An Overview of Recent Nucleon Spin Structure Measurements at Jefferson Lab

Kalyan Allada
Massachusetts Institute of Technology

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Outline

• A brief review of polarized inclusive electron scattering
  • structure functions, spin polarizabilities and sum rules

• Comparison of data with $\chi$PT calculations at low $Q^2$
  • Spin polarizabilities on $^3$He at low $Q^2$
  • $g_1$ moment on proton at low $Q^2$
  • Ongoing analysis of $g_2$ on proton at low $Q^2$

• Results of $g_2$ and $d_2$ measurements at large $Q^2$ on proton and neutron targets

• Semi-inclusive DIS: Transversity related measurements at JLab
Inclusive Electron Scattering

Kinematics

\[ \vec{q} = \vec{k} - \vec{k}' \]
\[ Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2} \]
\[ x = \frac{Q^2}{2M v} \]

Inclusive inelastic cross section:

\[ \sigma_0 = \sigma_{Mott} \left[ \alpha F_1(x, Q^2) + \beta F_2(x, Q^2) + \gamma g_1(x, Q^2) + \delta g_2(x, Q^2) \right] \]

Structure functions:

- spin-averaged (unpolarized): \( F_1 \) and \( F_2 \)
- spin-dependent (polarized): \( g_1 \) and \( g_2 \)
- electron and target spins are parallel (anti-parallel) or their spins are perpendicular
Experimental Technique

Cross-section differences:

$$\Delta \sigma_{||} = \begin{pmatrix} e^- \rightarrow \bullet \rightarrow e^- \end{pmatrix}$$

Longitudinally polarized nucleon

$$\frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\downarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2} \frac{E'}{E} \left[ (E + E' \cos \theta) g_1 - 2Mxg_2 \right]$$

Transversely polarized nucleon

$$\Delta \sigma_{\perp} = \begin{pmatrix} e^- \rightarrow \bullet \uparrow \rightarrow e^- \downarrow \end{pmatrix}$$

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

$\Delta \sigma_{\perp}$ is relatively difficult to measure experimentally – requires transversely polarized target
Structure Functions

- At Bjorken limit, $g_1$ related to polarized parton distribution functions

$$g_1 = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x) \quad \Delta q_i(x) = q_i^\uparrow(x) - q_i^\downarrow(x)$$

- No simple relation between $g_2$ and PDFs at Bjorken limit
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- $g_2$ contain leading twist ($g_2^{WW}$) + twist-3 part ($\bar{g}_2$)

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$

where
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where

$$g_2^{WW} = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(y, Q^2)$$

(Cortes, Pire & Ralston, 1992)

$$\bar{g}_2(x, Q^2) = -\int_x^1 \frac{\partial}{\partial y} \left[ \frac{m_q}{M} h_T(y, Q^2) + \zeta(y, Q^2) \right] \frac{dy}{y}$$

(Twist-2)

(Twist-3)

quark transverse momentum contribution (Transversity)

twist-3 part which arises from quark-gluon interactions
Spin Structure Moments

- First moment of $g_1$:

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2) \, dx$$

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6}$$

related total spin carried by the quarks

$g_A$: nucleon axial charge
Spin Structure Moments

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$g_A$ : nucleon axial charge

- First moment of $g_2$: $\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2) \, dx = 0$

Burkhardt-Cottingham (BC) Sum Rule
Spin Structure Moments

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  \[ \Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2) \, dx \]
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- First moment of $g_2$:
  \[ \Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2) \, dx = 0 \]  
  Burkhardt-Cottingham (BC) Sum Rule

- 2\textsuperscript{nd} moment of $g_2$ ($x^2$ weighting):
  At low $Q^2$ – spin polarizabilities, test of Chiral Perturbation ($\chi$PT) theory

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

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

$g_A$: nucleon axial charge

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  At low $Q^2$ – spin polarizabilities, test of Chiral Perturbation ($\chi$PT) theory

- At High $Q^2$ – color polarizability or color Lorentz force, test of lattice QCD
  \[ \bar{d}_2(Q^2) = \int_0^{x_0} dx \, x^2 \left[ 2g_1(x, Q^2) + 3g_2(x, Q^2) \right] \]
  $\bar{d}_2$ is a measure of color Lorentz force acting on the stuck quark in the instance after being hit by a virtual photon (M. Burkardt, PRD 88, 114502 (2013))
The BC Sum Rule

\[ \Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2) \, dx = 0 \]


- The sum rule satisfied within the errors for neutron and $^3$He
- For proton it is almost unmeasured
- JLab measurement will provide low and high $Q^2$ data for proton
Existing $d_2$ Measurements

