Spin Structure of the Nucleon

J. P. Chen, Jefferson Lab
Hirschegg Workshop, January 11-17, 2004

- Introduction
- Spin asymmetry at high $x \rightarrow$ valence quark spin distributions
- Sum rules, moments and polarizabilities
- Higher twist effects, quark-gluon correlations
- Quark-hadron duality
- SSA in semi-inclusive: transversity
- Summary
Polarized Deep Inelastic Electron Scattering

\[ x = \frac{Q^2}{2M \nu} \]  
Fraction of nucleon momentum carried by the struck quark

\[ Q^2 = 4\text{-momentum transfer of the virtual photon}, \quad \nu = \text{energy transfer}, \quad \theta = \text{scattering angle} \]

- All information about the nucleon vertex is contained in \( F_2 \) and \( F_1 \), the unpolarized (spin averaged) structure functions, and\[ g_1 \) and \( g_2 \) the spin dependent structure functions.
Quark-Parton Model

In the Bjorken scaling limit

\[ F_1(x) = \frac{1}{2} \sum_i e_i^2 f_i(x) \]

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

\[ f_i(x) = q_i^{\uparrow}(x) + q_i^{\downarrow}(x) \]

\[ \Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x) \]

\[ q_i(x) \quad \text{quark momentum distributions of flavor } i \]

\[ \uparrow(\downarrow) \quad \text{parallel (antiparallel) to the nucleon spin} \]

Observables of interest

\[ A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum \Delta q_i(x)}{\sum f_i(x)} \]

\[ R^{np}(x) = \frac{F_2^m(x)}{F_2^p(x)} \]
Parton Distributions

- After 40 years DIS experiments, unpolarized structure of the nucleon reasonably well understood.
- High $x \rightarrow$ valence quark dominating
Status of Spin Structure Study

• What we’ve learned (before JLab)
  • Total quark contribution to nucleon spin: 20-30%
  • Gluon contribution is probably large
  • Quark orbital angular momentum is important
  • Bjorken Sum Rule verified to ~5%
  • Ellis-Jaffe Sum Rule violated
  • First dedicated $g_2$ experiment (SLAC E155x): higher twist?

• What to be learn
  • Gluon contribution (HERMES, COMPASS, RHIC-Spin, SLAC)
  • $g_1$ at very low $x$ (RHIC-Spin, future ELIC)
  • Precision measurement of $A_1$ at high $x$
  • Precision measurement of $g_2$ (higher twists)
  • (Generalized) GDH Sum Rule, moments of $g_1$ and $g_2$, polarizabilities
  • Quark-hadron duality in $g_1$ and $A_1$

• Extend to semi-inclusive and exclusive
  • Spin-flavor decomposition
  • Transversity
  • Quark orbital angular momentum
Overview of Spin Structure Experiments

- High $Q^2$, DIS: SLAC, CERN, HERMES, RHIC-Spin
  - $<Q^2>$ above 1 GeV$^2$, polarized $p$, $d$ and $^3$He
- Real Photon:
  - Mainz/Bonn, JLab, LEGS, GRAAL, TUNL, SPRING-8
- Low-Intermediate $Q^2$:
  - JLab Hall A: neutron with polarized $^3$He
    $A_1^n$ at high $x$, valence quark spin structure, $Q^2$ range 3-5 GeV$^2$
    GDH*, $Q^2$ range 0.02 - 1 GeV$^2$
    $g_2$ at $x$~0.2, $Q^2$ from 0.5-1.5 GeV$^2$, higher twist
    Spin Duality: $Q^2$ from 1-4 GeV$^2$
  - JLab Hall B: proton and deuteron, $Q^2$ range 0.2-2 GeV$^2$
  - JLab Hall C: proton and deuteron, $<Q^2>$ ~ 1.3 GeV$^2$
- Semi-inclusive: HERMES, JLab
Valence Quark Spin Structure

$A_1$ at high $x$
Predictions for large $x_{Bj}$

Proton Wavefunction (Spin and Flavor Symmetric)

\[ |p \uparrow \rangle = \frac{1}{\sqrt{2}} |u \uparrow (ud)^{s=0} \rangle + \frac{1}{\sqrt{18}} |u \uparrow (ud)^{s=1} \rangle - \frac{1}{3} |u \downarrow (ud)^{s=1} \rangle - \frac{1}{3} |d \uparrow (uu)^{s=1} \rangle - \frac{\sqrt{2}}{3} |d \downarrow (uu)^{s=1} \rangle \]

