G2P(E08-027)

Status Update

Jixie Zhang
For g2p Collaboration

Hall A Collaboration Meeting, June 2012
Inclusive Scattering

Inclusive Polarized Cross Section:

\[
\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott} \left[ \frac{1}{\nu} F_2(x, Q^2) + \frac{2}{M} F_1(x, Q^2) \tan^2 \frac{\theta}{2} + \gamma g_1(x, Q^2) + \delta g_2(x, Q^2) \right]
\]
How to get $g_2$?

Need to measure inclusive polarized cross section differences !!!

(through absolute cross section and asymmetry)

\[
\frac{d^2 \sigma^{\uparrow \uparrow}}{d\Omega dE'} - \frac{d^2 \sigma^{\downarrow \uparrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2} \frac{E'}{E} \left[ (E + E' \cos \theta) g_1 - 2M x g_2 \right]
\]

\[
\frac{d^2 \sigma^{\uparrow \Rightarrow}}{d\Omega dE'} - \frac{d^2 \sigma^{\downarrow \Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2} \frac{E'}{E} \sin \theta \left[ g_1 + \frac{2ME}{\nu} g_2 \right]
\]
E08-027 Experiment
Proton g2 Structure Function

Primary Motivation

Measure the proton $g_2$ structure function at low or moderate $Q^2$(for the 1$^{\text{st}}$ time).

This will help to clarify several puzzles:

- **Test the Burkhardt-Cottingham sum rule at low $Q^2$**.

- **Extract the generalized longitudinal-transverse spin polarizability $\delta_{LT}$, allows to test Chiral Perturbation Theory ($\chi$PT)**

- **Hydrogen HyperFine Splitting :**
  Lack of knowledge of $g_2$ at low $Q^2$ is one of the leading uncertainties.

- **Proton Charge Radius :**
  One of the leading uncertainties in extraction of $<R_p>$ from $\mu$–H Lamb shift.
Local Dump

Septum

Purpose:
- Transverse target field
- Low beam current
- Low $Q^2$

Chicane

Polarized Target

Upside-down Girder
• Only 2 pairs of coils (00-48-16) turns was used in PREX
• Added 3rd pair of coils: 48-48-16 (can bend 2.82 GeV particles when run at 950A).
• 2 one-inch iron shims were added to each side, one on the top and the other at the bottom, to bend 2.89 GeV particles when run at 950 GeV.
• Left septum connected to HKS power supply (thanks to Hall-C) and right septum to BigBite power supply.
• Right septum short grounded after 3 weeks of running and repaired as 40-32-16 turns of top coils, down coils were not changed
• 2 weeks later, right septum short grounded again and the top coils were repaired to be 40-00-16 coils.
$M_p < W < 2 \text{ GeV}$

$0.02 < Q^2 < 0.2 \text{ GeV}^2$
Projected Results

LT Spin Polarizability

BC Sum Integral $\Gamma_2$

Projected Results

$\delta_{LT}$ [10^{-4} fm^4]

$Q^2$ (GeV^2)

data not taken
Polarized Ammonia Target

Dynamic Nuclear Polarization of $\text{NH}_3$

Has performed remarkably well after target group transplanted the Hall B coil package

5.01 T/ 140 GHz or 2.5 T/70 GHz operation

Helmholtz superconduct magnet

1K $^4\text{He}$ evaporation refrigerator

Cooling power: about 1 W

Microwave Power

$>1\text{W at 140 GHz}$

See Josh’s talk for details
Third Arm

- Measure the asymmetry of the elastic recoil proton
- Relative measurement of the product $P_B P_T$
- Non-magnetic: sampling set by the trigger threshold
- Very useful as an independent beam quality monitor.

courtesy Kalyan Allada and Chao Gu
Optics for g2p

- Goals:
  - About 1% uncertainty of scattering angle (require good accuracy of $\phi_{tg}$ (horizontal) $\theta_{tg}$ (vertical))
  - A few $10^{-4}$ precision of momentum
  - NEW g2p “I vs $P_0$” setting of HRS Quads from SNAKE tuning and
  - NEW g2p optics matrix for online analysis based on SNAKE tuning.
  - Straight through calibration is closed to finish (good for no target field data only).
- Strategy for data with the target field:

  Focus plane to target plane straight through reconstruction → linear project to sieve plane → sieve to target reconstruction (get matrix from simulation, will be calibrate with real data)
Before calibration:

- $Dp = -3.5\%$
- $Dp = +3.5\%$

After calibration (no target field):

- $Dp = -3.5\%$
- $Dp = +3.5\%$

courtesy Min Huang
$\theta_{tg}$ vs $\phi_{tg}$ after calibration (no target field)

Projected to Sieve Plane

Courtesies Min Huang
Initial perfect design: 48-48-16 coils (top) & 16-48-48 (bottom)

Left almost no change;
Right septum is not symmetric in Y any more, top is ~6.3% lower than bottom

After first broken: 40-32-16 coils (top) & 16-48-48 (bottom)

After 2<sup>nd</sup> repair: 40-00-16 coils (top) →

Field at the top of left septum top is about 1% smaller than that at the bottom, while ~10% at the right septum at 800A, (~12% at 950A)
Right HRS Optics

\( \theta_{tg} \) vs \( \phi_{tg} \)

Right Septum field is no longer symmetric in vertical (y)

courtesy Min Huang
Asymmetry

Very Very Preliminary!

Longitudinal 5T Physics Asymmetry at E=2254MeV

Transverse 5T Physics Asymmetry at E=2254MeV

courtesy Toby Badman
• We managed to accomplished most of our physics goals.

• This is the first time for the polarized amonia target system used in Hall-A. It worked very well. Average target polarization is about 30% at 2.5T and 75% at 5.0T target field. (See Josh’s talk for details).

• DAQ system was improved to take data at 6~7 kHz with <30% deadtime (see Ryan’s talk for detail).

• Beamline diagnostics worked well in range 50-100 nA. (See Pengjia’s talk for details).

• A transverse target field was added into the optics matrix for the first time, which make it really challenge.

• Will provide the definitive measurement of $g_2$ at low $Q^2$. 
Back up
Reasons for delay

A few minor mechanical setbacks delayed the start of the experiment by 149 days

Redesigned/Replaced/Repaired
- Polarized target magnet
- Chicane bellows
- Right Septa Magnet: fire
- Add shims to both Septa at last minute
- Local Dump Cooling
- Harp: wires broken ...

Thanks to all amazing supports!!!
The main uncertainties originate from the proton polarizability, and from different values of the Zemach radius.

**Polarizability**: Integrals of $g_1$ and $g_2$ weighted by $1/Q^4$

**Zemach radius**: Integral of $G_E G_M$ weighted by $1/Q^2$

Dominated by Kinematic region of E08-027 and E08-007
Proton $g_2$ data from SLAC

$Q^2 \approx 5 \text{ GeV}^2$

Precision does not allow unambiguous HT extraction
Proton $g_2$ data from JLAB SANE

$Q^2 \approx 3-6$ GeV$^2$

Leading Twist

very Preliminary
Stat Errors only

Generated by James Maxwell on 08/08/2011
RSS Experiment (Spokesmen: Rondon and Jones)

Q^2 = 1.3 GeV^2

\[ \Delta \Gamma_2 = -0.0006 \pm 0.0021 \] (proton)
consistent with zero
=> low x HT are small in proton.

\[ \Delta \Gamma_2 = -0.0092 \pm 0.0035 \] (neutron)
non-zero by 2.6\sigma

=> Significant HT at low x
needed to satisfy Neutron BC sum rule.

K.S., O. Rondon et al.
PRL 105, 101601 (2010)
Projected Results

BC Sum Rule

Spin Polarizability $\delta_{LT}$
Contribution to Hyperfine Splitting

![Graph showing contributions to Hyperfine Splitting](image)

- \( \Gamma_2^p \)
- \( B_2 \)
- Integrand of \( \Lambda_2 \)
Out of plane scattering angle

The 5T magnet field distorts the scattering plane much more than initial simulations revealed, especially at low momentum.

Effect discovered by Jixie Zhang (Geant4). confirmed by Min Huang (Snake), John Lerose
Spin Polarizabilities

Major failure (>8σ) of χPT for neutron δLT. Need g2 isospin separation to solve.

\[ \gamma_0(Q^2) = \left( \frac{1}{2\pi^2} \right) \int_{\nu_0}^{\infty} K(\nu, Q^2) \frac{\sigma_{TT}(\nu, Q^2)}{\nu^3} d\nu \]
\[ = \frac{16\alpha M^2}{Q^6} \int_{0}^{x_0} x^2 \left[ g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2) \right] dx. \]

\[ \delta_{LT}(Q^2) = \left( \frac{1}{2\pi^2} \right) \int_{\nu_0}^{\infty} K(\nu, Q^2) \frac{\sigma_{LT}(\nu, Q^2)}{\nu^{\nu^2}} d\nu \]
\[ = \frac{16\alpha M^2}{Q^6} \int_{0}^{x_0} x^2 \left[ g_1(x, Q^2) + g_2(x, Q^2) \right] dx. \]

this is the region we should start to be able to trust χPT
Assumptions:

the virtual Compton scattering amplitude $S_2$ falls to zero faster than $1/x$
$g_2$ does not behave as $\delta(x)$ at $x=0$.

Discussion of possible causes of violations


“If it holds for one $Q^2$ it holds for all”
BC Sum Rule

BC satisfied w/in errors for JLab Proton 2.8σ violation seen in SLAC data

BC satisfied w/in errors for Neutron

BC satisfied w/in errors for \(^3\text{He}\)
Spin Polarizabilities

Major failure (>8σ) of $\chi$PT for neutron $\delta_{LT}$

Low $Q^2$ region is the one we should start to be able to trust $\chi$PT
Spin Polarizabilities

Neutron

Heavy Baryon $\chi$PT Calculation
Kao, Spitzenberg, Vanderhaeghen

Relativistic Baryon $\chi$PT
Bernard, Hemmert, Meissner

Dramatic Failure of ChiPT

\[ \gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right] \]

\[ \delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 + g_2 \right] \]
New Data on the Neutron Polarizabilities

Large discrepancy with $\delta_{LT}$ remains

Plots courtesy of V. Sulkosky
Calculations also fail for proton $\gamma_0$

$$\gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right]$$
LT Spin Polarizability

Kochelev & Oh. arxiv:1103.4892. (2011)
Improves agreement with neutron,

No data yet on proton LT polarizability
The finite size of the nucleus plays a small but significant role in atomic energy levels.

Hydrogen HF Splitting

\[ \Delta E = 1420.405\,751\,766\,7(9) \text{ MHz} \]
\[ = (1 + \delta)E_F \]

\[ \delta = (\delta_{QED} + \delta_R + \delta_{small}) + \Delta_S \]

**Finite Size Effects**

**Hydrogen HyperFine Splitting** :
Lack of knowledge of $g_2$ at low $Q^2$ is one of the leading uncertainties.

**Proton Charge Radius** :
One of the leading uncertainties in extraction of $<R_p>$ from $\mu$–H Lamb shift.

The finite size of the nucleon (QCD) plays a small but significant role in calculating atomic energy levels in QED.

\[ \Delta_S = \Delta_Z + \Delta_{POL} \]

\[ \Delta_Z = -41.0 \pm 0.5 \text{ ppm} \]

\[ \Delta_{pol} \approx 1.3 \pm 0.3 \text{ ppm} \]

Elastic piece larger but with similar uncertainty.

\[ \Delta_{POL} = 0.2265 \left( \Delta_1 + \Delta_2 \right) \text{ ppm} \]

Integration of \( g_1 \) & \( F_1 \) pretty well determined from \( F_2, g_1 \) JLab data.
Hydrogen Hyperfine Structure

Integrand of $\phi_2$

Dominated by this region due to $Q^2$ weighting

$\Delta_2 = -24m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$

$= -0.57 \pm 0.57$

assuming CLAS model with 100% error

But, $g_2^p$ unknown in this region:

$\Delta_2 = -1.98$  MAID Model
$\Delta_2 = -1.86$  Simula Model

So 100% error probably too optimistic

E08-027 will provide first real constraint on $\Delta_2$
PSI measurement of the RMS proton radius

Spectroscopic measurement of the energy splitting of the $^{2S}_{1/2} - ^{2P}_{1/2}$ levels in muonic hydrogen (Lamb shift).

$$\Delta \tilde{E} = 209.9779(49) - 5.2262 \, r_p^2 + 0.0347 \, r_p^3 \text{ meV}$$
Proton Charge Radius from $\mu P$ lamb shift disagrees with eP scattering result by about 6%

<table>
<thead>
<tr>
<th>$&lt;R_p&gt;$</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamb shift in muonic hydrogen</td>
<td>$0.84184 \pm 0.00067$ fm</td>
<td>R. Pohl et al, Nature, July 2010</td>
</tr>
<tr>
<td>World analysis of eP scattering</td>
<td>$0.897 \pm 0.018$ fm</td>
<td>I. Sick PLB, 2003</td>
</tr>
<tr>
<td>CODATA world average</td>
<td>$0.8768 \pm 0.0069$ fm</td>
<td></td>
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</tbody>
</table>


C. Carlson (W&M): “Something is missing, this is very clear.” [Nature.com]

P. Mohr (NIST): “would be quite revolutionary.” [L.A. Times.]

B. Odom (N.Western): “…very surprised to find strong disagreement.” [N.P.R.]

J. Flowers (N.P.L.): “…could mean a complete rethink of QED”. “…opens door for a theorist to come up with next theoretical leap, and claim their Nobel prize”. [National Geographic, NY Times]
The main uncertainties originate from the proton polarizability, and from different values of the Zemach radius.

Polarizability: Integrals of $g_1$ and $g_2$ weighted by $1/Q^4$

Zemach radius: Integral of $G_E G_M$ weighted by $1/Q^2$

Dominated by Kinematic region of E08-027 and E08-007
Normalized Yields

E=2.2 GeV Left Arm

Nitrogen Elastic
- Proton Elastic/N Q.E.
- Delta Resonance

E-E' (MeV)

courtesy Ryan Zielinski
Target polarization @ 2.5T

Average Polarization >30% at 2.5 Tesla/70 GHz
courtesy James Maxwell
Target Polarization @ 5T

Average Polarization >75% at 5.0 Tesla/140 GHz

courtesy James Maxwell
Massive effort to commission new BPMs, BCMs, Harps, Tungsten Calo to operate Hall a beam at < 100 nA
courtesy Pengia Zhu
Acceptance effects become much more pronounced at low momentum.

E=1.7 GeV

E=2.2 GeV

courtesy Ryan Zielinski
Asymmetries

Transverse 2.5T Physics Asymmetry at E=1157MeV

Transverse 2.5T Physics Asymmetry at E=1711MeV

Transverse 2.5T Physics Asymmetry at E=2254MeV

E=2.2 GeV Elastic

courtesy Toby Badman

VERY VERY PRELIMINARY!
E=2254 MeV Asymmetry

(1/9)A_{\text{par}}
(1/4)A_{\text{perp}}

VERY VERY PRELIMINARY!

courtesy Toby Badman