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

- $d_2$ moments for proton and neutron
- Only contributions from the measured region
- Contributions from unmeasured low-$x$ region usually not significant due to $x^2$ weighting
- Recent JLab measurements will provide low $Q^2$ proton and high $Q^2$ neutron data
Jefferson Lab

- Continuous electron beam
- Energy 0.4 GeV to 6 GeV (until 2012)
- Avg. Polarization: ~ 85%
- Beam Current: up to 200 uA
- Energy upgrade: up to 12 GeV (in-progress)
- Four Halls: A, B, C and D (new)
- High energy run expected in Fall 2015
Jefferson Lab at 6 GeV

- Hall A: Polarized $^3$He, NH$_3$
- Hall B: Polarized NH$_3$, ND$_3$
- Hall C: polarized NH$_3$, ND$_3$
Recent Measurements at JLab

- **E97-110 (saGDH, Hall A):**
  \(^3\text{He}(n)\) to measure \(g_1\) and \(g_2\) at very low \(Q^2\) (0.02-0.3 GeV\(^2\)) (preliminary results)

- **EG4 (CLAS, Hall B):**
  \(\text{NH}_3(p)\) and \(\text{ND}_3(d)\) to measure \(g_1\) at very low \(Q^2\) (0.02 - 0.5 GeV\(^2\)) (preliminary results)

- **E08-027 (g2p, Hall A):**
  \(\text{NH}_3(p)\) to measure \(g_2\) moments at very low \(Q^2\) (0.02-0.2 GeV\(^2\)) (analysis)

- **E06-014 (d2n, Hall A):**
  \(^3\text{He}(n)\) to measure \(g_1\) and \(g_2\) at high \(Q^2\) (2-6 GeV\(^2\)) (published)

- **E07-003 (SANE, Hall C):**
  \(\text{NH}_3(p)\) to measure \(g_2\) at high \(Q^2\) (2-6 GeV\(^2\)) (preliminary results)
E97-110: Small Angle GDH Experiment

**Spokespersons:** J.-P. Chen, A. Deur, F. Garibaldi

- Precision measurement of the moments of spin structure functions at low $Q^2$ (0.02-0.24) GeV$^2$ for the neutron ($^3$He)

- Covered an unmeasured region of kinematics to test theoretical calculations (Chiral Perturbation theory)

- Inclusive experiment: $^3\text{He}(e, e')X$

- Polarized electron beam
  - Avg. $P_{\text{beam}} = 75\%$

- Polarized $^3\text{He}$ target (para & perp):
  - Avg. $P_{\text{target}} = 40\%$

- Measured cross-section differences

$$I_{\text{GDH}} = \int_{\nu_{\text{th}}}^{\infty} \frac{\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)}{\nu} d\nu = -2\pi^2\alpha\left(\frac{\kappa}{M}\right)^2$$

$\kappa$: anomalous magnetic moment

![Generalized GDH integral graph]
$$\Gamma_1 = \int_0^{x_0} g_1(x, Q^2) \, dx$$

**Neutron**

- JLab E94010
- HERMES
- JLab CLAS EG1a
- SLAC E143
- GDH sum rule
- Phen. Model 1 (Burkert-Ioffe)
- Phen. Model 2 (Soffer-Teryaev 2004)

**Neutron (zoomed)**

- Xpt heavy baryons
- Xpt Relativistic

V. Sulkosky (UVa)
E97-110: Spin Polarizability

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

- Generalized spin polarizabilities \( \gamma_0 \) and \( \delta_{LT} \) are a benchmark test of \( \chi PT \)

- Difficulty in including the nucleon resonance contributions

- \( \gamma_0 \) is sensitive to resonances, \( \delta_{LT} \) is not

- Neutron results for \( \gamma_0 \)

(V. Sulkosky)
E97-110: Spin Polarizability

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

- Neutron results for \( \delta_{LT} \)

- \( \delta_{LT} \) is seen as a more suitable testing ground – insensitive to \( \Delta \)-resonance

- Data is in significant disagreement with \( \chiPT \) calculations (old)

- New calculations available from:
  - Bernard et al., PRD 87, 054032 (2013) – covariant B\( \chiPT \)
  - Kochelev & Oh, PRD85 (2012) 016012 – axial anomaly
  - Lensky et al., PRC 90, 055202 (2014) – B\( \chiPT \) approach

B\( \chiPT \) approach by Lensky et al., seems to agree with MAID model

(\text{V. Sulkosky} )
The BχPT approach is in reasonable agreement with MAID model.
The EG4 Experiment