<table>
<thead>
<tr>
<th>Nucleon Model</th>
<th>$F_2^n/F_2^p$</th>
<th>$d/u$</th>
<th>$\Delta u/u$</th>
<th>$\Delta d/d$</th>
<th>$A_1^n$</th>
<th>$A_1^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(6)</td>
<td>2/3</td>
<td>1/2</td>
<td>2/3</td>
<td>-1/3</td>
<td>0</td>
<td>5/9</td>
</tr>
<tr>
<td>Valence Quark</td>
<td>1/4</td>
<td>0</td>
<td>1</td>
<td>-1/3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pQCD</td>
<td>3/7</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tbody>
</table>
# Physics Overview as $x \rightarrow 1$

<table>
<thead>
<tr>
<th>Diquark Spin State</th>
<th>$F^n_2/F^p_2$</th>
<th>$A^p_1$</th>
<th>$A^n_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S=1 and S=0 equiprobable: SU(6)</td>
<td>$2/3$</td>
<td>$5/9$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td>$d/u=1/2$</td>
<td>$\Delta u/\Delta d \rightarrow 2/3$</td>
<td>$\Delta d/\Delta d \rightarrow -1/3$</td>
</tr>
<tr>
<td>S=1 suppressed, S=0 retained</td>
<td>$1/4$</td>
<td>$+1$</td>
<td>$+1$</td>
</tr>
<tr>
<td></td>
<td>$d/u=0$</td>
<td>$\Delta u/\Delta d \rightarrow 1$</td>
<td>$\Delta d/\Delta d \rightarrow -1/3$</td>
</tr>
</tbody>
</table>

F. Close, Phys. Lett. 43B (1973) 422.  

S = 1, $S_Z = 1$ suppressed  
S = 1, $S_Z = 0$ and S = 0 retained  

G. Farrar, Phys. Lett. 70B (1977)346

Instantons!  
N. Kochelev, hep-ph/9711226
World Data on $A_1^n$ and Models

- SU(6): $A_1^n = 0$
- Valence quark models
- pQCD assuming HHC (hadron helicity conservation)
- PDF fits (LSS)
- Statistical model
- Chiral Soliton model
- Local duality model
- Cloudy bag model

Need precision data at high $x$
JLab E99-117

Precision Measurement of $A_1^n$ at Large $x$
Spokespersons: J. P. Chen, Z. -E. Meziani, P. Souder, PhD Student: X. Zheng

- First precision $A_1^n$ data at high $x$
- Extracting valence quark spin distributions
- Test our fundamental understanding of valence quark picture
  - SU(6) symmetry
  - Valence quark models
  - pQCD (with HHC) predictions
  - Other models
- Quark orbital angular momentum
- Crucial input for pQCD fit to PDF
JLab Polarized $^3$He Target

- Laser optics
- Three (four) 30W Diode Lasers (795nm)
- RF Drive Coil
- Oven
- EPR optics
- EPR RF Coil
- Pick-Up Coils
- RF Drive Coil

Main Holding Helmholtz Coil

Main Holding Helmholtz Coil
JLab E99-117 $A_1^n$ Results

- First precision $A_1^n$ data at $x > 0.3$
- Comparison with model calculations
  - SU(6) symmetry
  - Valence quark models
  - pQCD (with HHC) predictions
  - Other models
- Crucial input for pQCD fit to PDF
- PRL 92, 012004 (2004)
$A_2^n$ results

- Obtained as a by-product
- Precision as good as the world best results
Precision $g_1^n$ and $g_2^n$ results
Pion Asymmetry

- Another by-product
Inclusive pion asymmetry
- Dominated by photon production
- Awaiting theoretical calculations
  (J. M. Laget, …)
$A_1$ and $A_2$ vs. $x$
Polarized Quark Distributions

- Combining $A_1^\Lambda$ and $A_1^\Lambda$ results
- Valence quark dominating at high $x$
- $u$ quark spin as expected
- $d$ quark spin stays negative!
  - Disagree with pQCD model calculations assuming HHC (hadron helicity conservation)
  - Quark orbital angular momentum
- Consistent with valence quark models or pQCD PDF fits
Discussion

