The $g_{2^p}$ Experiment

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Outline

- Review of physics motivation
- Brief review of experiment setup
- Status of experiment run
Inelastic scattering

- Inclusive unpolarized cross section:

\[
\frac{d^2 \sigma}{d\Omega dE'} = \sigma_{\text{Mott}} \left[ \frac{1}{\nu} F_2(x, Q^2) + \frac{2}{M} F_1(x, Q^2) \tan^2 \frac{\theta}{2} \right]
\]

Structure Function which indicates the parton distribution
Inelastic scattering

• Inclusive polarized cross section:

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

2 addition Structure Function which related to the spin distribution
Motivation

- Measure proton $g_2$ structure function at low $Q^2$ region (0.02–0.2GeV$^2$) for the first time
- Will help to clarify several puzzles:
  - Test the Burkhardt-Cottingham (BC) Sum Rule at low $Q^2$
  - Extract the generalized longitudinal-transverse spin polarizability $\delta_{LT}$ to give a test for Chiral Perturbation Theory ($\chi$PT)
  - Improve the calculation of Proton Hyperfine Splitting
  - Proton charge radius from $uP$ lamb shift disagrees with $eP$ scattering result
Existing Data

SLAC:
- $Q^2 \sim 5\text{GeV}^2$

JLab SANE:
- $Q^2 3\sim 6\text{GeV}^2$
assumed for the electromagnetic form factors fits [20] to our data to evaluate the moments in the measurement, and the unmeasured ('u') portion below.

The inner (outer) error bars represent statistical (total) uncertainties. The uncertainty arising from this approach is estimated to be negligible heavy quark contributions.

*rss fit.*

The Burkhardt-Cottingham (BC) sum rule [32] predicts a divergence of

\[ \sum_{2}^{I} \sigma \sim \frac{1}{x} \]

\[ \Gamma_{Q}^{2} \] vanishes for all \( x \). The elastic contribution is negligible here. We have also estimated [26] to be negligible for the proton - neutron.

The open circle is the measurement truncated moments converge, so there is little difference between our experimental data, and similar values of twist-3 at more than 6 \( Q^{2} \) are also consistent with zero within errors for the proton, which are consistent with the E155 results. The elastic contribution to the deuteron wave function has been removed using the CN and Nachtman truncated moments. The deuteron non-singlet (proton - neutron) contribution as was necessary in some previous analyses [9].

The calculation of the integral. This can be used in comparing with nucleon models. The values of twist-3 results to previous expectation [33] is nearly constant and consistent with zero within errors for the proton, we determined this upper limit by assuming a divergence of

\[ \langle Q^{2} \rangle \]

\[ g_{2} \] RSS Data \[ g_{2} \] RSS Fit \[ g_{2}^{ww} \] RSS Fit

JLab RSS: \( Q^{2} \sim 1.3\text{GeV}^{2} \)

BC Sum Rule

• BC Sum Rule:

\[ \int_{0}^{1} g_2(x, Q^2) \, dx = 0 \]


• BC Sum Rule will fail if \( g_2 \):
  • exhibits non-Regge behavior at low \( x \)
  • exhibits a delta function singularity at \( x=0 \)

BC Sum Rule

- SLAC E155x
- Hall C RSS
- Hall A E94-010
- Hall A E97-110 (preliminary)
- Hall A E01-012 (preliminary)

- BC satisfied within errors for Neutron and $^3$He
- Mostly unmeasured for proton
Generalized Longitudinal-Transverse Polarizability

- Start from forward spin-flip doubly-virtual Compton scattering (VVCS) amplitude $g_{TT}$ and $g_{LT}$

$$\text{Re}[g_{TT}^{\text{non-pole}}(\nu, Q^2)] = \frac{\nu}{2\pi^2} \mathcal{P} \int_{\nu_\pi}^{\infty} \frac{d\nu' K}{\nu'^2 - \nu^2} \sigma_{TT}(\nu', Q^2)$$

$$\text{Re}[g_{LT}^{\text{non-pole}}(\nu, Q^2)] = \frac{1}{2\pi^2} \mathcal{P} \int_{\nu_\pi}^{\infty} d\nu' \frac{\nu' K}{\nu'^2 - \nu^2} \sigma_{LT}(\nu', Q^2)$$

- $g_{TT}$ and $g_{LT}$ can be expanded in power series of $\nu$

$O(\nu^3)$ term of $g_{TT}$ leads to the generalized forward spin polarizability $\gamma_0$

$$\gamma_0(Q^2) = \frac{1}{2\pi^2} \int_{\nu_\pi}^{\infty} \frac{K(\nu, Q^2)}{\nu} \frac{\nu^3}{\nu^3} d\nu$$

$$= \frac{16\alpha M^2}{Q^6} \int_0^{x^0} x^2 [g_1 - \frac{4M^2}{Q^2} x^2 g_2] dx$$

$O(\nu^2)$ term of $g_{LT}$ leads to the generalized longitudinal-transverse polarizability $\delta_{LT}$

$$\delta_{LT}(Q^2) = \frac{1}{2\pi^2} \int_{\nu_\pi}^{\infty} \frac{K(\nu, Q^2)}{\nu} \frac{\sigma_{LT}(\nu, Q^2)}{Q\nu^2} d\nu$$

$$= \frac{16\alpha M^2}{Q^6} \int_0^{x^0} x^2 [g_1 + g_2] dx$$
At low $Q^2$, the generalized polarizabilities have been evaluated with NLO $\chi$PT calculations:


