The Status of g2p & GEp(II) Analysis

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On behalf of the E08-027(g2p)/E08-007(GEp) collaboration

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g_2p motivation

Measure $g_2$ in the low $Q^2$ region ($0.02 < Q^2 < 0.2 \text{GeV}^2$)
g2p motivation

- Extract longitudinal-transverse spin polarizability ($\delta_{LT}$) benchmark test of $\chi$PT, discrepancy seen for neutron data
- Test Burkhardt-Cottingham (BC) Sum Rule violation suggested for proton in high $Q^2$ (SLAC E155x)
- Hydrogen hyperfine splitting correction for proton structure contributes to uncertainty
- Proton charge radius contributions to uncertainty include proton polarizability
GEp motivation

Asymmetry

\[ A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

\[ A = f P_b P_t \left( a \cos \theta^* G_M^2 b \sin \theta^* \cos \phi^* G_E G_M \right) \]

\[ \frac{c G_M^2 + d G_E^2}{G_E G_M} \]

Elastic Form Factor Ratio

\[ \sim 2\%-3\% \text{ uncertainty at } Q^2 \sim 0.015 - 0.06 \text{ GeV}^2 \]
GEP motivation

The proton radius puzzle

\[ G_{E,M}(Q^2) = \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r} = \int \rho(\vec{r}) d^3\vec{r} - \frac{\vec{q}^2}{6} \int \rho(\vec{r}) \vec{r}^2 d^3\vec{r} + \ldots \]

<table>
<thead>
<tr>
<th>#</th>
<th>Extraction</th>
<th>Method</th>
<th>( &lt;r_E&gt;^2 ) [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sick</td>
<td>ep scattering</td>
<td>0.895±0.018</td>
</tr>
<tr>
<td>2</td>
<td>CODATA</td>
<td></td>
<td>0.8768±0.0069</td>
</tr>
<tr>
<td>3</td>
<td>Mainz</td>
<td>ep scattering</td>
<td>0.879±0.008</td>
</tr>
<tr>
<td>4</td>
<td>GEP part I</td>
<td>ep scattering</td>
<td>0.870±0.010</td>
</tr>
<tr>
<td>5</td>
<td>Combined 2–4</td>
<td></td>
<td>0.8764±0.0047</td>
</tr>
<tr>
<td>6</td>
<td>Muonic Hydrogen</td>
<td>( \mu H ) Lamb shift</td>
<td>0.842±0.001</td>
</tr>
</tbody>
</table>

Result from Lamb shift in muonic hydrogen disagree with other results

**Experimental setup**

- **Polarized NH3 target**
  - Slow raster (id 3)
  - **Low current** (50~100nA for g2p, 5~10nA for GEp)
  - Super-harps (id 6)
  - Tungsten calorimeter (id 4)
  - New BPM/BCM receiver (readout)
    - Hall A Standard BCM/BPM (id 1/id 8)
- **High transverse target field (2.5~5T)**
  - Chicane dipole magnet (id 7)
  - Local beam dump (id 11)
- **6deg scattering angle detection**
  - Septum
Detector efficiency

Cherenkov efficiency ~99.96%

Lead glass efficiency ~99.6%

All of our detector efficiency is in very good situation
Detector efficiency

Track efficiency (with multi track) >99%

Pion rejection ~0.004

All of our detector efficiency is in very good situation
Target polarization

Average polarization:
5T: ~70%
2.5T: ~15%
Beam position reconstruction

- Beam position and angle at the target
- Fitted function from simulation to transport position from BPMs to target
Beam position reconstruction

- Event by event position and angle
  - Use BPM information as average beam position
  - Calibrate Raster magnet current information as position deviation from center position
  - Combine BPM, slow/fast raster magnet current informations

\[ X = \langle X_{BPM} \rangle + X_{fast} + X_{slow} \]
Beam position reconstruction

- Uncertainty
  - Best situation: 1mm for position, 1.1mrad for angle
  - Main uncertainty part:
    - Pedestal fluctuation
    - Too close for two BPMs -- 26.5cm difference
HRS Optics – without target field

Angle matrix -- sieve slit
  • Angle at sieve slit got from survey

\[ \delta, y, \theta, \varphi \]