- First precision data of $A_1^n$ and $g_1^n$ at high $x$ (up to 0.6)
- $A_1^n$ positive above $x=0.5$
- Extracted $\Delta u/u$ and $\Delta d/d$
  - $\Delta d/d$ stays negative!
- Provide important input for pQCD fit to spin PDF

- Consistent with pQCD fit of spin PDF to previous data
- Consistent with SU(6) breaking valence quark models
- Disagree with leading order pQCD model
  - Hadron Helicity conservation assumption in question
  - Quark orbital angular momentum important

The results published in PRL 92, 012004 (2004), and also in the news:
  - AIP Physics News Update
  - Science online (Science Now)
  - Science News
A$_1^n$ with 12 GeV Upgrade

One of the flagship experiments:

- Complete a chapter on the valence quark structure
- Use $^3$He target and 15 $\mu$A beam
- Use a new medium (wide) acceptance spectrometer for e detection
Generalized GDH Sum Rule

Moments and Polarizabilities
Gerasimov-Drell-Hearn Sum Rule

\[ \int_{\nu_{in}}^{\infty} \left( \sigma_{J_2}(\nu) - \sigma_{3J_2}(\nu) \right) \frac{d\nu}{\nu} = -\frac{2 \pi^2 \alpha_{EM}}{M^2} \kappa^2 \]

• A fundamental relation between the nucleon spin structure and its anomalous magnetic moment
• Based on general physics principles
  - Lorentz invariance, gauge invariance, unitarity
  - unsubtracted dispersion relation applied to forward Compton amplitude
• First measurement on proton up to 800 MeV (Mainz) and up to 3 GeV (Bonn)
• Results agree with sum rule with assumptions for higher energy contributions
• Next: Mainz, GRAAL, SPring-8, LEGS, HIGS, JLab, SLAC
• The neutron
Generalized GDH Sum Rule

- Dispersion relations on Virtual Compton Scattering lead to Generalized GDH sum rule valid at all $Q^2$ (Ji and Osborne)

- $Q^2$-evolution of GDH Sum Rule provides a bridge linking strong QCD to pQCD
  - Bjorken and GDH sum rules are two limiting cases
  - Operator Product Expansion of higher twists: $> 1 \text{ GeV}^2$
  - Chiral Perturbation Theory: $< 0.1 \text{ GeV}^2$
  - Intermediate region: Lattice QCD calculations
Why is $I^{GDH}(Q^2)$ interesting?

One of the few opportunities to "zoom out" from tiny length scales (DIS) to large length scales

$-\frac{2\pi^2\alpha}{M^2} \kappa^2$

$2\pi^2\alpha S_1(0; Q^2)$

$rac{16\pi^2\alpha}{Q^2} \Gamma_1$

Non-perturbative, confinement

PQCD

OPE, Bjorken, Ellis-Jaffe

Many of the underlying assumptions are the same as those being tested in high-energy spin-structure tests
Moments of \( g_1, g_2 \)

At large \( Q^2 \), twist expansion (OPE):

\[
\Gamma_1(Q^2) = a_0 + \frac{M^2}{9Q^2} (a_2 + 4d_2 - 4f_2) + O\left(\frac{M}{Q}\right)^4
\]

\( a_0 \): leading twist, \( a_2 \): target mass term, \( d_2 \) and \( f_2 \) related to color E-M polarizibilities

Define \( d_2 \) to be

\[
d_2(Q) = \int_0^1 x^2 \left[ 2g_1(x, Q^2) + 3g_2(x, Q^2) \right] dx = 3 \int_0^1 x^2 \left[ g_2(x, Q^2) - g_2^{ww}(x, Q^2) \right] dx
\]

at large \( Q^2 \), \( d_2 \) is the twist 3 term as in OPE

Wanndzura-Wilczek term

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

Burkhardt-Cottingham (B-C) sum rule

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

Nucleon Forward Spin Polarizabilities:

\[
\gamma_0(Q^2) = \frac{1}{2\pi^2} \int_{v_0}^{\infty} \frac{K \sigma_{TT}(v, Q^2)}{v^3} dv = \frac{16\alpha M^2}{Q^6} \int_0^x x^2 \left\{ g_1(x, Q^2) - \frac{4M}{Q^2} x^2 g_2(x, Q^2) \right\} dx
\]

\[
\delta_{LT}(Q^2) = \frac{1}{2\pi^2} \int_{v_0}^{\infty} \frac{K \sigma_{LT}(v, Q^2)}{Q v^2} dv = \frac{16\alpha M^2}{Q^6} \int_0^x x^2 \left\{ g_1(x, Q^2) + g_2(x, Q^2) \right\} dx
\]

