Nucleon Spin Structure Measurements with Lepton Beams at Low $Q^2$

Spin 2016
Champaign, Il
9/27/2016

Karl Slifer
University of New Hampshire
This Talk

Brief Review

Inclusive Scattering & Structure Functions
Spin Polarizabilities & Moments.

Jlab Data

Halls A, B & C
0.04 < Q^2 < 6 GeV^2

JLab Tensor Structure Program

E12-13-011: “The b_1 experiment”
E12-15-005: “A_{zz} for x>1”
Inclusive Scattering

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

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

Inclusive Polarized Cross Section
Cross Section Differences

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

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

\[
\frac{d^2 \sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2 \sigma^{\downarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2} \frac{E'}{E} \sin \theta \left[g_1 + \frac{2ME}{\nu} g_2\right]
\]
Moments

Spin polarizabilities

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

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

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

Spin polarizabilities

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

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

$$\bar{d}_2(Q^2) = \int_0^{x_0} dx \, x^2 \left[ 2g_1(x, Q^2) + 3g_2(x, Q^2) \right],$$

Color polarizability

$$g_{TT} = g_1 - \left( 4M_N^2 x^2 / Q^2 \right) g_2$$
Moments

Spin polarizabilities

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

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

\[ \bar{d}_2(Q^2) = \int_0^{x_0} dx \, x^2 \left[ 2g_1(x, Q^2) + 3g_2(x, Q^2) \right], \]

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

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

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

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

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

$$\bar{d}_2(Q^2) = \int_0^{x_0} dx \, x^2 \left[ 2g_1(x, Q^2) + 3g_2(x, Q^2) \right],$$

$$I_A(Q^2) = \frac{2M_N^2}{Q^2} \int_0^{x_0} dx \, g_{TT}(x, Q^2),$$

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

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

Generalized GDH

Burkhardt Cottingham

$$g_{TT} = g_1 - \left(4M_N^2x^2/Q^2\right)g_2$$
Thanks to these Collaborations

**EG4 Proton**: M. Ripani (Contact), M. Battaglieri, A. Deur, R. De Vita

**EG4 Deuteron**: A. Deur (Contact), G. Dodge, K. Slifer

**g2p**: K. Slifer (contact), JP Chen, D. Crabb, A. Camsonne

**sagdh**: JP Chen (contact), A. Deur

**SANE**: O. Rondon (contact), M. Jones

**E94010**: Z. Meziani (contact), G. Cates, JP Chen
Neutron 1$^{\text{st}}$ Moment

See talk of Chao Peng, A. Deur
Proton 1\textsuperscript{st} Moment

Plot courtesy of H. Kang (EG4)
Deuteron $1^{st}$ Moment

$\Gamma_1^d$

Plot courtesy of K. Adhikari (EG4)
Neutron GDH Integral

Plot courtesy of K. Adhikari (EG4)
\[ \gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[ g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right] \]

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

\[ \text{Dramatic Discrepancy with } \chi\text{PT} \]

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

Relativistic Baryon $\chi$PT
Bernard, Hemmert, Meissner
Proton $\gamma_0$

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

Older Calcs also failed for proton $\gamma_0$

PLB 672 12, 2009

published data goes down to about 0.06 GeV$^2$
\( P-N \) and \( P+N \) \( \gamma_0 \)

and for isoscalar isovector combinations

Neutron $\gamma_0$

BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

See talk of Chao Peng
Neutron $\delta_{LT}$

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

See talk of Chao Peng
Proton $\gamma_0$

Lensky, Alarcon, Pascalutsa.
PRC 90(2014) 055202

NLO: Blue Band

$\chi$PT: good agreement with the proton $\gamma_0$

Proton $\delta_{LT}$


NLO: Blue Band

$B\chi PT$ : good agreement with the proton $\gamma_0$

$B\chi PT$ : reasonable agreement with MAID model for $\delta_{LT}$

$\delta_{LT}$ puzzle Solved? Need data to confirm data anticipated from EG4+g2p experiments
Deuteron $\gamma_0$

\[ g_1^D = \left(1 - \frac{3}{2}\omega_D\right)(g_1^p + g_1^n) \]

Plot courtesy of K. Adhikari (EG4)
Spin Polarizabilities Summary

1st moments: Pretty good agreement with chPT calculations

δ_{LT}: Pretty good agreement for neutron
waiting on proton data

γ_{0}: Proton looks good
Neutron (Deutron) big discrepancy

What can be done from Experimental side?

