Proposal PR12-12-011:
Asymmetry Measurements to Extract $G_E^n$ and $G_M^n$ at $Q^2 = 1 - 2.6 \text{(GeV/c)}^2$ from the Inclusive $^3\text{He}(\bar{e},e')$ Reaction

Vincent Sulkosky
Massachusetts Institute of Technology
On Behalf of T. Averett (W&M), D. W. Higinbotham (JLab), B. E. Norum (UVa)
for the PR12-12-011 Collaboration

Hall C Summer Workshop
June 23rd, 2012
Motivation

- **Neutron** not understood to the same accuracy as the proton
- No pure neutron target
- **Indirect measurements** using appropriate targets: deuteron and/or $^3\text{He}$

- High precision measurement will help pin down theoretical treatments on the extraction of the neutron electromagnetic form factors from different nuclei (deuteron and $^3\text{He}$) and different reaction channels $A(e,e')$ and $A(e,e'n)$

- Theoretical models and parameterizations begin to diverge for $Q^2 > 1 (\text{GeV}/c)^2$

- Compared to the other form factors the precision on $G_E^n$ is poorly constrained over the measured $Q^2$ range (**only** three data points have a precision better than 10%)
Extraction of $G_E^n$ at $Q^2 = 0.98$ (GeV/c)$^2$ by Measurements of $^3\text{He} (e, e')$

- $G_E^n$ was extracted for the first time by inclusive polarized measurements from $^3\text{He}$ at $Q^2 = 0.98$ (GeV/c)$^2$
- Form the ratio of asymmetries for longitudinal and transverse target polarization; use the well known proton electromagnetic and the neutron magnetic form factors
- **Proton and neutron contributions calculated in PWIA**
- This technique agrees with previous measurements; uncertainty $\sim 19\%$ (limited by statistics in only a few shifts of data)
- **Note:** M. Sargsian and G. Salme` are ready to support full model extractions of precision data
Helicity Asymmetry in Electron Scattering

$$A = -\frac{\sin \theta \cos \phi \nu_{TL} R_{3He} R_{TL} + \cos \theta \nu_T R_{3He} R_{T'}}{\nu_L R_{3He} L + \nu_T R_{3He} T'}$$

where $R$'s are response functions and $\nu$'s are kinematics factors

Ratio of Asymmetries

when $\theta^* = 0$, transverse asymmetry

$$A_{TL'} = -\frac{v_{TL'} R^{3He}_{TL'}}{v_L R^{3He}_L + v_T R^{3He}_T}$$

when $\theta^* = \pi / 2$ and $\phi^* = 0$, transverse-longitudinal asymmetry

$$A_{TL'} = -\frac{v_{TL'} R^{3He}_{TL'}}{v_L R^{3He}_L + v_T R^{3He}_T}$$

$$\Rightarrow \frac{A_{TL'}}{A_T'} = \frac{v_{TL'} R^{3He}_{TL'}}{v_T R^{3He}_T}.$$
$^{3}\text{He}$ Inclusive Response Functions near the Quasi-elastic Peak in PWIA

Transverse-longitudinal:

\[ R^{^{3}\text{He}}_{\text{TL'}} = -\sqrt{2} \left[ 2 G_E^p G_M^n H_p^{\text{TL'}} + G_E^n G_M^p H_n^{\text{TL'}} \right] \]

Transverse:

\[ R^{^{3}\text{He}}_{T'} = \frac{Q^2}{2qM} \left[ 2(G_M^p)^2 H_p^{T'} + (G_M^n)^2 H_n^{T'} \right] \]

where $H'$s are calculated by momentum distribution and nucleon polarization in $^{3}\text{He}$

A. Kievsky, E. Pace, G. Salme’, and M. Viviani, PRC 56 (1997) 64
\[ ^3\text{He} \text{ spin structure} \]

- Spin-1/2 Particle, 3 spin-1/2 Nucleons (Proton and Neutron)
- Protons are in spin-singlet state. \(^3\text{He}\) spin is dominated by spin of \(n\). Therefore \(^3\text{He}\) can be used as an effective \(n\) target
- S’ mixed symmetry, (spin-isospin)-space correlations

\[
\frac{\mu_{^3\text{He}}}{\mu_n} = \frac{-2.131}{-1.913} \approx 1
\]

Angular Momentum:
- S: \(L=0\) \(\sim 90\%\)
- S’: \(L=0\) \(\sim 1-2\%\)
- D: \(L=2\) \(\sim 8\%\)
Ratio of Asymmetries as a Function of Form Factors

\[ \frac{A_{TL'}}{A_T'} = \frac{v_{TL'}(-\sqrt{2} [2 G_E^p G_M^p H^{p TL'} + G_E^n G_M^n H^{n TL'}])}{v_T' \left( \frac{Q^2}{2qM} \left[ 2(G_M^p)^2 H^{p T'} + (G_M^n)^2 H^{n T'} \right] \right)} \]

