Spin Structure at Low $Q^2$
with Applications to Hyperfine Splitting

Spin 2018
23rd International Spin Symposium
Ferrara Italy
2018-09-12

Karl Slifer
University of New Hampshire
This Talk

Inclusive double polarized electron scattering

Physics Motivation
- Inclusive Scattering
- Structure Functions
- Results from the g2p & sagdh Experiments
  - Spin Polarizabilities & Moments.
  - Hyperfine Contributions

Tensor Program
- E12-13-011: “The $b_1$ experiment”
- E12-15-005: “$A_{zz}$ for $x>1$”
- LOI-12-16-006: “Nuclear Gluometry”

Technical Developments
Inclusive Scattering

When we add spin degrees of freedom to the target and beam, 2 Additional SF needed.

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

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

\[ \frac{d^2 \sigma^{\uparrow \rightarrow}}{d\Omega dE'} - \frac{d^2 \sigma^{\downarrow \rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2} \frac{E'}{E} \sin \theta \left[ g_1 + \frac{2ME}{\nu} g_2 \right] \]
Proton $g_2$ data from SLAC

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

Precision does not allow unambiguous HT extraction
SANE Proton $g_1$ and $g_2$ $(Q^2 \approx 2-6 \text{ GeV}^2)$

Models are showing $g_2^\gamma\gamma$.

**RSS Experiment**

$Q^2 = 1.3 \text{ GeV}^2$

$\Delta \Gamma_2 = -0.0006 \pm 0.0021$ (proton)

consistent with zero

$\Rightarrow$ low $x$ HT are small in proton.

$\Delta \Gamma_2 = -0.0092 \pm 0.0035$ (neutron)

non-zero by $2.6\sigma$

$\Rightarrow$ Significant HT at low $x$

needed to satisfy Neutron BC sum rule.

K. Slifer., O. Rondon et al.
PRL 105, 101601 (2010)
SSF Moments

Generalized Forward Spin polarizabilities

\[
\Gamma_1(Q^2) = \int_0^{x_0} dx \ g_1(x, Q^2)
\]

\[
\Gamma_2(Q^2) = \int_0^{x_0} dx \ g_2(x, Q^2)
\]

Generalized GDH Sum

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

\[
\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1(x, Q^2) + g_2(x, Q^2) \right] dx
\]
Spin Structure Experiments at Low $Q^2$

Jefferson Lab Hall A

$g^{2p}$

NH$_3$ Target (proton)

$0.02 < Q^2 < 0.4$

$W < 1.8$ GeV

$\theta = 6$ deg

$sagdh$

3He Target (neutron)

$0.02 < Q^2 < 0.4$

$W < 2.5$ GeV

$\theta = 6.9$ deg
BC Sum Rule: violation suggested for proton at large $Q^2$, but found satisfied for the neutron & $^3$He.

Spin Polarizability: Major failure ($>8\sigma$) of $\chi$PT for neutron $\delta_{LT}$

Hydrogen HFS: Structure dependent corrections
**Largest Installation in Hall A History**

**Polarized proton target**
- upstream chicane
- downstream local dump

**Low current polarized beam**
- Upgrades to existing Beam Diagnostics to work at 85 nA

**Lowest possible Q^2 in the resonance region**
- Septa Magnets to detect forward scattering

**Diagram**
- Septa
- Chicane
- Local Dump
- Polarized Target
- New Beam Diagnostics (BPM, BCM, Harps, Tungsten Calo)
E08-027 : Proton $g_2$ Structure Function

5T: Large $Q^2$ data preparing for publication

2.5T: Low $Q^2$ data finalizing

Packing Fraction
courtesy R. Zielinski
Sagdh Experiment

Spokesmen: J.-P. Chen, A. Deur, F. Garibaldi

PhD Students: V. Solkosky, J. Singh, J. Yuan, C. Peng, N. Ton

![Graph showing experimental data with Q^2 vs. W, showing data points and trend lines for different periods and cells.]