δ_{LT} proton data
Higher order generalized spin polarizabilities?
We can evaluate these higher moments for neutron, proton and He-3 down to below $Q^2=0.05$.
Higher Order Forward Spin Polarizabilities

$$\gamma_0 = \frac{1}{2\pi^2} \int_{\nu_0}^\infty \frac{\sigma_{TT}(\nu, Q^2)}{\nu^5} d\nu$$
Higher Order Forward Spin Polarizabilities

$^3\text{He}$ higher moments

$$\int_{x_0}^0 dx \ x^2 \ g_{1^{3\text{He}}}(x, Q^2)$$

$$\int_{x_0}^0 dx \ x^2 \ g_{2^{3\text{He}}}(x, Q^2)$$

Free from Nuclear Corrections

Unpublished
Would love to get theory curves on these plots. Any Interest??
EG4 Target & Double-Spin Asymmetry

\[ A_{LL} \]

\[ \vec{e}\bar{p} \rightarrow e\pi^+(n) \]


Accepted Phys. Rev. C (2016)
EG4 Target & Double-Spin Asymmetry

\[ A_{UL} \]

\[ \vec{e}p \rightarrow e\pi^+(n) \]


Accepted Phys. Rev. C (2016)
Proton $x^2g_1$ and $x^2g_2$
SANE Proton results for $x^2g_1$ and $x^2g_2$

Plot courtesy of W. Armstrong (SANE)
SANE Proton results for $d_2$
E08-027 : Proton $g_2$ Structure Function

Camsonne, Crabb,
Chen, Slifer

**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 $\delta_{LT}$
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
E08-027 Highlights & Prelim Results

Acceptance and Dilution Analysis ongoing

Most other tasks complete
Longitudinal 5T Physics Asymmetry at $E=2254\text{MeV}$

Transverse 5T Physics Asymmetry at $E=2254\text{MeV}$

$\langle Q^2 \rangle \approx 0.1 \text{ GeV}^2$

courtesy Toby Badman (UNH)
E08-027 Highlights & Prelim Results

Polarized Structure Functions, Kinematic Set L

g^0_2 Collaboration, Dec. 2 2015
Preliminary radiative corrections
Model input for unpolarized XS
Preliminary systematics
Preliminary dilution factor and packing fraction

Very Preliminary

courtesy M. Cummings (W&M)
Projections

LT Spin Polarizability

BC Sum Integral $\Gamma_2$

- Lensky et al. NLO
- Bernard et al. (VM+Δ)
- Bernard et al.
- Kao et al. O(p^3 + p^4)
- MAID
- E08-027 Projected

- Elastic
- MAID
- E155x (Total)
- RSS (Resonance)
- RSS (Total)

SANE Coverage
E12-13-011: “The $b_1$ experiment”  
30 Days in Jlab Hall C  
A- Physics Rating  
Conditional Approval (Target Performance)

E12-15-005: “$A_{zz}$ for $x>1$”  
44 Days in Jlab Hall C  
A- Physics Rating  
Conditional Approval (Target Performance)
Inclusive Scattering

Construct the most general Tensor $W$ consistent with Lorentz and gauge invariance

Frankfurt & Strikman (1983)
Hoddbhoy, Jaffe, Manohar (1989)

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu}$$

Unpolarized Scattering

$$+i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)$$

Vector Polarization
Tensor Structure Functions

Construct the most general Tensor $W$ consistent with Lorentz and gauge invariance