Spokespersons

NH\textsubscript{3} (p): M. Battaglieri, A. Deur, R. De Vita, M. Ripani (Contact)
ND\textsubscript{3} (d): A. Deur (Contact), G. Dodge, K. Slifer

- Low Q\textsuperscript{2} measurement of g\textsubscript{1} from NH\textsubscript{3} (p) and ND\textsubscript{3} (d)
- Goal: test of χPT as Q\textsuperscript{2} \rightarrow 0

Kinematic coverage

E = 1.0, 1.3, 2.0, 2.5, 3.0 GeV

0.02 < Q\textsuperscript{2} < 0.7 GeV\textsuperscript{2}

Resonance Region

Courtesy K. Slifer (UNH)
The EG4 Experiment: Proton $g_1$

$Q^2 = 0.024 - 0.071 \text{ GeV}^2$

Plots by H. Kang (SNU, Seoul)
The EG4 Experiment: Proton $g_1$

$Q^2 = 0.084 - 0.244 \text{ GeV}^2$

Plots by H. Kang (SNU, Seoul)
The EG4 Experiment: Proton $g_1$

$Q^2 = 0.292 - 0.592 \text{ GeV}^2$

Plots by H. Kang (SNU, Seoul)
The EG4 Experiment: Proton $\Gamma_1$

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

Heavy baryon ChPT:
- X. Ji et al., PLB v 472, 1-4
- C. Kao et al., PRD v69 056004

Phenomenological model:
- Burkert-Ioffe, PLB v296 223

Relativistic Baryon ChPT:
- V. Bernard et al., PRD v87 054032

Data+DIS: includes low-x contribution (model)
The EG4 Experiment: Deuteron $g_1$

$Q^2 = 0.02 - 0.71$ GeV$^2$

Plots by K. Adhikari (MSState)
The EG4 Experiment: Deuteron $\Gamma_1$

$$\Gamma_1^d = \int_{0}^{x_0} g_1(x, Q^2) \, dx$$

Data+Model: includes low-x contribution (model)
Hall A g2p Experiment

**Spokespersons:** A. Camsonne, J.-P. Chen, D. Crabb, K. Slifer

- First measurement of $g_2$ for the proton at low to moderate $Q^2$
  - BC sum rule, $\delta_{LT}$ polarizability, check $\chi$PT calculations

- Polarized electron beam

- Transversely polarized NH$_3$ (p) target
  - Two different magnet settings (5 T, 2.5 T)
  - Ave. pol. for 5T: ~70%
  - Avg pol. for 2.5T: ~15%

- Will measure cross-section differences to extract $g_2(p)$
  - $\Delta\sigma_{||}$ from EG4 expt.
  - $\Delta\sigma_{\perp}$ from this expt.

\[ W < 2 \text{ GeV} \]
\[ 0.02 < Q^2 < 0.2 \text{ GeV}^2 \]
g2p Experiment: Projections for Proton

See Ryan Zielinski’s talk on Thursday afternoon for details:
Parallel Session 5: Hadron Structure & Meson Baryon Interaction WG
Goal: Measure the proton spin structure function $g_2(x, Q^2)$ and spin asymmetry $A_1(x, Q^2)$

$Q^2 = 2.5 - 6.5$ GeV$^2$

$x = 0.3 - 0.8$

Method: Measure parallel and near-transverse inclusive double spin asymmetries

Polarized NH$_3$ (p) target
Proton $g_1$ (SANE)

- BETA proton data
- DIS and Resonances
- $g_1, g_2^{WW}$ curves from PDFs at $Q^2 = 4$ GeV$^2$
- $E' \geq 0.6$ GeV
- more data at $Q^2 = 1.6$ GeV$^2$ coming
- SLAC E143, E155, E155x, SMC and HERMES DIS data

![Proton $g_1$ plot](image-url)

(Curves are $g_1$ from PDFs)
SANE Experiment: Proton $g_2$

- BETA proton data
- DIS and Resonance data
- $g_2^{WW}$ curves using $g_1$ at $Q^2 = 4$ GeV^2
- $E' > 0.6$ GeV
- More data at $Q^2 = 1.6$ GeV^2
Nachtmann moments are needed to get twist-3 free of target mass corrections

Expected statistical errors for $d_2$
E06-014 (d2n) Experiment

Spokespeople: B. Sawatzky, S. Choi, X. Jiang and Z.-E. Meziani

- Goal: Measure $d_2$ and $A_1$ spin asymmetry for neutron
- Polarized electron beam: $E=4.74, 5.89$ GeV, polarization $\sim 71\%$
- Polarized $^3$He target $\sim 50\%$
- HRS used for absolute cross section measurements at $45^\circ$
- Bigbite used for asymmetries measurements at $45^\circ$
E06-014 Experiment: $x^2 g_1$ for $^3$He

$\langle Q^2 \rangle = 3.2 \text{(GeV/c)}^2$
$\langle Q^2 \rangle = 4.3 \text{(GeV/c)}^2$
E06-014 Experiment: $x^2g_2$ for $^3$He

$\langle Q^2 \rangle = 3.2 \text{ (GeV/c)}^2$
$\langle Q^2 \rangle = 4.3 \text{ (GeV/c)}^2$

• Panel (a) shows comparison to world data
• Panel (b) is zoomed on y-axis to show error bars

Posik et al., PRL 113 022002 (2014)
E06-014 Experiment: $d_2$ for the Neutron

- Results are consistent with Lattice QCD prediction
- $d_2^n$ extracted at
  - $<Q^2> \sim 3.3 \text{ GeV}^2$ (E=4.7 GeV data)
  - $<Q^2> \sim 4.3 \text{ GeV}^2$ (E=5.9 GeV data)
- Shaded boxes in inset are systematic uncertainties
- Low-x contribution ($0.02 < x < 0.25$) is provided by fits to world data (small impact)
- $^3\text{He} \rightarrow \text{neutron}$ correction using eff. polarization method applied to $d_2$
What about quark transverse spin distribution?
Transversity Distribution ($h_1$)

- **Transversity**: distribution of transversely polarized quarks in transversely polarized nucleon

- Related to nucleon **tensor charge**: 
  \[ \delta q = \int_0^1 \left[ h_1^q(x) - h_1^{\bar{q}}(x) \right] dx \]

- **Helicity flip amplitude** -

- Suppressed in the DIS process – need another chiral odd function

- Can be accessed through Semi-inclusive DIS via chiral-odd **Collins fragmentation function**

\[ \sigma^{ep^{\uparrow}\rightarrow ehX} \propto \sum_q h_1^q \otimes \sigma^{eq^{\rightarrow}eq} \otimes FF^{q\rightarrow h} \]

- Measure transverse target single spin asymmetry: 
  \[ A_{UT} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = A_{UT}^{Collins} + A_{UT}^{Sivers} + A_{UT}^{Pretz} \]
Hall A Transversity Experiment: Collins and Sivers Moments

\[ e + n_{\text{eff}}^\uparrow \rightarrow e' + \pi^\pm + X \]

- Neutron SSA extracted from measured $^3$He asymmetry in SIDIS
- Covers valence region
- Favors negative values for $\pi^+$ Sivers
- Neutron Collins and Sivers moments consistent with models predictions (2011)

\[
A_{UT}^{\text{Collins}} \propto \frac{\sum e_q^2 h_1^q \otimes H_1^q}{\sum e_q^2 f_1^q \otimes D_1^q}
\]

\[
A_{UT}^{\text{Sivers}} \propto \frac{\sum e_q^2 f_1^q \otimes D_1^q}{\sum e_q^2 f_1^q \otimes D_1^q}
\]

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

X. Qian et al., PRL 107 (2011) 072003
Global Extraction of Transversity

- Global analysis of transversity:
  - includes HERMES (p), COMPASS (p/d) and JLab ($^3$He) data

- Still large uncertainties – need more precise data
  - A comprehensive SIDIS program at JLab 12 GeV

Transversity distribution

Z-B. Kang et al., arXiv:1505.05589
Summary

• Data on nucleon spin structure from several recent measurements at JLab are now available:
  • preliminary data for proton $g_1$ at low $Q^2$
  • preliminary data on $\Gamma_1$ and $\delta_{LT}$ on neutron at low $Q^2$
  • preliminary data on $g_1$ and $g_2$ for proton at high $Q^2$ (DIS, Resonances)
  • published data on $g_1$ and $g_2$ for neutron at high $Q^2$ (DIS)

• Low $Q^2$ proton $g_2$ data is still being analyzed

• Many recent advances on the $\chi$PT theory front to explain the $\delta_{LT}$ puzzle
  • Much needed low $Q^2$ data on proton will be available soon

• Data from first generation of experiments led to the extraction of transversity distribution
  • Very precise SIDIS data to follow in the 12 GeV era at JLab
Spare Slides
N. Kochelev and Y. Oh, PRD 85, 016012 (2012)

Improved agreement with neutron