Target

Septa

Q1

Q2

Dipole

VDC

Q3

\[ x, y, \theta, \varphi \]
HRS Optics - without target field

\[ \delta \text{ matrix} \]
- \( \delta \) calculated from Carbon Elastic

\[ \delta, y, \theta, \varphi \]

\[ x, y, \theta, \varphi \]

\[ \text{Target} \]
\[ \text{Septa} \]
\[ \text{Q1} \]
\[ \text{Q2} \]
\[ \text{Dipole} \]
\[ \text{VDC} \]
\[ \text{Q3} \]
HRS Optics – without target field

Performance summary of RMS values without target field

<table>
<thead>
<tr>
<th>RMS</th>
<th>LHRS</th>
<th>RHRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$ [dp]</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Theta$ [out-of-plane angle]</td>
<td>$1.59$ mrad</td>
<td>$1.57$ mrad</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$3.3$ mm</td>
<td>$2.9$ mm</td>
</tr>
<tr>
<td>$\varphi$ [in-plane angle]</td>
<td>$0.99$ mrad</td>
<td>$0.82$ mrad</td>
</tr>
</tbody>
</table>
HRS Optics - with target field

• Septum broke during the experiment, need to use the data taken with the broken septum to recalibrate angle matrix

• A simulation package is written to deal with the ray tracing in the target field

  • For the recalibration of the matrix, the simulation package is used to calculate reference angles

  • For reconstruction, the simulation package is used to calculate the real scattering angles
Acceptance

Unpolarized cross section

\[ \frac{d\sigma_{\text{raw}}}{d\Omega dE'} = \frac{N \ast ps \ast RC}{Q/q \ast N_{tg} \ast L \ast \epsilon_{det}} \frac{Acc}{\Delta\Omega \Delta E'} \]

Method:

- Match the simulation and data in all of planes
- Use simulation to get acceptance

\[ \frac{Acc}{\Delta\Omega \Delta E'} = \frac{1}{\Delta\Omega^\text{MC} \Delta E^\text{MC}} \frac{N^\text{MC}_{\text{simu}}}{N^\text{MC}_{\text{acc}}} \]

- we are working on obtaining the comparison of angles and momentum on target plane
- The simulation results match data on focal plane very well, and this will largely help the comparison on target plane.
Simulation

- Runge-Kutta method with self-adjusting step length to improve speed and accuracy
- HRS SNAKE models are included to get the focus plane variables
- Several cross-section models are also included, an event generator is written with these models
- Energy loss models included

Ongoing:
- Match data with simulation
- Packing fraction study with simulation

Comparison between simulated dp vs optics run dp
Define: \( p_f = 1 - \frac{Y_{\text{in}}^{\text{He}}}{Y_{tg}} \)

- Yield from He in dummy target cell
- Yield from NH3 target cell

\( \approx l_{tg} \)

-- effective NH3 target thickness

NH3 beads filled by liquid He
Packing fraction

• Only use elastic peak
  • Fitting routine to obtain level of contamination from QE peaks

• Ongoing
  • Radiation length matching between production and dummy runs
  • Updating fitting routine to include multiple contributions to second peak
  • Repeat analysis for other materials/energy settings

Fit to Elastic and QE Peaks – Production Run

Current Result: (2.2 GeV, 2.5T Setting, Material 8)

\[ p_f = 0.551 \]
Dilution

Remove the Background from N, He, Aluminum foil

\[ A_{\text{raw}} = \frac{Y_+ - Y_-}{Y_+ + Y_- + bg} \]

\[ A_{\text{phy}} = \frac{1}{P_b P_t D} A_{\text{raw}} \]

\[ Y_{+/--} \quad \text{Yield from proton} \]

\[ bg = Y_N + Y_{He} + Y_f \quad \text{Yield from N, He, foil} \]

\[ P_b P_t \quad \text{Polarization of beam and target} \]

\[ D = 1 - \frac{bg}{Y_{\text{total}}} \]

Yf: Extract from dummy and empty target

YHe*: Extract from empty target

YN: Extract from carbon target and scale it to nitrogen using P.Bosted cross section model
Dilution

Comparison of C&N XS from P.Bosted model

Current result:
3.350GeV 5T Transverse Dilution result

- Still Ongoing

ν(MeV)
Bosted model tuning using saGDH data

-- saGDH unpolarized radiative correction study

- saGDH has similar kinematics with g2p (0.02~0.2GeV²)
- saGDH has pure nitrogen data (gas nitrogen target)
- g2p only took dilution data on carbon, need to scale to match actual nitrogen background
- For the nitrogen background subtraction for dilution study
Summary for g2p Analysis status

**Completed:**
- Run database
- Beamline
  - BCM calibration
  - BPM calibration
  - Helicity decode
  - Dead time calculation
- Detector Calibration
  - Gas Cerenkov
  - Lead Glass
  - Trigger efficiency
- Target Polarization Analysis
- HRS Optics
  - Straight through
  - With target field - Left arm
- g2p simulation package:
  - Geometry and optics part for optics
  - Cross section models
  - Energy loss models

**Ongoing:**
- HRS Optics
  - With target field - Right arm
- Acceptance study
- Packing fraction
- Dilution
- g2p simulation
  - Match data with simulation
Summary for GEp Analysis status

Asymmetries 1.1 GeV

![Graph showing asymmetries with χ²/ndf = 65.92/89 and p0 = 0.02115 ± 0.000596]

Asymmetries 2.2 GeV

![Graph showing asymmetries with χ²/ndf = 69.28/60 and p0 = 0.02468 ± 0.0004062]

### Experimental asymmetries

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Q² (GeV²)</th>
<th>Cut I</th>
<th>Cut II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.013</td>
<td>2.11</td>
<td>2.8</td>
</tr>
<tr>
<td>1.7</td>
<td>0.027</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>2.2</td>
<td>0.045</td>
<td>1.78</td>
<td>1.5</td>
</tr>
<tr>
<td>2.2</td>
<td>0.065</td>
<td>2.47</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- Asymmetries behave as expected, although too low, probably due to dilution analysis procedure.
- Final uncertainties expected to be ~1%-2% statistical and ~3% systematical.
g2p collaboration

Spokesperson
Alexander Camsonne
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Ellie Long
James Maxwell

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Ryan Zielinski

Thank You!
Pengjia Zhu

GEp collaboration

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Douglas Higinbotham
Guy Ron
John Arrington
Ronald Gilman

Graduate Student
Moshe Friedman
backup
g2p motivation

- BC Sum Rule

\[ \int_0^1 g_2(x, Q^2) \, dx = 0 \]

![Graph showing data points for g2p projected, with labels for SLAC E155x, Hall C RSS, Hall A E94-010, Hall A E97-110 (preliminary), and Hall A E01-012 (preliminary).]
g2p motivation

- $\delta_{LT}$ is seen as a more suitable testing ground of $\chi$PT – insensitive to $\Delta$ resonance
- Significant disagreement between data and both $\chi$PT calculations
- No proton data yet

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 [g_1 + g_2] dx$$
**g2p motivation**

**Hydrogen Hyperfine Splitting**

\[
\Delta E = (1 + \delta) E_F \\
\delta = \delta_{\text{QED}} + \delta_R + \delta_{\text{small}} + \Delta_S
\]

- \(\Delta_S\) is largest portion of theoretical

\[
\Delta_S = \Delta_Z + \Delta_{\text{pol}}
\]

\[
\Delta_{\text{pol}} = \frac{\alpha m_e}{\pi g_p m_p} (\Delta_1 + \Delta_2)
\]

- \(\delta_{\text{QED}}\): QED radiative correction
- \(\delta_R\): recoil effect
- \(\delta_{\text{small}}\): hardronic/muonic vac pol, weak

\(\Delta_2\) is dominated by low \(Q^2 g_2^p\)
GEp motivation

(Part I)

Recoil Polarization

\[ I_0 P_t = -2\sqrt{\tau(1 + \tau)} G_E G_M \tan \frac{\theta_e}{2} \]

\[ I_0 P_l = \frac{E_e + E_{e'}}{M} \sqrt{\tau(1 + \tau)} G_M^2 \tan^2 \frac{\theta_e}{2} \]

\[ R \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan \frac{\theta_e}{2} \]


\(~1\%\) uncertainty at \(Q^2\sim 0.3 - 0.7\) GeV\(^2\)
GEp motivation

~2%-3% uncertainty at $Q^2 \sim 0.015 - 0.06 \text{ GeV}^2$
Experimental setup

1 beam current monitor
2 fast raster
3 slow raster
4 tungsten calorimeter
5 moller polarimeter
6a super harp(named 1H04)
6b super harp(named 1H05A)
7 chicane dipole
8a beam position monitor(BPM A)
8b beam position monitor(BPM B)
9 NH3 target
10 septum magnet
11 local beam dump
12 third arm detector
13 high resolution spectrometer's dipole and quadrocles
14 high resolution spectrometer's detectors

Beam direction:
50~100nA for g2p, 5~10nA for gep
Beam position reconstruction

- **BPM Calibration**
  - 2Hz software filter
  - get better resolution
  - Current vs ADC value fit at same position
    - $\phi = f(A - A_{ped}) = a(A - A_{ped} + b)$
  - remove current effect
- BPM pedestal fluctuation during experiment
  - use nearest pedestal value for each run

- **Beam position reconstruction at target**
  - Fitted function using target field map to transport position from BPMs to target
  - Event by event position and angle at target position
    - \( X = \langle X_{BPM} \rangle + X_{\text{fast}} + X_{\text{slow}} \)
  - Use Carbon hole to calibrate slow raster

- **Uncertainty**
  - Best situation: 1mm for position, 1.1mrad for angle
  - Main uncertainty part:
    - Pedestal fluctuation
    - Too close for two BPMs - 95.5cm vs 69cm upstream of target
Matrix Calibration: Angle

Before Calibration

After Calibration

Resolution: 1.6mrad (RMS)
Matrix Calibration: Momentum

**Before Calibration**

**After Calibration**

RMS: $1.5 \times 10^{-4}$
Matrix Calibration: y

Before Calibration

After Calibration

Red: y calculated from survey
Black: y from reconstruction

RMS: 3.3mm
HRS Optics - with field

- Know beam position at reaction point, the position of sieve slit hole, and target field map
  - Get the effective angle at sieve slit
  - Linear backward position at sieve to target plan to get effective position
  - Fit matrix between effective variables and focal plan variables

- Reconstruction for each production run:
  - Use fitted matrix to get effective variables at target plan for each event
  - Linear forward to sieve position
  - Use field map to traject the effective variables to real reacting variables
Packing fraction -> effective NH3 target thickness
NH3 beads filled by liquid He

Define: \( p_f = 1 - \frac{Y_{in}}{Y_{tg}} \)

\[ Y_{in}^{He} = \frac{l_{tg}}{l_{tot}} Y_{dummy} \]
Yield from He inside cell if only He in cell

\[ Y_{tg} = Y_{prod} - Y_{out}^{He} \]
Yield from materials within the target cell

\[ Y_{out}^{He} = \frac{l_{tot} - l_{tg}}{l_{tot}} Y_{dummy} \]

\( Y_{prod}, Y_{dummy} \) From N and He elastic peak

Assumes uniform acceptance throughout

\[ l_{tot}, target \ nose \]
\[ l_{tg}, target \ cell \]
Dilution

\[ A_{\text{raw}} = \frac{Y_+ - Y_-}{Y_+ + Y_- + bg} \]

\[ A_{\text{phy}} = \frac{1}{P_b P_t D} * A_{\text{raw}} \]

\[ D = 1 - \frac{Y_N + Y_{He} + Y_f}{Y_{total}} \]

- \(Y_{+/-}\) Yield from proton
- \(bg = Y_N + Y_{He} + Y_f\) Yield from N, He, foil
- \(P_b P_t\) Polarization of beam and target
- \(D\) Dilution factor

Empty target

Dummy target

Carbon target

NH3 target

\[ Y_f = Y_{\text{dummy}} - Y_{\text{empty}} \]

\[ Y_{He} = (1 - p_f) \alpha Y_{\text{empty}} \]

\[ Y_N = \gamma p_f \frac{\rho_N l_{tg} M_C}{\rho_C l_C M_N} \left( Y_C - \left(1 - \frac{l_C}{l_{tg}}\right) \beta Y_{\text{empty}} \right) \]

\(\alpha, \beta, \gamma\) Used to scale material radiation lengths

From carbon nitrogen xs ratio
Dilution

Current result:
3.350GeV 5T Transverse Dilution result

• Still Ongoing