Cates - University of Virginia
- Nilanga Liyanage - University of Virginia
- Bogdan Wojtsekhowski - Jefferson Lab
EXPERIMENTAL APPARATUS OVERVIEW
THE BigBite SPECTROMETER IN MC
Major Goals of the Analysis

Major tasks:

1. Find electron tracks, reconstruct the vertex and momentum
2. Reconstruct the nucleon cluster and calculate the momentum via ToF
3. Separate quasielastic events with a set of cuts
4. Identify the charge of the nucleon cluster

Then we may...

- Construct the raw asymmetry
- Correct for all appreciable experimental realities, *i.e.* events that contaminate (or dilute) the quasielastic neutral sample
Cuts on the invariant mass, the missing momentum components and the missing mass largely select the QE region for $Q^2 \approx 1.16 \text{ GeV}^2$. 
The inelastic region is heavily suppressed by the cut selection, resulting in negligible inelastic corrections to $A_{\text{raw}}$.

A final cut of $0.8 < W < 1.15$ GeV is applied.
Nucleon Charge Identification

Side view of the neutron detector depicting the ideal scenario of charge identification within MC. The recoiling nucleons have a kinetic energy of 1.3 GeV prior to entering the detector.
Major Corrections to the Raw Asymmetry

The raw asymmetry for the QE neutral sample:

\[ A_{\text{raw}} = \frac{N^+ - N^-}{N^+ + N^-}, \]

where \( N^{\pm} \) denotes the QE neutral count for \( \pm \) beam helicity.

A summary of the largest dilution factors:\(^1\)

- Accidental background: 5%
- Nitrogen in \(^3\)He target cell: 5%
- Protons misidentified as neutrons: 20%
- Nuclear effects + FSI (GEA): 10%

\(^1\)If interested, more details may be found in the Appendix.
**Charge Misidentification**

**Notation:** $\eta_{\text{true}}^{\text{obs}}$ where true is particle that left the target and obs is the result of charge ID $\Rightarrow \eta_p^p$ protons correctly ID'ed as protons

**Simulation:**

- Generate elastic $eN$ coincidence events and compare to the results of the charge identification procedure (prev. slide)
- Calculate the probability that the true nucleon gets correctly identified

**Data:**

- Analyze the QE uncharged to charged ratio for three targets ($H_2$, $^3\text{He}$, C) to constrain the three $\eta$ ratios
- Need all three ratios to calculate the misidentification correction to $A_{\text{raw}}$ for the uncharged and charged samples
**Charge Misidentification Comparison**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
<th>Simulation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\eta_p^n}{\eta_p^p}$</td>
<td>0.021 ± 0.002</td>
<td>0.020 ± 0.001</td>
<td>Protons observed as neutrons</td>
</tr>
<tr>
<td>$\frac{\eta_p^n}{\eta_p^p}$</td>
<td>Undetermined</td>
<td>0.384 ± 0.001</td>
<td>Neutrons observed as protons</td>
</tr>
<tr>
<td>$\frac{\eta_p^n}{\eta_p^p}$</td>
<td>0.559 ± 0.027</td>
<td>0.636 ± 0.001</td>
<td>Neutrons observed as neutrons</td>
</tr>
<tr>
<td>$D_p$</td>
<td>0.812 ± 0.017</td>
<td>0.839 ± 0.001</td>
<td>Proton dilution factor</td>
</tr>
</tbody>
</table>

*Table:* Charge ID results for the data and the simulation.

The multiplicative correction to the neutral $A_{raw}$ due to proton misidentification is given by $D_p$.  