Frankfurt & Strikman (1983)
Hoodbhoy, Jaffe, Manohar (1989)

\[
W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu} \\
+ i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma) \\
- b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\
+ \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) \]

Tensor Polarization
Tensor Structure Functions

Construct the most general Tensor $W$ consistent with Lorentz and gauge invariance

Frankfurt & Strikman (1983)
Hoodbhoy, Jaffe, Manohar (1989)

\[ W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu} + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma) - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) \]

Tensor Polarization

Caution: There is an alternate similar formulation by Edelmann, Piller, Weise
# Tensor Structure Functions

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>$\frac{1}{3} \sum_q e_q^2 [q_\uparrow^1 + q_\uparrow^{-1} + q_\uparrow^0]$</td>
</tr>
<tr>
<td>$g_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_\uparrow^1 - q_\downarrow]$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$\frac{1}{3} \sum_q e_q^2 [q_\uparrow^0 - q_\downarrow]$</td>
</tr>
</tbody>
</table>

$F_1$ : quark distributions averaged over target spin states  
$g_1$ : difference of distributions of quarks aligned/anti-aligned with hadron  
$b_1$ : difference of helicity-0/helicity non-zero states of the deuteron
# Tensor Structure Functions

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$  $\frac{1}{2} \sum_q e_q^2 [q_{\uparrow}^{1/2} + q_{\uparrow}^{-1/2}]$</td>
<td>$\frac{1}{3} \sum_q e_q^2 [q_1^1 + q_1^{-1} + q_1^0]$</td>
</tr>
<tr>
<td>$g_1$  $\frac{1}{2} \sum_q e_q^2 [q_{\uparrow}^{1/2} - q_{\uparrow}^{-1/2}]$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_1^1 - q_1]$</td>
</tr>
<tr>
<td>$b_1$  $\ldots$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q^0 - q^1]$</td>
</tr>
</tbody>
</table>

$F_1$ : quark distributions averaged over target spin states  
$g_1$ : difference of distributions of quarks aligned/anti-aligned with hadron  
$b_1$ : difference of helicity-0/helicity non-zero states of the deuteron  

$b_2$ : related to $b_1$ by A Callan-Gross relation  

$b_4$ : Also Leading Twist, but kinematically suppressed for a longitudinally polarized target.  

$b_3$ : higher twist, like $g_2$
**b₁ Structure Function**

\[
b₁(x) = \frac{q^0(x) - q^1(x)}{2}
\]

q⁰ : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the **Deuteron** is in state m=0

q¹ : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the **Deuteron** is in state |m| = 1

**Nice mix of nuclear and quark physics**

measured in DIS (so probing quarks), but depends solely on the deuteron spin state

**Investigate nuclear effects at the level of partons!**
$b_1$ Structure Function

Hoodbhoy, Jaffe and Manohar (1989)

$b_1$ vanishes in the absence of nuclear effects

i.e. if...

\[
\text{deuteron} = n + p
\]

Proton Neutron in relative S-state

Even accounting for D-State admixture $b_1$ expected to be vanishingly small

Khan & Hoodbhoy, PRC 44, 1219 (1991) : $b_1 \approx O(10^{-4})$
Relativistic convolution model with binding

Umnikov, PLB 391, 177 (1997) : $b_1 \approx O(10^{-3})$
Relativistic convolution with Bethe-Salpeter formalism
Data from HERMES

C. Reidl PRL 95, 242001 (2005)
Data from HERMES

\[ b_1 = -\frac{3}{2} F_1 A_{zz} \]

C. Reidl PRL 95, 242001 (2005)
no conventional nuclear mechanism can reproduce the Hermes data,

but that the 6-quark probability needed to do so ($P_{6Q} = 0.0015$) is small enough that it does not violate conventional nuclear physics.
The Deuteron Polarized Tensor Structure Function $b_1$

JLAB E12-14-011

A- rating by PAC40

(C1: conditional on target performance)