- By measuring \( A_{TL}/A_T \) and using \( G_E^p, G_M^p, \) and \( G_M^n \) as known parameters can one extract \( G_E^n \)
$G_E^n$ from $^3\text{He}(e,e')$ at $Q^2=0.98$ (GeV/c)$^2$
with a few shifts of data

Analysis by Jin Ge

$G_E^n = 0.0414 \pm 0.0077$ (stat) $\pm 0.0019$ (syst)

Hall C Summer Workshop   23 June 2012   Inclusive GEn Measurements
Overview of Experiment

\[ \text{Measure inclusive double-polarized } \ ^3\text{He asymmetries} \]

\[ \text{Use the Hall C Super High Momentum Spectrometer (SHMS) to detect the scattered electrons at 6 and 8.5 degrees with 11 GeV beam} \]

\[ \text{Use the upgraded polarized } \ ^3\text{He target planned for the } A_1^n (E12-06-110) \text{ and } d_2^n (E12-06-121) \text{ experiments} \]

\[ \text{Considering to detect the knock-out proton in the High Momentum Spectrometer (HMS)} \]
6-GeV Performance of $^3$He Target

- Luminosity: $L(n) = 10^{36}$ cm$^{-2}$ s$^{-1}$
- Achieved record high steady $\sim 60\%$ polarization with a beam current up to 15 $\mu$A

![Average $^3$He pol. = 55%](image)

![History of Figure of Merit of Polarized $^3$He Target](image)
Planned $^3\text{He}$ Target for 12-GeV Experiments

- Upgrade takes advantage improvements of hybrid spin exchange optical pumping and spectrally narrowed lasers

- This proposal takes advantage of the already planned factor of 8 improvement in polarized luminosity discussed in the approved $A_1^n$ experiment (Hall C)
  - “Dual transfer tube” design for convection mixing of polarized gas
  - Additional diagnostics for direct measurement of $^3\text{He}$ and alkali-vapor polarizations
  - Metal end-cap cells, partial metal cell and/or Be end windows

- Goal: 60% target polarization with a beam current of 60 $\mu$A on a 60-cm long target
Form Factor Sensitivity to Asymmetry Ratio

\[ A_{ratio} = \frac{A_{TL'}}{A_T} \]
Kinematics and Rates

- Utilize full capabilities of SHMS (11 GeV forward angle)
- Take advantage of the rate boost from $\sigma_{\text{Mott}}$
- Helps minimize inelastic backgrounds
- Estimated quasi-elastic counting rates for a 42-cm long target with 60% target polarization, 80% beam polarization at 60 $\mu$A
- Based on J. Arrington parameterization for $G_E^p$ and $G_M^p$ and CLAS data for $G_M^n$

<table>
<thead>
<tr>
<th>$E_0$ [GeV]</th>
<th>$E'$ [GeV]</th>
<th>$\theta_{\text{SHMS}}$ [deg]</th>
<th>Range of $\theta_{\text{lab}}$ [deg]</th>
<th>$Q^2$ (GeV/c)$^2$</th>
<th>e$^-$ rate [kHz]</th>
<th>$t_\parallel$ [hrs]</th>
<th>$t_\perp$ [hrs]</th>
<th>$\Delta A_\parallel$ [$\cdot 10^{-4}$]</th>
<th>$\Delta A_\perp$ [$\cdot 10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0</td>
<td>10.437</td>
<td>6</td>
<td>5 – 6</td>
<td>1.057</td>
<td>7.70</td>
<td>48</td>
<td>6</td>
<td>0.8</td>
<td>2.2</td>
</tr>
<tr>
<td>11.0</td>
<td>10.229</td>
<td>6</td>
<td>6 – 7</td>
<td>1.446</td>
<td>1.446</td>
<td>1.446</td>
<td>1.446</td>
<td>1.446</td>
<td>1.446</td>
</tr>
<tr>
<td>11.0</td>
<td>9.874</td>
<td>8.5</td>
<td>7.5 – 8.5</td>
<td>2.114</td>
<td>0.37</td>
<td>240</td>
<td>36</td>
<td>1.6</td>
<td>4.1</td>
</tr>
<tr>
<td>11.0</td>
<td>9.612</td>
<td>8.5</td>
<td>8.5 – 9.5</td>
<td>2.604</td>
<td>240</td>
<td>36</td>
<td>1.6</td>
<td>4.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Expected Results

\[ G_E^n \]

- Neutron Recoil Polarization
- Polarized Deuteron
- Polarized He-3
- E05-102
- This Proposal

\[ Q^2 \left[ (\text{GeV}/c)^2 \right] \]
Concerns Raised by PAC 39 and TAC

- Polarized Inelastic background contamination
- Final State Interactions (FSI) and Meson Exchange Currents (MEC)
- Relativistic Effects
Inelastic Contamination