Figure: Double polarization data: $^3\overline{\text{He}}(\overline{e}, e'n)$ (blue markers), $\overline{d}(\overline{e}, e'n)$ (green markers), and $d(\overline{e}, e'n)$ (red markers). Largest contributions to systematic uncertainty come from target and beam polarization measurements. The error bar in this work is the total uncertainty.
## Systematic Error Budget

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\delta/G_E^n$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta G_E^n$</td>
<td>0.126</td>
<td>Total uncertainty contribution</td>
</tr>
<tr>
<td>$\delta_{\text{sys}}$</td>
<td>0.105</td>
<td>Systematic</td>
</tr>
<tr>
<td>$\delta_{\text{stat}}$</td>
<td>0.070</td>
<td>Statistical</td>
</tr>
<tr>
<td>$\delta P_{3\text{He}}$</td>
<td>0.077</td>
<td>Target polarization</td>
</tr>
<tr>
<td>$\delta P_{\text{beam}}$</td>
<td>0.040</td>
<td>Beam polarization</td>
</tr>
<tr>
<td>$\delta D_{\text{bk}}$</td>
<td>0.028</td>
<td>Background dilution</td>
</tr>
<tr>
<td>$\delta D_p$</td>
<td>0.028</td>
<td>Proton dilution</td>
</tr>
<tr>
<td>$\delta G_M^n$</td>
<td>0.025</td>
<td>Error from chosen $G_M^n$</td>
</tr>
<tr>
<td>$\delta D_{\text{FSI}}$</td>
<td>0.025</td>
<td>Nuclear corrections</td>
</tr>
<tr>
<td>$\delta_{\text{other}}$</td>
<td>0.023</td>
<td>Sum of remaining contributions</td>
</tr>
</tbody>
</table>

Contributions to the systematic uncertainty of $G_E^n$ from individual sources, and presented as a fraction of $G_E^n$. 
Appendix
## Major Corrections: $A_{\text{RAW}} \rightarrow A_{\text{PHYS}}$

<table>
<thead>
<tr>
<th>$\langle Q^2 \rangle$ [GeV$^2$]</th>
<th>1.16</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$ [GeV]</td>
<td>0.8 – 1.15</td>
<td>Invariant Mass</td>
</tr>
<tr>
<td>$p_\perp$ [GeV]</td>
<td>&lt; 0.150</td>
<td>Missing $\perp$ momentum</td>
</tr>
<tr>
<td>$p_\parallel$ [GeV]</td>
<td>&lt; 0.250</td>
<td>Missing $\parallel$ momentum</td>
</tr>
<tr>
<td>$m_{\text{miss}}$ [GeV]</td>
<td>&lt; 2</td>
<td>Missing mass</td>
</tr>
<tr>
<td>$\langle P_e \rangle$</td>
<td>0.870 ± 0.020</td>
<td>Longitudinal beam polarization</td>
</tr>
<tr>
<td>$\langle P_{\text{He}} \rangle$</td>
<td>0.416 ± 0.019</td>
<td>Polarization $^3$He nucleus</td>
</tr>
<tr>
<td>$D_{\text{bkgr}}$</td>
<td>0.949 ± 0.029</td>
<td>Accidental background</td>
</tr>
<tr>
<td>$D_{N_2}$</td>
<td>0.954 ± 0.005</td>
<td>Nitrogen in target</td>
</tr>
<tr>
<td>$D_p$</td>
<td>0.812 ± 0.017</td>
<td>Proton contamination</td>
</tr>
<tr>
<td>$D_{\text{in}}$</td>
<td>0.980 ± 0.011</td>
<td>Inelastic contamination</td>
</tr>
<tr>
<td>$D_{\text{FSI}}$</td>
<td>0.896 ± 0.013</td>
<td>Nuclear effects + FSI (GEA)</td>
</tr>
</tbody>
</table>

\[
A_{\text{phys}} = \frac{1}{P \cdot D} \left( A_{\text{raw}} - \sum A_{\text{corr}} \right),
\]

where $A_{\text{corr}}$ are corrections to $A_{\text{raw}}$ which are associated to a dilution factor $D$ within the table, and $P = P_e P_{\text{He}}$. 

\[
A_{\text{phys}} = \frac{1}{P \cdot D} \left( A_{\text{raw}} - \sum A_{\text{corr}} \right),
\]
TARGETS OF E02-013

- Polarized $^3$He is used as an effective neutron target as the symmetric S-state dominates the ground-state in which proton spins tend to cancel ⇒ $\sim 86\%$ of the nuclear spin is carried by the neutron
- Hybrid spin-exchange optical pumping (alkali vapors Rb and K) was used to polarize the $^3$He target
- Target cells exceeded polarizations of $50\%$, operating at a pressure of $\sim 10$ atm with a beam current of $8\mu A$
- Other targets included BeO-C foils and an empty ref. cell that may be filled with $H_2 / N_2$
- Targets are mounted to a ladder which is suspended in a 0.25” thick iron “target-box”
The **BigBite Spectrometer**