-- With \(x^2\) weighting, the integration mostly from low energy part

-- \(\delta_{LT}\) is not sensitive to the Delta and should be converging fast in ChPT
Measurement of Neutron ($^3\text{He}$) Spin Structure Function at Low $Q^2$, a Connection between Bjorken and GDH Sum Rules

Spokespersons: G. Cates, J. P. Chen, Z.-E. Meziani
PhD Students: A. Deur, P. Djawotho, S. Jensen, I. Kominis K. Slifer

- Investigate $Q^2$ evolution of Spin Structure Functions
- Investigate $Q^2$ evolution of GDH and Bjorken sum rules
- Study GDH integral over transition from perturbative regime to non-perturbative regime
- First results (GDH) published in PRL89,242301 (2002)
- Second results (moments) accepted for publication in PRL
Hall A $g_1^{^3\text{He}}$ and $g_2^{^3\text{He}}$

- First JLab experiment using polarized $^3\text{He}$ target to study neutron spin structure functions

- Parallel and perpendicular asymmetries and cross section measurements $\rightarrow$ precision $g_1$ and $g_2$

- $g_2 \sim -g_1$ in the $\Delta$ resonance region
  (i.e. $\sigma_{LT} \sim 0$)
First Moment of $g_1^n$

- High precision data
- Resonance contributions to the first moment significant
- Smooth transition
- Test fundamental understanding
  - ChPT at low $Q^2$
  - Twist expansion at high $Q^2$
  - Models
  - Future Lattice QCD
• Additional CLAS data have been taken at lower and higher energies for more complete kinematic coverage.
• For the 5.6 GeV data, $g_1$ is positive.
• The $\Delta$ drives the 1.6 GeV data negative.
• The newer data generally extend to lower $x$, and require less extrapolation when calculating moments.
Moments of $g_1^p - g_1^n$

Hall B results of moment $\Gamma_1^p$
- Resonance significant contribution
- Zero crossing

Combine Hall A $g_1^n$ with Hall B $g_1^p$ data

Chiral Perturbation Theory ($\chi$PT)

Bjorken Sum Rule (Verification of QCD)

PRELIMINARY
Moments of $g_2^n$

- First moment:
  Burkhardt-Cottingham sum rule
- Second moment $d_2$
  Twist-3 matrix element
- Same assumptions as GDH, with super-convergence
- Color polarizabilities
- ChPT (low $Q^2$), MAID model and Lattice QCD (high $Q^2$)
- Elastic and high energy contributions
- B-C sum rule satisfied within uncertainties
- Need intermediate $Q^2$ data
Forward Spin Polarizabilities

- ChPT expected to work at low $Q^2$ (up to 0.1-0.2 GeV$^2$?)
  - $\gamma_0$ sensitive to resonance
  - $\delta_{LT}$ insensitive to $\Delta$ resonance
- Comparison with two group’s ChPT calculations
- Good agreement with MAID model predictions
Forward Spin Polarizabilities

- Expected to scale at high $Q^2$
- Reasonable agreement with MAID model predictions
JLab E97-110
GDH Sum Rule and Spin Structure of $^3$He and Neutron with Nearly Real Photons

Spokespersons: J. P. Chen, A. Deur, F. Garibaldi; PhD Students: J. Singh, V. Sulkosky, J. Yuan

• Measured generalized GDH at $Q^2$ near zero for $^3$He and neutron
  Slope of GDH sum rule at $Q^2 \sim 0$
  Check ChPT
  Extrapolation to real photon point
  Constraints on resonance models

• Overlap with previous Hall A GDH experiment E94-010 (PRL89, 242301 (2002))

• Data acquisition completed
• Analysis underway
Future GDH Measurements

- Hall A will extend its polarized neutron structure function measurements to low $Q^2$ by using a septum magnet to get down to $6^\circ$ scattering angles (left graph).

- Hall B will extend its polarized proton structure function measurements to low $Q^2$ by using a new small-angle Cherenkov counter (right graph).

- Together, these experiments will map out the approach to the Gerasimov-Drell-Hearn (GDH) limit.