Spokespersons
Slifer (contact), Solvignon, Long, Chen, Rondon, Kalantarians
Experimental Method

\[ A_{zz} = \frac{2}{fP_{zz}} \frac{\sigma_\uparrow - \sigma_0}{\sigma_0} = \frac{2}{fP_{zz}} \left( \frac{N_\uparrow}{N_0} - 1 \right) \]

Observable is the Normalized XS Difference

B-Field, density, temp, etc. held same in both states

\[ b_1 = -\frac{3}{2} F_1^d A_{zz} \]

\( \sigma_\uparrow \): Tensor Polarized cross-section

\( \sigma_0 \): Unpolarized cross-section

\( P_{zz} \): Tensor Polarization

\( f \approx \frac{6}{20} \)

\( f \): dilution factor
Unpolarized Beam
UVa/JLab Polarized Target

Magnetic Field Held Along Beam Line at all times

$L = 10^{35}$
Projected Results for $P_{zz} = 35\%$

false asymmetries suppressed by $1/P_{zz}$

\[ \delta A_{zz} = \pm \frac{2}{f P_{zz} \sqrt{N_{cycles}}} \delta \xi \]
Very Large Tensor Asymmetries predicted

++Measure $T_{20}$ over widest ever $Q^2$ range

Sensitive to the S/D-wave ratio in the deuteron wave function

4$\sigma$ discrim between hard/soft wave functions
6$\sigma$ discrim between relativistic models

"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
See James Maxwell’s talk

“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

New lQCD result for first moment of $\Delta(x,Q^2)$
Detmold, Shanahan, arXiv:1606.04505

Encouraged for full submission by PAC44

$\Delta(x,Q^2)$ double helicity flip structure function
TENSOR SPIN OBSERVABLES WORKSHOP

MARCH 10-12, 2014
JEFFERSON LAB

TOPICS:
• Tensor Polarization in DIS
• Tensor Structure Functions
• Hidden Color at Large x
• Tensor Observables in x>1
• Solid Tensor-Polarized Target Development
• Elastic Deuteron Form Factors
• Tensor Polarization at EIC
• Analyzing Powers in Scattering From Tensor-Polarized Targets

ORGANIZING COMMITTEE:
Karl Stiller (Chair, University of New Hampshire)
Douglas Higinbotham (Jefferson Lab)
Christopher Keith (Jefferson Lab)
Elena Long (University of New Hampshire)
Minak Sarkarian (Florida International University)
Patricia Sovignon (University of New Hampshire)

www.jlab.org/conferences/tensor2014
Tensor Polarized Target

Significant progress at UVa

Enhancing $P_{zz}$

understanding the NMR lineshape


Promising, but need to confirm in ND$_3$

T20 measurement at Higgs to verify NMR analysis
Just Began Construction of new Vertical fridge for use in 5T superconducting solenoid.

Oxford ITC readout of Sensors
CCS
Allen Bradley
Cernox

Roots pump set: 7000 m³/h
6000 + 1000 m³/h, backed by rotary vane DUO 65
KNF Neuberger Separator Pump
PM27186-1200

Helium Evaporative Refrigerator
Calibrated Target Cup Temperature

**UNH Polarized Target Lab**
UNH Polarized Target Lab

NMR circuit and Labview controls

Q-Meter tuned to 12.8 MHz (proton@0.3T)
λ/2 cable=9.9m
12.8 MHz Crystal Oscillator

We can also tune to 32.7 MHz (Deuteron@ 5T) and 213 MHz (Proton@5T)

1 T @ room temperature
Summary

Spin Polarizabilities

\[ \delta_{LT} \text{ puzzle and } \chi^\text{PT} \text{ calculations: progress is being made.} \]

but still large discrepancies data/calcs

New proton data under analysis should help clarify.

Higher order generalized spin polarizabilities.

Tensor Program

E12-13-001: Tensor Polarized Structure function b1 of the Deuteron

E12-14-002: Tensor Asymmetry A_{zz} for x>1

LOI12-14-001: Tensor Structure Function Δ

Significant progress has been made to develop the targets.