- The purpose is to measure the four momentum of the quasielastically scattered electron
- BigBite is a large dipole magnet that subtends $\sim 76$ msr and accepts scattered $e^-$ in the range $0.6 < p < 1.8$ GeV.
- Three multiwire drift chambers (15 wire planes) reconstruct the scattered track post magnetic deflection
- A segmented lead-glass preshower + shower package for triggering and pion rejection. Can reconstruct track energy and is used to confine search region of track recon.
- A hodoscope consisting of 13 scintillator paddles (resolution of 35 ps/channel) is used for event timing information
The Neutron Detector

- The purpose is to measure the momentum of the recoiling nucleons in coincidence via ToF and to identify the charge
- Designed to match the acceptance of BigBite at the largest $Q^2$ point
- A time of flight resolution of 300 ps has been obtained
- Detector consists of two “veto” layers (charge ID) and seven neutron layers (ToF)
- The veto layers are built out of 48 rows of long/short scintillating bars with two PMTs per row
- The neutron layers consist of rows of scintillating bars (1 per row) with two PMTs per row
The two veto layers (charge identification) and the seven neutron layers (nucleon ToF)
**Background Subtraction**

- Shift data in time before QE cuts are applied ⇒ adjust $\beta$:

$$\beta_{bk} = \frac{1}{\beta_{QE}} + 0.8 \approx 0.5 \implies \beta_{bk}^{-1} = 2$$

where 0.8 is a shift parameter and $\beta_{QE} = 0.8$.

- Apply QE cuts, and the result is random background
RAW ASYMMETRY

Top Panel:

- BB single arm trigger rate T2 is sensitive to beam helicity
- Total sign = (target sign) × (precession sign) × (HWP sign)

Bottom Panel:

- Background corrected raw asymmetry
- Need to apply additional corrections to remove unwanted events
**NITROGEN DILUTION**

- No N$_2$ data ⇒ use C foils and exclude the BeO foil

\[
D_{N_2} = 1 - \frac{\Sigma(C) - \Sigma_{\text{back}}(C)}{\Sigma - \Sigma_{\text{back}}} \frac{Q(\text{He})}{Q(C)} \frac{\rho_{N_2}(\text{He})}{\rho_C(C)} \frac{t_{\text{He}}}{t_C}
\]
Vertex Resolution

\[ \sigma_{v_z} \approx 6.5 \text{ mm} \]
**MOMENTUM RESOLUTION**

\[ \sigma_p \approx 1\% \text{ or } 10 \text{ MeV} \]
BB ENERGY RESOLUTION

\[ \sigma \approx 7.5\% \]

Entries 16214
\[ \chi^2 / \text{ndf} \quad 123.9 / 82 \]
Constant 677.7 \( \pm \) 6.8
Mean \(-0.0122 \pm 0.0006\)
Sigma \(0.07554 \pm 0.00047\)
NA ToF Resolution

\[ \sigma_{NA} \approx 300 \text{ ps} \]
Corrections

- Accidental Background: 2%
- Nitrogen dilution: 5%
- Misidentified protons: 20%
  - Evaluated through data and Geant4 monte carlo
- Inelastic Events: 0 - 15%
  - Evaluated through Geant4 monte carlo + MAID
- Nuclear effects + FSI: 5%

Figure: S. Riordan 2012 SBS Review
In case I forget...

\[ t_{\text{ToF,ex}} = \frac{\ell}{c} \sqrt{1 + \left( \frac{M}{|\vec{q}|} \right)^2} \]

\[ \beta = \frac{v}{c} = \frac{|\vec{\ell}|}{c \ t_{\text{ToF}}} \]

\[ p_{\text{na}} = \frac{M\beta}{\sqrt{1 - \beta^2}} \]

\[ \delta p = \frac{M c \beta^2}{\ell} \left( \frac{1}{(1 - \beta^2)^{\frac{3}{2}}} \right) \delta t \]