- Used the cross section models from Misak Sargsian and Peter Bosted ([http://arxiv.org/abs/1203.2262](http://arxiv.org/abs/1203.2262))
- The two models agree well with each other at the top of the quasi-elastic peak with less than a 0.5% absolute difference

\[ \delta = 2\% \]
Inelastic Contamination

- Used the cross section models from Misak Sargsian and Peter Bosted (http://arxiv.org/abs/1203.2262)
- The two models agree well with each other at the top of the quasi-elastic peak with less than a 0.5% absolute difference
- By varying the momentum cut, the effect of the contamination can be studied with the data

<table>
<thead>
<tr>
<th>$Q^2$ (GeV/c$^2$)</th>
<th>Contamination $x = 1$ [%]</th>
<th>Contamination (dp = 2%) [%]</th>
<th>Contamination (dp = 1.5%) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.06</td>
<td>0.3</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>1.45</td>
<td>1.5</td>
<td>3.0</td>
<td>1.7</td>
</tr>
<tr>
<td>2.11</td>
<td>4.6</td>
<td>8.8</td>
<td>4.9</td>
</tr>
<tr>
<td>2.60</td>
<td>7.8</td>
<td>11.9</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Inelastic Contamination on Asymmetry

\[ A_{QE} = \frac{(A_{raw} - f_c \cdot A_{in})}{1 - f_c} \]

- \( f_c \) is the amount of contamination under the quasi-elastic peak
- \( A_{QE}, A_{raw}, \) and \( A_{in} \) are the quasi-elastic, measured and inelastic asymmetries
- Using the determined contamination numbers from the models and the measured asymmetries from experiments E01-012 and E05-102 with the assumption that \( A_{in} = A_{\Delta} \), the effect on the asymmetry was calculated

<table>
<thead>
<tr>
<th>( Q^2 ) (GeV/c)^2</th>
<th>( A_{raw} )</th>
<th>( A_{QE} )</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>-0.1656</td>
<td>-0.1699</td>
<td>2.5</td>
</tr>
<tr>
<td>2.6</td>
<td>-0.2325</td>
<td>-0.2258</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Comparison of Cross Sections at $Q^2 \sim 2.5 \text{ GeV}^2$

The quasi-elastic cross section is about a factor of 70x larger at forward angle compared to the GEN-1 data point.

• The proposed measurement benefits from the SHMS resolutions compared to BigBite
• We will also measure the inelastic contribution within the SHMS momentum acceptance, allowing us to **carefully choose our cuts for each $Q^2$ point**

Cross section model from P. Bosted
FSI and MEC vs. $Q^2$

- Experiment E08-005: recent $^3\text{He}^{\uparrow}(e,e'\text{n})$ single spin asymmetry ($A_y$) measurements, target polarized normal to scattering plane
- $A_y$ vanishes in PWIA, and measurements of this asymmetry are a good check of FSI and MEC contributions
- Small asymmetry near 1 (GeV/c)$^2$ is indicative that these mechanisms have become negligible
- Analysis by E. Long
Relativistic Effects

- Misak Sargsian compared his model calculation using the Virtual Nucleon and Light Cone approximations.
- He provided the difference in these two methods as the uncertainty due to relativistic effects.
- Giovanni Salme is constructing a Poincare invariant approach for the relativistic treatment in his calculation.
Relative systematic uncertainties from nucleon form factors, model (updated numbers from M. Sargsian), experimental (beam pol. 1.5%, target pol. 1%, radiative corrections 1%), and the inelastic contamination

GEp: 1% at $Q^2 = 1$ (GeV/c)$^2$ with a linear increase up to 3% at 3 (GeV/c)$^2$

GMp: 1% over the planned $Q^2$ range

GMn: 2% to 2.4% from the high precision Hall B data (J. Lachniet et al.)
# Beam Time Request

<table>
<thead>
<tr>
<th>Description</th>
<th>Time (Hours)</th>
<th>Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long. Pol. $^3$He at 11 GeV, 6 degs</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>Trans. Pol. $^3$He at 11 GeV, 6 degs</td>
<td>6</td>
<td>0.25</td>
</tr>
<tr>
<td>Long. Pol. $^3$He at 11 GeV, 8.5 degs</td>
<td>240</td>
<td>10</td>
</tr>
<tr>
<td>Trans. Pol. $^3$He at 11 GeV, 8.5 degs</td>
<td>36</td>
<td>1.5</td>
</tr>
<tr>
<td>Dilution, calibrations</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total Time Requested</strong></td>
<td><strong>336 + 24</strong></td>
<td><strong>14 + 1</strong></td>
</tr>
</tbody>
</table>