<table>
<thead>
<tr>
<th>Target Cell</th>
<th>Angle</th>
<th>Beam Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penelope</td>
<td>6.10°</td>
<td>2134.2</td>
</tr>
<tr>
<td>Priapus</td>
<td>6.10°</td>
<td>2134.9</td>
</tr>
<tr>
<td>Priapus</td>
<td>6.10°</td>
<td>2844.8</td>
</tr>
<tr>
<td>Priapus</td>
<td>6.10°</td>
<td>4208.8</td>
</tr>
<tr>
<td>Priapus</td>
<td>9.03°</td>
<td>1147.3</td>
</tr>
<tr>
<td>Priapus</td>
<td>9.03°</td>
<td>2233.9</td>
</tr>
<tr>
<td>Priapus</td>
<td>9.03°</td>
<td>3318.8</td>
</tr>
<tr>
<td>Priapus</td>
<td>9.03°</td>
<td>3775.4</td>
</tr>
<tr>
<td>Priapus</td>
<td>9.03°</td>
<td>4404.2</td>
</tr>
</tbody>
</table>
sagdh Floor Plan

Hall A Floor Plan

Left HRS
- Pion Rejectors (Pb glass)
- Cerenkov
- VDCs
- Scintillators
- Q1, Q2, Q3
- Shower (Pb glass)

Right HRS
- Laser Hut
- Septum
- Q1
- Scintillators
- Preshower

Compton Polarimeter
Moller Polarimeter

at 18°
To Beam Dump

at 6° or 9°
data

SORRY, WE JUST CAN'T TRUST YOU...
E08-027 Structure Functions (5T data)

\[ Q^2 = 0.08 \text{ GeV}^2 \]

\[ Q^2 = 0.13 \text{ GeV}^2 \]

\[ Q^2 = 0.04 \text{ GeV}^2 \]

Preliminary (but analysis complete)

Figure 8-21: Born spin structure functions for the 5 T kinematic settings.

Figure 8-24: E08-027 spin structure functions.

courtesy R. Zielinski, UNH
g2p 2.5T data

Q^2 = 0.05 GeV^2

Q^2 = 0.02 GeV^2

Q^2 = 0.01 GeV^2

Finalizing df/pf

courtesy R. Zielinski, UNH
Neutron $\Gamma_1$ (saGHD)

BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202
BC Sum Rule

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

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

\[ \Gamma_2(Q^2) = \int_0^{x_0} dx \ g_2(x, Q^2) \]

\(0 < x < 1\)

Mostly unmeasured

Nuclear Sum Rule
$\Gamma_2(Q^2) = \int_0^{x_0} dx \ g_2(x, Q^2)$
E08-027 Proton BC Integral

Unmeasured low $x$ contribution has large uncertainty at low $Q^2$.

=> Difficult to make strong statement on BC with current low $x$ estimates.
Neutron $\Gamma_2$ (saGHD)
Spin Polarizabilities

\[
\gamma_0(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} dx \, x^2 g_{TT}(x, Q^2),
\]

\[
\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} dx \, x^2 \left[ g_1(x, Q^2) + g_2(x, Q^2) \right]
\]

\[
g_{TT} = g_1 - (4M_N^2 x^2/Q^2) g_2
\]

Good Test of ChPT.
Cht respects all symmetries of QCD but its Lagrangian is constructed from hadron degrees of freedom.

Heavy Baryon \(\chi PT\): Treats the Baryon as a heavy static particle
Kao, Vanderhaeghen, et al

Relativistic Baryon: large momentum effects are absorbed in the low energy consts
\(\Delta(1232)\) included explicitly. Other Resonances are included systematically through additional low energy constants

1: Meissner, Bernard, Krebs, Epelbaum
2: Lensky, Alarcon, Pascalutsa
\[ \gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right] \]

\[ \delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 [g_1 + g_2] \]

Dramatic Discrepancy with \( \chi \)PT

**Heavy Baryon ChPT Calculation**
Kao, Spitzenberg, Vanderhaeghen

**Infrared Relativistic Baryon ChPT**
Bernard, Hemmert, Meissner
Older Calcs also failed for proton $\gamma_0$

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

Published data goes down to about 0.06 GeV$^2$
Neutron $\gamma_0$ and $\delta_{LT}$ (saGHD)

BERNARD et al. PRD 87, 054032 (2013)
Lensky et al. PRC 90(2014) 055202
Neutron $\gamma_0$ and $\delta_{LT}$ (saGHD)

BERNARD et al. PRD 87, 054032 (2013)
Lensky et al. PRC 90(2014) 055202

Big disagreement with data
$\delta_{LT}$ Proton (E08-027)

Preliminary

Bernard et. al ($B\chi PT$)

Lensky et al ($B\chi PT$)

$\delta_{LT}(Q^2)[10^{-4} \text{ fm}^4]$

$Q^2 \text{ (GeV}^2\text{)}$

MAID
Hall B
E08-027
**χPT Comparison Summary**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>Pretty good agreement with $\chi$PT calculations</td>
</tr>
</tbody>
</table>
| $\delta_{LT}$ | Big disagreement for neutron for all calcs
Proton data favors $B_{\chi PT}$ (Lensky et al) |
| $\gamma_0$ | Good agreement for proton for $B_{\chi PT}$ (Lensky et al)
Decent agreement for neutron for $B_{\chi PT}$ (Bernard et al) |

Some tension remains between data and $\chi$PT
Some tension remains between $\chi$PT calculations
Hyperfine Splitting
Hydrogen Hyperfine Splitting

- Higher energy state
- Spin flip

1420 MHz
\( \lambda = 21 \text{ cm} \)

Hydrogen hyperfine structure

1s

5.9 \( \times \) 10^{-6} \text{ eV}

1420 MHz
\( \lambda = 21 \text{ cm} \)
Hydrogen Hyperfine Splitting

Discovery of 21 cm line → birth of radio astronomy
First evidence for existence of dark matter
The finite size of the nucleus plays a small but significant role in atomic energy levels.

Hydrogen HF Splitting

$$\Delta E = 1420.405\,751\,766\,7(9)\,\text{MHz}$$

$$= (1 + \delta)E_F$$
The finite size of the nucleus plays a small but significant role in atomic energy levels.

Hydrogen HF Splitting

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

\[ = (1 + \delta)E_F \]

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

Elastic Scattering

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

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

\[ \Delta_Z = -2 \alpha m_e r_Z (1 + \delta^\text{rad}_Z) \]

\[ r_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[ G_E(Q^2) \frac{G_M(Q^2)}{1 + \kappa_p} - 1 \right] \]
Structure dependence of Hydrogen HF Splitting

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

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

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

Elastic piece larger but with similar uncertainty

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

integral of \( g_1 \) & \( F_1 \)

pretty well determined from JLab data
Structure dependence of Hydrogen HF Splitting

\[ \Delta S = \Delta Z + \Delta_{POL} \]

Inelastic

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

Elastic piece larger but with similar uncertainty

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

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

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

weighted heavily to low $Q^2$
Hydrogen Hyperfine Structure

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

\[ = -0.57 \pm 0.57 \]

assuming CLAS model with 100% error
Δ₂ = \(-24m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)\)

= \(-0.57 \pm 0.57\)

assuming CLAS model with 100% error

But, \(g_2^p\) unknown in this region:

\(\Delta_2 = -1.98\) \hspace{1cm} \text{MAID Model}

\(\Delta_2 = -1.86\) \hspace{1cm} \text{Simula Model}

So 100% error probably too optimistic

E08-027 will provide first real constraint on \(\Delta_2\)

Dominated by this region due to \(Q^2\) weighting
g_2 contribution to the Hyperfine Splitting

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

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

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

- Dev. from leading twist expected
- Agreement within uncertainty to two models
good agreement with the MAID and most recent Hall B models

200% difference from Hall B 2007 model used in PRA78, 02251
Tensor Spin Observables

E12-13-011: “The $b$, experiment”
30 Days in Jlab Hall C
A- Physics Rating
Conditional Approval (Target Performance)
Contact: K. Slifer, UNH

E12-15-005: “$A_{zz}$ for $x>1$”
44 Days in Jlab Hall C
A- Physics Rating
Conditional Approval (Target Performance)
Contact: E. Long, UNH
$b_1 = -\frac{3}{2} F_1^d A_{zz}$

$A_{zz} = \frac{2}{f P_{zz}} \frac{\sigma_+ - \sigma_0}{\sigma_0}$

$T_{20} \approx \frac{A_{zz}}{d_{20} \sqrt{2}}$
JEFFERSON LAB E12-15-005

See Ellie Long’s Talk

Long (Contact), Slifer, Solvignon, Day, Higinbotham, Keller

Projected Results for $P_{zz} = 35\%, 30$ Days

- Measure tensor $A_{zz}$ in the $x>1$ Region, and $T_{20}$
- Very large Tensor Asymmetries predicted
- Sensitive to the S/D-wave ratio
- $4\sigma$ discrim between hard/soft wave functions
- $6\sigma$ discrim between relativistic models
- $A^-$ rating, Conditional on target performance

“further explores the nature of short-range pn correlations, the discovery of which was one of the most important results of the 6 GeV nuclear program.”

PAC44 Theory Report
• Measure leading twist tensor structure function $b_1$ with a solid ND$_3$ target in Jlab Hall C
• $b_1$ allows to discriminate between deuteron components with different spins (quarks/gluons)
• Provides a unique probe of 6 quark hidden color effects
• Verification of the zero crossing essential for satisfaction of Close-Kumano Sum
• A- physics rating, Conditional on target performance
Gluon Contribution to Tensor Structure

Efremov and Teryaev (1982, 1999)

Gluons (spin 1) contribute to both moments

Quarks satisfy the first moment, but

Gluons may have a non-zero first moment!

\[ \int b_1(x) \, dx = 0 \]
\[ \int x b_1(x) \, dx = 0 \]

A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)
Gluons (spin 1) contribute to both moments

Quarks satisfy the first moment, but

Gluons may have a non-zero first moment!

$2^{nd}$ moment more likely to be satisfied experimentally since the collective glue is suppressed compared to the sea

Study of $b_1$ allows to discriminate between deuteron components with different spins (quarks vs gluons)

Efremov, Teryaev (1982, 1999)


A.V. Efremov, O.V. Teryaev JINR-E2-94-95 (1999)

James Maxwell (contact), R. Milner, …

“Nuclear Gluonometry”

Look for novel gluonic components in nuclei that are not present in nucleons

Non-zero value would be a clear signature of exotic gluon states in the nucleus

Deep inelastic scattering experiment:
- Unpolarized electrons
- Polarized $^{14}$NH$_3$ Target
- Target spin aligned transverse to beam

$\Delta(x,Q^2)$ double helicity flip structure function

Encouraged for full submission by PAC44
Technical Developments
**Tensor Polarized Target**

*MC overlap with d-butanol. NMR experimental points (Pn=51→45, Qn=20→31%)*

**Significant progress at UVa**

Enhancing $P_{zz}$ via semi-selective saturation & understanding the NMR lineshape


$T_{20}$ measurement at Higgs to verify NMR analysis
Achieved so far

- Before recent research (1984): ~20%
- Recent studies SSS (2014-2015): ~30%
- AFP with SSS (2016): ~34%
- Rotation SSS so far: ~38% (neg Q possible)

Still more to come, we can probably do much better than this by improving B/T should expect Q>>40%
2 faculty
- K. Slifer & Ellie Long

1 post-doc to hire

3 grad students:
-- David R: significant time
-- Nathalie S.: partial time
-- Michael S.: full time

lots of undergrads

Projects

- Polarized Target Material Production & Labview controls for E1039

- Tensor Polarization R&D
UNH He Evaporation Refrigerator

All Machining at UNH
✓ Heat Exchanger
✓ Separator Pot
✓ Radiation Baffles
✓ Needle valves
✓ Vacuum Shells

Welding done off-site at Lesker

UNH Machinist
Phil DeMaine

(assemb “upside down”)
Complete Fridge

Vacuum shell assembly

LHe Cooldown in Feb and Apr

Achieved 1 K in new fridge

All Machining at UNH
✓ Heat Exchanger
✓ Separator Pot
✓ Radiation Baffles
✓ Needle valves
✓ Vacuum Shells

Welding done off-site at Lesker
Reached 1K/7T
Have Working NMR system
Developed high vacuum expertise
Just Completed Commissioning of a new fridge
Still assembling the microwave subsystem
Vapor Pressure

T = 1.2K

Calibrated thermistor

CCS target temperature

CCS target temperature and Flow Rates
**Status**

- Gas line completed
- System completely contained in fume hood

- We produced about 200 grams of NH₃ so far for E1039
Target Material Production at UNH

- We produced about 200 grams of NH₃ so far for E1039
- Aiming for 1 kg by end of year.
Tensor Polarization progress

- $P_{zz} \approx 12\%$ (Butanol)
  - $A_{zz}$ approved C1
  - $b_{1}$ approved C1

- $P_{zz} \approx 20\%$ (Butanol)
  - $A_{zz}$ approved C2

- $P_{zz} > 30\%$ (Butanol)
  - $A_{zz}$ approved C1

- $P_{zz} \rightarrow 40\%$ (Butanol+ND3,LID)
  - Remove Conditional
Summary

$g_{2p}$

Hyperfine splitting contributions from $g_2$ very different from previous model pred

Large $Q^2$ data finalized. Low $Q^2$ data we are still working on PF systematics.

$\delta_{LT}$ favors Lensky et al ($B\chi$PT)

$sagdh$

neutron $\delta_{LT}$ results can not be understood by any existing calculation

Analysis finalized. Publication soon to follow.

Tensor Program/Target

E12-13-001: $b_1$ of the Deuteron (systematics suppressed by $1/P_{zz}$)

E12-14-002: $A_{zz}$ for $x>1$ (HUGE asymmetries expected)

LOI12-14-001: Tensor Structure Function $\Delta$

High tensor polarizations demonstrated with SSS and rotation: $P_{zz} \rightarrow 40$

Dramatic improvement in statistic and systematic uncertainties.

No reason this represents a limit. Much higher polarizations may be possible.

UNH target lab soon fully functional.