One issue in the calculation is how to properly include the nucleon resonance contributions, especially the $\Delta$ resonance

- $\gamma_0$ is sensitive to resonances
- $\delta_{LT}$ is insensitive to the $\Delta$ resonance
- $\delta_{LT}$ should be more suitable than $\gamma_0$ to serve as a testing ground for the chiral dynamics of QCD
• Neutron Data shows a large deviation from the χPT calculations
• No proton data yet
• This experiment will provide a test with proton data
Hydrogen Hyperfine Structure

- Hydrogen hyperfine splitting in the ground state has been measured to a relative high accuracy of $10^{-13}$

\[ \Delta E = 1420.4057517667(9) \text{MHz} = (1 + \delta) E_F \]

- $\delta = (\delta_{\text{QED}} + \delta_R + \delta_{\text{small}}) + \Delta_S$

- $\Delta_S$ is the proton structure correction and has the largest uncertainty

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

- $\Delta_Z$ can be determined from elastic scattering, which is $-41.0 \pm 0.5 \times 10^{-6}$

- $\Delta_{\text{pol}}$ involves contributions of the inelastic part (excited state), and can be extracted to 2 terms corresponding to 2 different spin-dependent structure function of proton
Hydrogen Hyperfine Structure

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

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

\[ B_2(Q^2) = \int_0^{x_{th}} dx \beta_2(\tau)g_2(x, Q^2) \]

\[ \beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau + 1)} \]

- \( B_2 \) is dominated by low \( Q^2 \) part
- \( g_2^p \) is unknown in this region, so there may be huge error when calculating \( \Delta_2 \)
- This experiment will provide a constraint

Nazaryan, Carlson, Griffieon, PRL, 96(2006)163001
Size of the Proton

- 2 ways to measure:
  - energy splitting of the $2S_{1/2}-2P_{1/2}$ level (Lamb shift)
  - scattering experiment
- The result do not match when using muonic hydrogen
  - $\langle R_p \rangle = 0.84184\pm0.00067$ fm by Lamb shift in muonic hydrogen
  - $\langle R_p \rangle = 0.87680\pm0.0069$ fm CODATA world average
- The main uncertainties originates from the proton polarizability and different values of the Zemach radius
  - This experiment will reduce the uncertainty of proton polarizability

Primary Motivation

Measure proton $g_2$ structure function at $0.02 < Q^2 < 0.2 \text{ GeV}^2$ region with an uncertainty of 5–7%
How to get $g_2$

\[ \Delta \sigma_\parallel = \frac{d^2 \sigma^\uparrow\uparrow}{d\Omega dE'} - \frac{d^2 \sigma^\downarrow\uparrow}{d\Omega dE'} \]

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

JLab Hall B experiment EG4 measured this quantity and extracted $g_1^p$ at low $Q^2$

\[ \Delta \sigma_\perp = \frac{d^2 \sigma^\uparrow\Rightarrow}{d\Omega dE'} - \frac{d^2 \sigma^\downarrow\Rightarrow}{d\Omega dE'} \]

\[ = \frac{4\alpha^2 E'^2}{M \nu Q^2 E} \sin \theta \left[ g_1 + \frac{2E}{\nu} g_2 \right] \]

$g_2^p$ experiment will measure this, combing the EG4 $g_1^p$ data to get $g_2^p$ at low $Q^2$
Updated beam diagnostics:
- Beam position monitor (BPM)
- Beam current monitor (BCM)
- Rasters

Polarized NH$_3$ Target

Hall A High Resolution Spectrometer (HRS)
Experiment Setup

• Challenge: lowest possible $Q^2$
• Small scattering angle ($\sim 6^\circ$)
  - Use septa magnet to detect forward scattering
• Polarized NH$_3$ target: 2.5T~5T magnetic field
  - Use Chicane to provide an incident angle
  - Outgoing beam is not straight: use local dump
• Low current polarized beam
  - Upgrades to existing Beam Diagnostics to work at 50 nA
Kinematics Coverage

- The Experiment was conducted at JLab Hall A successfully from 3/2/2012 to 5/18/2012

- Statistics:

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<tr>
<th>Beam Energy (GeV)</th>
<th>Target Field (T)</th>
<th>Recorded trigger</th>
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<tr>
<td>3.352</td>
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</tbody>
</table>

\[ M_p < W < 2 \text{ GeV} \]
\[ 0.02 < Q^2 < 0.2 \text{ GeV}^2 \]
Online results

E=2254 MeV Normalized Yield

Nitrogen elastic peak
Proton elastic peak
Delta resonance

E=2254 MeV Asymmetry

\[ \Delta \sigma_\perp = \sigma_{\text{total}} \cdot A_\perp \]
Conclusion

• We managed to accomplish most of our physics goals

• New instruments are demonstrated working well during the experiment

• Will provide an accurate measurement of $g_2$ in low $Q^2$ region

• Will also extract the fundamental quantities $\delta_{LT}$ to provide a test of $\chi$PT calculations
Thanks