We requested a total of 15 days of beam time but we were deferred.
Summary

- Experiment is a straightforward $^3\text{He (e, e')}$ measurement at $Q^2$ from 1 to 2.6 (GeV/c)$^2$
- Already have theoretical support from G. Salme and M. Sargsian to make $G_E^n$ extractions from the data
- Makes use of the Hall C investments for the $A_1^n$ and $d_2^n$ experiments without requiring additional equipment
- We requested 15 days of beam
- However, the proposal was deferred with a recommendation from the PAC to take data parasitically during $A_1^n$ and $d_2^n$ at a $Q^2$ where $G_E^n$ is reasonably measured to test our extraction method
Thank You!
**PR12-12-011 Collaboration**

D. S. Armstrong, T. Averett (Spokesperson), M. Cummings, W. Deconinck, H. Yao

**College of William and Mary**

K. Allada, A. Camsonne, O. Hansen, D. W. Higinbotham (Spokesperson), B. Sawatzky, P. Solvignon

**Thomas Jefferson National Accelerator Facility**

C. Hanretty, B. E. Norum (Spokesperson)

**University of Virginia**

W. Bertozzi, S. Gilad, A. Kelleher, S. Kowalski, V. Sulkosky (Spokesperson)

**Massachusetts Institute of Technology**

B. Anderson, E. Long

**Kent State University**

M. Mihovilović, S Širca

**Jožef Stefan Institute and University of Ljubljana**


**University of New Hampshire**

L. El Fassi, R. Gilman, K. E. Myers, A. Tadepalli, Y. Zhang

**Rutgers, The State University of New Jersey**

P. Markowitz

**Florida International University**

J. Huang

**Los Alamos National Lab**

W. Tireman

**Northern Michigan University**

T. Holmstrom

**Longwood University**

K. Aniol

**University of Califorina**
Boost from Mott Cross Section

E05-105 Kinematics

$\sigma_{\text{Mott}}$ [$\mu b$/Sr] vs $Q^2$ [GeV/$c$]^2

- $E_{\text{beam}} = 3.6$ GeV
- $E_{\text{beam}} = 2.2$ GeV
- $E_{\text{beam}} = 4.4$ GeV
- $E_{\text{beam}} = 6.6$ GeV
- $E_{\text{beam}} = 8.8$ GeV
- $E_{\text{beam}} = 11.0$ GeV
Expected Results
Motivation

$^3\text{He}(e,e'n)$ and $^3\text{He}(e,e')$ data:
- Becker EPJA 6 (1999) 329 + FSI
- Becker EPJA 6 (1999) 329 no FSI
- Bermuth PLB 564 (2003) 199
- Meyerhoff PLB 327 (1994) 201
- Riordan PRL 105 (2010) 262302

$^d(e,e'n)$ and $d(e,e'n)$ data:
- Passchier PRL 82 (1999) 4988
- Eden PRC 50 (1994) R1749
- Herberg EPJA 5 (1999) 131
- Ostrick PRL 83 (1999) 276 + FSI
- Zhu PRL 87 (2001) 081801
- Madey PRL 91 (2003) 122002
- Glazier EPJA 24 (2005) 101

Fits:
- Galster NPB 32 (1971) 221
- Kelly PRC 70 (2004) 068202
Polarized $^3$He Target

- Improved figure of merit
  - Rb+K hybrid mixture cell
  - Narrow bandwidth lasers
- **Compact size**: No cryogenic support needed

$^3\text{He} \approx S \quad S \quad D$

$\sim 90\% \quad \sim 1.5\% \quad \sim 8\%$

Insert diagram with the following labels:

- Laser 795 nm
- Oven 230 °C
- Pumping Chamber
- 25 G Holding Field
- Target Chamber
- Beam: 40 cm
- $\Phi = 3^\circ$
- Rb-K-$^3$He Spin Exchange

MIT and Jefferson Lab logos are present.
Planned $^3$He Target for 12-GeV Experiments

- Upgrade takes advantage improvements of hybrid spin exchange optical pumping and spectrally narrowed lasers

- This proposal takes advantage of the already planned factor of 8 improvement in polarized luminosity discussed in the and the Hall C approved $A_1^n$ experiment
  - “Dual transfer tube” design for convection mixing of polarized gas
  - Additional diagnostics for direct measurement of $^3$He and alkali-vapor polarizations

- Goal: 60% target polarization with a beam current of 60 μA on a 60-cm long target
Current Status of EM Form Factors

\[ \frac{G_E}{G_D} \quad \frac{G_P}{\mu_p} \]

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

\[ 10^{-1} \quad 1 \quad 10 \]

\[ 10^{-1} \quad 1 \quad 10 \]

\[ G_E^p \quad G_M^p \mu_p \quad G_D \]

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

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \]

\[ G_E^p \quad G_M^p \mu_p \quad G_D \]

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

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \]