Nucleon Spin Structure at JLab

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Jefferson Laboratory

CEBAF is a superconductive electron accelerator

- continuous beam
- high longitudinal polarization
- energy range $\rightarrow 0.75 - 5.9$ GeV
- current range $\rightarrow 0.1$ nA – 200 $\mu$A
- Beam polarization 80-90%

Jefferson Lab experiments

Hall A
- E94-010 – Neutron extended GDH
- E97-103 – g2n
- E97-110 – GDH sum rule, spin structure $^3$He
- E99-117 – High precision $A_1^n$ at large $x$
- E01-012 – Spin duality

Hall B
- eg1 – p and D spin structure and moments, duality
- eg4 – low Q2 GDH
- eg1dvcs – semiinclusive and GPD

Hall C
- RSS – Resonance Spin Structure
- SANE – Spin Asymmetries on the Nucleon
Hall A

High Resolution Spectrometers (HRS)
- Angular acceptance 6 msr
- Resolution $1 \times 10^{-4}$ FWHM
- Large momentum range (0.3-4.3 GeV, 0.3-3.3 GeV)
- Proton Polarimeter

• Longitudinal, transverse and vertical
• Luminosity =$10^{36}$ (1/s) (highest in the world)
• Effective polarized neutron target
• P=40% with 12µA beam

$P = 40-45 \%$
@ $I = 12 \, \mu A$

3x30W @795nm

Diode Laser
Diode Laser
Diode Laser

Photo-Diode for EPR

Cell: $L = 40 \, \text{cm}$
windows: $\sim 100 \, \mu \text{m}$

NMR RF Drive Coils

Helmholtz Coils
Focus on low $Q^2$ (GDH, $\chi$PT) => lower beam energies (up to 3 GeV), new Cherenkov for optimal acceptance in outbending configuration, $\theta_e$ as small as 6 degrees.

Largest possible kinematic coverage

$\rightarrow$ inbending and outbending configuration, $E = 1.6 \ldots 5.8$ GeV

**CEBAF Large Acceptance Spectrometer**

- Six individually instrumented sectors
- Toroidal magnetic field
- Multi-particle final state
- Large acceptance

**Hall B: EG1 and EG4 with CLAS**

**EG1**: $Q^2 = 0.05 \ldots 5$ GeV$^2$

**EG4**: $Q^2_{\text{min}} = 0.015$ GeV$^2$

$1998 - 2001$

**Focus on low $Q^2$ (GDH, $\chi$PT) => lower beam energies (up to 3 GeV), new Cherenkov for optimal acceptance in outbending configuration, $\theta_e$ as small as 6 degrees**
The polarized target

EG1/EG4 target (CLAS):
Polarization up to 0.9 (p) or 0.4 (d)
Luminosity up to $\sim 10^{34}$

Irradiated ammonia beads
Hall C: RSS and **SANE**

**SANE setup**

**Electron Arm:**
- Tracker
- Cerenkov
- Lucite
- BigCal

**HMS: High Momentum Spectrometer**
- Hall-C Spectrometer
- Packing Fractions

**Target**
- Polarized NH$_3$/ND$_3$ targets
- Dynamical Nuclear Polarization
- Same as Hall B, but it can be rotated
  - Transverse polarization!
- In-beam average polarization
  - 70-90% for p
  - 30-40% for d
- Luminosity up to ~$10^{35}$ (Hall C)

**Polarized Electron Beam:** 4.7, 5.9 GeV

**Polarized Proton Target:** ~⊥, ∥

**Ammonia (NH$_3$) Polarized via DNP in 5T Magnetic Field**

**"BETA" Electron Arm**
JLab experiments

“Everything”

- Sum Rules at low $Q^2$
- very low $Q^2$ - $\chi$PT
- $Q^2$-dep. of $g_2$
- $A_{1n}$ at high $x$
- Duality

- Res. Region, Duality

8 completed experiments

3 (+3) approved with 6 GeV JLab

3 (+1) approved with 12 GeV (A/B/C)
DIS of lepton off nucleon

Virtual photon probes the structure

Important variables:

\[ Q^2 = -q^2 = 4 EE' \sin^2 \frac{\theta}{2} \]

\[ W^2 = M^2 + 2 M \nu - Q^2 \]

\[ x = \frac{Q^2}{2 M \nu} \]

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

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

\[
\frac{d^2 \sigma^{\uparrow \Rightarrow}}{d \Omega d E'} - \frac{d^2 \sigma^{\downarrow \Leftarrow}}{d \Omega d E'} = \frac{4 \alpha^2 E'}{v E Q^2} \sin \theta \left[ g_1(x,Q^2) - \frac{2 M E}{\nu} g_2(x,Q^2) \right]
\]
Virtual photon asymmetries

Experimentally:

\[
A_{\parallel} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\downarrow\uparrow}}{2d\sigma_{\text{unpol}}} = D\left(A_1 + \eta A_2\right)
\]

\[
A_{\perp} = \frac{d\sigma^{\uparrow\Rightarrow} - d\sigma^{\downarrow\Leftarrow}}{2d\sigma_{\text{unpol}}} = d\left(A_1 + \zeta A_2\right)
\]

\[
\gamma^2 = \frac{4M^2x^2}{Q^2}
\]

The virtual photon asymmetries $A_1$ and $A_2$ can be extracted by varying the direction of the nucleon polarization or by varying the beam energy at fixed $Q^2$, $v$.

Large-x behavior of the $A_1$ asymmetry

- SU(6) \(\rightarrow\) $A_1^p = \frac{5}{9}$, $A_1^n = 0$
- Hyperfine perturbed QM
  - makes $S=1$ pairs more energetic than $S=0$ pairs $\rightarrow A_1 \rightarrow 1$
- In DIS, and in pQCD
  - Minimal gluon exchanges
  - Spectator pair: quarks have opposite helicities
  - At large $x$ struck quark carries the helicity of the nucleon
  - $A_1 \rightarrow 1$

Isgur, PRD 59, 034013 (1999)  
Farrar and Jackson, PRL 35, 1416 (1975)
$A_1$ deuteron for different $Q^2$ bins
Virtual Photon Asymmetry $A_1$

- $P$ and $d$ results fall below parameterization of world data at 10 GeV$^2$ \(\rightarrow\) include in DGLAP fits
- To be used to extract $\Delta q/q$ in this momentum transfer region
- $P$ and $d$ results are in better agreement with the HFP quark model


$HP$ perturbed QM N. Isgur, Phys. Rev. D 59, 34013

E. Close and W. Melnitchouk, Phys. Rev. C 68, 035210
Virtual Photon Asymmetry $A_1$

- New results from CLAS eg1b
- Better statistical precision
- Better systematic errors
\( A_{1,2}^n - \text{Hall A} \)

- \( Q^2 = 2.7 - 4.8 \text{ GeV}^2 \)
- Large \( x \)
- \( A_1^n \) crosses zero and becomes positive \( \rightarrow \) SU(6) breaking

**References**

PRC 70, 065207 (2004)
Spin Structure Function $g_1$ and $g_2$

$$g_1(x) = \frac{l}{2} \sum_q e_q^2 (\Delta q + \Delta \bar{q}) = \frac{l}{2} \sum_q e_q^2 (q^+(x) - q^-(x) + \bar{q}^+(x) - \bar{q}^-(x))$$

- $S_\gamma + S_N = 1/2$
- $S_\gamma + S_N = 3/2$

Virtual photon couples to quarks of opposite helicity
$q^+(x)$ or $q^-(x)$ are chosen by changing the configuration of the incident lepton and target nucleon spin
$g_1(x) \sim \sigma_{1/2} - \sigma_{3/2}$

$$g_2(x,Q^2) = g_{2WW}(x,Q^2) + g_2(x,Q^2)$$

- Not a simple interpretation
- $g_{2WW}$ leading twist (twist 2)
- $g_{2WW}$ related to $g_1$ by the Wandzura-Wilczek relation
  $$g_{2WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2) \frac{dy}{y}$$
- $g_2$ higher twist – quark-gluon, quark-quark correlations
$g_1^p \atop \text{Jefferson Lab}$

World data on the proton before JLab (without COMPASS)
$g_1^p @$ Jefferson Lab

World data on the proton before JLab (without COMPASS)

World data on the proton including EG1
World data on the proton before JLab (without COMPASS)

World data on the proton including EG1

...including resonance region data!
$g_1(x, Q^2)$ proton for different $Q^2$ bins – eg1
$g_1$ and $g_2$ for $p$ and $d$

$Q^2 = 1.3$ GeV$^2$

Hall C RSS, PRL 98, 132003 (2007)
\( g_2 \) for neutron – Hall A

- Measure higher twist \( \rightarrow \) quark-gluon correlations.
- Positive deviation from \( g_2^{WW} \) \( \rightarrow \) higher twist contributions

Hall A, E97-103 K. Kramer et al.,
PRL 95, 142002 (2005)

E97-103:
- \( Q^2 \) from 0.58 to 1.36 GeV\(^2\)
- \( x \approx 0.2 \)
- Dedicated exp \( g_2^n \) in DIS region at low \( Q^2 \)
Polarized quark distribution functions

Assuming the naïve parton model with no sea contribution, quark polarizations in the valence region can be estimated directly from the data:

\[
\frac{\Delta u}{u} \approx \frac{5g_1^p - 2g_1^d}{5F_1^p - 2F_1^d} \left(1 - 1.5\omega_D\right)
\]

\[
\frac{\Delta d}{d} \approx \frac{8g_1^d}{8F_1^d - 5F_1^p} \left(1 - 1.5\omega_D\right) - 5g_1^p
\]

- Also NLO analysis on this data
- New results for recent data coming soon!

Orbital angular momentum may change this picture

Effect of CLAS data on NLO fits of PDFs

\[ g_1(x, Q^2)_{\text{exp}} = g_1(x, Q^2)_{LT} + h^{g_1}(x)/Q^2 \]

NLO fit by Leader, Stamenov and Siderov, including both CLAS data and new COMPASS data on the deuteron
First moment $\Gamma_1$ and GDH

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

At high $Q^2$ - QPM

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

$$\Gamma_1^p = \frac{1}{9} \left( \frac{3}{4} a_3 + \frac{1}{4} a_8 + a_0 \right)$$

$$\Delta \Sigma = a_0$$

$Q^2 \rightarrow 0$ - GDH

$$\Gamma_1 = \int g_1(x, Q^2) \ dx \xrightarrow{Q^2 \rightarrow 0} \frac{Q^2}{2M^2} I_{GDH}$$

$$I_{GDH} = \frac{M^2}{8\alpha \pi^2} \int_{\text{thr}}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu} = -\frac{1}{4} \kappa^2$$

A connection between dynamic and static properties.
First moment $\Gamma_1$ and GDH - CLAS

\[ \Gamma_1(P) \]

\[ \Gamma_1(D)/2 \]

PRELIMINARY
First moment $\Gamma_1$ and GDH - CLAS

\[ \Gamma_1(P) \]

\[ \Gamma_1^{(D)/2} \]

\[ \begin{array}{c}
\text{EG1b data} \\
\text{EG1b data+model} \\
\text{EG1 sys data} \\
\text{EG1 sys data+model} \\
\text{Model}
\end{array} \]

PRELIMINARY
First moment $\Gamma_1$ and GDH – low $Q^2$

Neutron

\[ \Gamma_1 \]

Burkhardt - Cottingham Sum Rule

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

Brown: SLAC E155x
Red: Hall C RSS
Black: Hall A E94-010
Green: Hall A E97-110 (preliminary)
Blue: Hall A E01-012 (very preliminary)

BC = Meas+low_x+Elastic

“Meas”: Measured x-range
“low-x”: refers to unmeasured low x part of the integral.
Assume Leading Twist Behaviour
Elastic: From well know FFs (<5%)
Burkhardt - Cottingham Sum Rule

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

BC satisfied w/in errors for Neutron
(But just barely in vicinity of $Q^2=1$)

BC satisfied w/in errors for $^3$He
Γ₁ of p-n – Bjorken integral
Duality

Structure functions averaged over resonances behave like DIS.

$$\langle g_1(Q^2) \rangle = \frac{\int_{x_i}^{x_h} g_1(x,Q^2)dx}{x_h - x_i}$$

1.08 < W < 1.38 GeV

1.38 < W < 1.58 GeV

1.58 < W < 1.82 GeV

1.82 < W < 2.00 GeV

Global duality

1 < W < 2 GeV

Local duality

Excludes elastic

Includes elastic

Includes quasi-elastic

Excludes quasi-elastic

Q^2 (GeV^2/c^2)
2 particles final state

\[ \sigma(W, Q^2, \theta^*, \phi^*) \propto \sigma_o + P_e \sigma_e + P_t \sigma_t + P_e P_t \sigma_{et} \]

- Different sensitivities to resonant and non resonant contributions for the double \((\sigma_{et})\) and target \((\sigma_t)\) polarization terms
- Polarized measurements to provide new constraints to phenomenological models which are based on previous unpolarized photo- and electro-production data

- H(e,e’\pi^0)p
- H(e,e’\pi^+)n
- D(e,e’p\pi^-)p
- rho production
- eta production

- Semi-inclusive

- e p \rightarrow e’ p X
- Struck quark of different flavors produce the hadron with different probabilities
- SIDIS can help to separate contributions from quark flavors
- Access to orbital angular momentum of quarks
- Transverse momentum distributions
Semi-inclusive

\[ p(e, e'p)\pi^0 \]
Study of the semi-inclusive pion production (E05-113)

TMDs and Collins fragmentation function as well as DVCS

Expected Precision for $\sin\phi$ and $\sin2\phi$

moments of target SSA

$E_{\text{beam}} = 6$ GeV

60 days ($P_H = 75\%$)

uses $2\pi$ inner calorimeter for $\gamma/\pi^0$ coverage

Completed in Fall 2009
Study of spin orbit correlations in semi inclusive DIS and Sivers distribution function (E08-015)

HD target

$E_{\text{beam}} = 6 \text{ GeV}$

25 days ($P_H = 75\% \; P_D = 25\%$)

Potential to add to world data on $g_2$ and $A_2$
CLAS12

12 GeV program

Proton \( W > 2; Q^2 > 1 \)

Deuteron

Also semi-inclusive proposals!
Conclusions

- Broad spin program at Jefferson Lab.
- Complex look at the structure of the nucleon.
- Many observables asymmetries, structure functions, sum rules, moments
- New information to understand the transition between hadron and partonic degrees of freedom
- Plenty results from Jefferson Lab, large acceptance and access to resonance region
- Much more to come COMPASS+RHIC, Spring8, JLab @ 12 GeV, J-PARC, FAIR, … EIC?

Thanks to Sebastian Kuhn, Nevtzat Guler, Yelena Prok, Keith Griffioen, Jiang-Peng, Karl Slifer, Narbe Kalantarians, Oscar Rondon, K. Adhikari
Overview

• Spin Physics
• Experiments at JLab
• Nucleon Structure Functions results
• Future experiments
• Summary
Extracting $A_2 / g_2$ - CLAS

Black points: EG1b data
Blue points: RSS data
Line: EG1b model for $A_2$
\( g_1 / F_1 \) falls below the DIS extrapolation at low \( Q^2 \) (dashed curve)
Large-x behavior of the $A_1$ asymmetry

Large x region dominated by valence quarks → can test quark models

• SU(6) QM: Exact SU(6) symmetry
  Equal probability for $S=0$ and $S=1$ di-quark configuration

• Hyperfine perturbed QM
  makes $S=1$ pairs more energetic than $S=0$ pairs

• Duality
  Suppress transitions to specific resonances ($56^+$ and $70^-$)

• In DIS, pQCD: Minimal gluon exchanges

<table>
<thead>
<tr>
<th>Model for $x \to 1$</th>
<th>$A_{1p}$</th>
<th>$A_{1n}$</th>
<th>$d/u$</th>
<th>$\Delta u/u$</th>
<th>$\Delta d/d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(6)</td>
<td>5/9</td>
<td>0</td>
<td>1/2</td>
<td>2/3</td>
<td>-1/3</td>
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<tr>
<td>w/ hyperfine ($E_{S=0} &lt; E_{S=1}$)</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>One gluon exchange</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>Suppressed symmetric WF</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>S=1/2 dominance</td>
<td>1</td>
<td>1</td>
<td>1/14</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{1/2}$ dominance</td>
<td>1</td>
<td>1</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
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<tr>
<td>pQCD (conserved helicity)</td>
<td>1</td>
<td>1</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Close and Melnitchouk, PRC 68, 035210 (2003)
Farrar and Jackson, PRL 35, 1416 (1975)
Parton Distributions Functions and NLO pQCD

- Two effects modify simple parton picture:
  - pQCD evolution makes PDFs $Q^2$-dependent (NLO DGLAP equations) – mild logarithmic dependence
  - (Gluon) radiative corrections change elementary cross section generating a contribution to $g_1$ due to the gluon polarization

\[
g_1^{\text{NLO}}(x, Q^2) = g_1^{\text{LO}} + \frac{1}{2} \langle e^2 \rangle \sum_q e_q^2 \left[ \Delta q(x, Q^2) \otimes C_q + \Delta g(x, Q^2) \otimes C_g \right]
\]

we can extract information on the gluon from DIS
Jefferson Laboratory and CLAS

CEBAF
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- high longitudinal polarization
- energy range $\rightarrow 0.75 - 5.9$ GeV
- current range $\rightarrow 0.1 \text{nA} - 200\text{mA}$
- Beam polarization 80-90%
Experiments EG1 and EG4 with CLAS

EG1: $Q^2 = 0.05 \ldots 5 \text{ GeV}^2$

Largest possible kinematic coverage
→ inbending and outbending configuration, $E = 1.6 \ldots 5.8 \text{ GeV}$

EG4: $Q^2_{\text{min}} = 0.015 \text{ GeV}^2$

note: $m_\pi^2 = 0.02 \text{ GeV}^2$

Focus on low $Q^2$ (GDH, $\chi$PT) => lower beam energies (up to 3 GeV), new Cherenkov for optimal acceptance in outbending configuration, $\theta_e$ as small as 6 degrees
$g_1(x, Q^2)$ proton for different $Q^2$ bins
Virtual photon asymmetries

\[
\frac{d\sigma}{dE'd\Omega} = \Gamma_v \left[ \sigma_T + \varepsilon \sigma_L + P_e P_t \left( \sqrt{1 - \varepsilon^2} A_1 \sigma_T \cos\psi + \sqrt{2\varepsilon(1 - \varepsilon)} A_2 \sigma_T \sin\psi \right) \right]
\]

\[
A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \quad A_2 = \frac{\sigma_{LT'}}{\sigma_T}
\]

the asymmetries \( A_1 \) and \( A_2 \) can be extracted by varying the \textit{direction of the nucleon polarization} or by varying the \textit{beam energy} at fixed \( Q^2, \nu \)

\[
A_{||} = D(A_1 + \eta A_2)
\]

\[
A_{\perp} = d(A_1 + \zeta A_2)
\]

[where \( D, \eta, d, \zeta \) are functions of \( Q^2, E', E, R, \) e.g.:

\[
D = \frac{1 - \varepsilon E'/E}{1 + \varepsilon R}
\]

\[
\eta = \frac{\varepsilon \sqrt{Q^2}}{E - \varepsilon E'} \quad R = \frac{\sigma_L}{\sigma_T}
\]

EG1 used parameterization of world data on \( A_2 \) to extract \( A_1 \) (\( \eta \) is usually small)
The asymmetry analysis

\[ A_{\text{raw}} = \frac{N^-/Q^- - N^+/Q^+}{N^-/Q^- + N^+/Q^+} \]

- N\(^+/−\): Yield for electron/target spins
- antiparallel (−) or parallel (+)
- Q\(^+/−\): gated FC

Physics asymmetry \( A_{||} \)

\[ A_{||\perp} = \frac{C_{\text{back}} A_{\text{raw}}}{P_e P_t \times DF} \]

\[ A_1 + \eta A_2 = \frac{A_{||}}{D} \]

\( A_1, g_1 \) can be extracted

the structure functions \( g_1 \) and \( g_2 \) are linear combinations of \( A_1 \) and \( A_2 \)

\[ g_1(x, Q^2) = \frac{\tau}{1 + \tau} \left( A_1 + \frac{1}{\sqrt{\tau}} A_2 \right) F_1 = \frac{\tau}{1 + \tau} \left( \frac{A_{||}}{D} + \left( \frac{1}{\sqrt{\tau}} - \eta \right) A_2 \right) F_1 \]

\[ g_2(x, Q^2) = \frac{\tau}{1 + \tau} (\sqrt{\tau} A_2 - A_1) F_1 \]

\[ D = \frac{1 - E'\varepsilon / E}{1 + \varepsilon R}; \quad \eta = \frac{\varepsilon \sqrt{Q^2}}{E - E'\varepsilon}; \quad R = \frac{\sigma_L}{\sigma_T} \]

\[ \tau = \frac{v^2}{Q^2} \]
Outlook: The Future at JLab

- Remaining experiments at 6 GeV
  - Hall A
    - E-06-010: Transverse target single spin asymmetry in $n \uparrow (e,e'\pi^-)$
    - E-06-011: Transverse target single spin asymmetry in $n \uparrow (e,e'\pi^+)$
    - E-06-014: Precision measurement of $d_2$ on the neutron
    - E-08-027: $g_{2p}$ and $\delta_{LT}$
  - Hall B
    - E-05-113: Semi-inclusive pion production (and DVCS) on $p \rightarrow$
    - E-08-015: Semi-inclusive pion production (and DVCS) on $p \uparrow$
  - Hall C
    - E-07-011: High precision $g_{1d}$ in DIS region
    - E-07-003: SANE (SSFs on $p$, with emphasis on $g_2$)

- Approved experiments for 12 GeV
  - Hall A/C
    - E12-06-122: $A_{1n}$ at high $x$ with 8.8 GeV and 6.6 GeV beam in Hall A
    - E12-06-121: Precision measurement of $g_2$ and $d_2$ on the neutron
  - Hall B
    - E12-06-10: SSFs on longitudinal target with CLAS12
    - E12-07-107: Semi-inclusive pion production on $p \rightarrow$