- GDH extrapolation shows $\Gamma_1 \rightarrow -\kappa^2 Q^2 / 8M^2$ as $Q^2 \rightarrow 0$. 
Higher Twists:
Quark-gluon Correlations

Quark-hadron Duality

Transversity
Quark-Gluon Correlations

\[ g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2) \]
\[ g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x g_1(y, Q^2) \frac{dy}{y} \]

- In simple partonic picture \( g_2(x) = 0 \)
- Wandzura and Wilczek have shown that \( g_2 \) can be written in two parts:
  - twist-2 contributions given by \( g_1 \)
  - the other originating from quark-gluon correlations (twist-3)

\[
d_2^n(Q^2) = \int_0^1 x^2 \left[ 2g_1^n(x, Q^2) + 3g_2^n(x, Q^2) \right] dx \quad \text{and} \quad d_2 = (2\chi_B + \chi_E) / 3
\]
• Inclusive DIS of polarized electrons from a polarized $^3$He target.
• Precision $g_2^n$ data covering $0.57 < Q^2 < 1.34\ \text{GeV}^2$ at $x \sim 0.2$.
• Direct comparison to \textit{twist-2} $g_2^{ww}$ prediction using world $g_1^n$ data.
• Quantitative measurement of higher twist effects provides information on nucleon structure beyond simple parton model (e.g. quark-gluon correlations.)
Jefferson Lab E97-103
Preliminary Results

- Measured $g_1^n$ agree with NLO fit to world data, evolved to our $Q^2$.

- Measured $g_2^n$ consistently higher than $g_2^{ww}$ at low $Q^2$.

- E97-103 improved precision of $g_2^n$ by an order of magnitude.
Measurement of neutron ($^3$He) spin structure functions in the resonance region

Spokespersons: J. P. Chen, S. Choi, N. Liyanage; PhD student: P. Solvignon

- Measured $g_1^n$ and $A_1^n$ in the resonance region for $1.0 < Q^2 < 4.0$ GeV$^2$

- Combined with DIS measurements:
  provide a first test of spin-flavor dependence of quark-hadron duality

- Quark-hadron duality: scaling curve seen at high $Q^2$ is an accurate average over the resonance bumps at lower $Q^2$ (observed for $F_2^p$)

- $g_1^n$ at $Q^2 \sim 1$ GeV$^2$ from E94-010 shows hints of duality

- If duality established
  - Powerful tool to study very high $x$ behavior
Hint from E94-010 data: approaching duality

- E94-010 resonance $g_1$ data, $Q^2$ from 0.58 to 0.9 GeV$^2$
- Comparing with SLAC DIS $g_1$ data, $Q^2 = 5$ GeV$^2$
- First hint of approaching quark-hadron duality
Projected results shown here (black triangles), compared to published resonance data (blue squares) and DIS data (red circles), are from one of the four kinematic settings of the experiment.

- Data taken early 2003
- Data analysis in progress
- Preliminary results expected this Spring.
- Beam energy 5.755 GeV.
- HMS spectrometer at 13.08°.
- $< Q^2 > = 1.3$ GeV$^2$.
- First JLab measurement using ammonia targets to measure $\perp$ configuration.
Comparison of NH$_3$ and ND$_3$ Asymmetries

Replay by Frank Wesselmann
Neutron Transversity through $^3\text{He}(e,e'\pi)$

Transverse target single spin asymmetry $n(e,e'\pi)X$

First transversity measurement on neutron

- high polarized luminosity
- $x$: 0.19-0.34, $Q^2$: 1.8-2.7 GeV$^2$, $W$: 2.5-2.9 GeV
- separation of Collins and Sivers effects
- complementary to the proton data of HERMES run-II
Summary

- JLab precision spin structure data
  - $A_1$ at high $x$: valence quark spin distributions
    - $A_1^n$ went to positive above $x=0.5 \rightarrow$ SU(6) breaking,
      - $\Delta d/d$ stays negative $\rightarrow$ quark orbital angular momentum
  - GDH* sum rule, moments, polarizabilities
    - Bridge linking strong QCD to pQCD
    - ChPT, OPE twist expansion, and Lattice QCD
  - Higher twister: q-g correlations
  - Quark-hadron duality
  - Transversity

- Outlook: even more exciting
  - Near term: several experiments planned
  - Long term: 12 GeV upgrade (Friday 1/16 talk by J. P. Chen)