Measurement of Spin Structure Functions in Hall C

Mark Jones
Jefferson Lab

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Hall C Program

- Spin Structure Functions (SSF)
  - Inclusive measurements
    * SSF in the Nucleon Resonance Region
      E01-006 preliminary data
    * SSF at high Bjorken $x$
      E03-109 Cond. approved
  - Semi-Inclusive in DIS measurements
    * Spin asymmetries in $(e, e'h)$  \[ h = \pi^\pm, K^\pm \]
      PAC26 proposal

- Tools
  - CEBAF Polarized beam
  - Solid Polarized NH$_3$ and ND$_3$ targets
    Target field direction parallel and perpendicular to beam direction
  - Hall C High Momentum Spectrometer (HMS) for E01-006
  - Non-magnetic detector, BETA (Big Electron Telescope Array)
    for E03-109 and PAC26 proposal
Resonances Spin Structure (RSS)

Precision Measurement of the Nucleon Spin Structure Functions
in the Region of the Nucleon Resonances


Spokesmen: Oscar A. Rondon (U. of Virginia) and Mark K. Jones (Jefferson Lab)

- Measure proton and deuteron spin asymmetries \( A_1(W, Q^2) \) and \( A_2(W, Q^2) \)
at momentum transfer \( Q^2 \approx 1.3 \) GeV\(^2\) and invariant mass \( 0.8 < W < 2 \) GeV.

- Extract \( g_1 \) and \( g_2 \) structure functions and study:
  - \( W \) dependence
  - Onset of polarized local duality
  - twist-3 effects in \( d_2 \) matrix element
• Final state mass region $W < 2$ GeV (resonances) dominates kinematic plane for four-momentum transfer $Q^2 < 5$ GeV$^2$
  - few data in high Bjorken $x$ region
  - DIS-resonances connection (duality)

• Good $W$ resolution required for resonances (Not available at HEP labs - SLAC, HERMES, SMC)
  - JLab Hall C High Momentum Spectrometer (HMS) has $\Delta W < 30$ MeV
Quantitative tests of duality of unpolarized SF (SLAC, JLab) and to a lesser degree polarized SF (SLAC, Hermes, JLAB). (Talk by S. Liuti)

- SLAC 143: $g_1$ from $A_\parallel$ assuming $A_2 = 0$
- Resolution in W too wide for local duality test
- Global duality ratio of integrals has large error bars.
• Polarized and unpolarized structure functions share common interpretation:
  
  – DIS: Parton model and Operator Product Expansion (OPE)
    
    \[ A_1(x) \approx \frac{g_1(x)}{F_1(x)} = \frac{\sum e_i^2 \Delta q_i}{\sum e_i^2 q_i} \]
  
  – Resonances: forward virtual Compton scattering
    
    \[ A_1(Q^2, \nu) = \frac{\sigma_{1/2}^T - \sigma_{3/2}^T}{\sigma_{1/2}^T + \sigma_{3/2}^T} = \frac{M \nu G_1(Q^2, \nu) - Q^2 G_2(Q^2, \nu)}{W_1(Q^2, \nu)} \]
  
  – Connection: scaling limit
    
    \[ \lim_{Q^2, \nu \to \infty} M \nu G_1(Q^2, \nu) = g_1(x) \quad \lim_{Q^2, \nu \to \infty} MW_1(Q^2, \nu) = F_1(x) \]
Electron-Nucleon Polarized Scattering

\[ \Delta \sigma(\theta, \theta_N, \phi) = \frac{d^2 \sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2 \sigma^{\uparrow\downarrow}}{d\Omega dE'} \]

\[ \Delta \sigma(\theta_N = 0) = \frac{4 \alpha^2 E'}{Q^2 E} \left\{ (E + E' \cos \theta)MG_1 - Q^2 G_2 \right\} = 2\sigma_u A_{||} \]

\[ \Delta \sigma(\theta_N = \frac{\pi}{2}) = \frac{4 \alpha^2 E'}{Q^2 E} E' \sin \theta \cos \phi (MG_1 + 2EG_2) = 2\sigma_u A_{\perp} \]
Relation between $A_1, A_2$ and $A_{\parallel}, A_{\perp}$

- Clean extraction of $A_1, A_2$ for protons and deuterons is crucial.
- Solution: measure $A_{\parallel}, A_{\perp}$ on polarized ammonia

$$A_1 = \frac{C}{D}(A_{\parallel} - dA_{\perp})$$

$$A_2 = \frac{C}{D}(c' A_{\parallel} - d' A_{\perp})$$

- Kinematic variables $C, c', d, d'(E, E', \theta), D(E, E', \theta, R)(R = \sigma_L/\sigma_T)$
- $d' \approx 1, c' \approx d \leq 1$ (at RSS kinematics)
- Comparable systematic errors for both $A_{\parallel}, A_{\perp}$ is important.
SSF $g_1, g_2$ and Spin Asymmetries $A_1, A_2$

- $g_1, g_2$ can be extracted directly from $A_\parallel, A_\perp$ or $A_1, A_2$

\[
g_1 = \frac{F_1}{1 + \gamma^2}(A_1 + \gamma A_2)
\]

\[
g_2 = \frac{F_1}{1 + \gamma^2}(\frac{A_2}{\gamma} - A_1); \quad \gamma^2 = \frac{Q^2}{\nu^2}
\]

- Need $F_1 = F_2(1 + \gamma^2)/2x/(1 + R)$ in the resonance region.
  Measurement of F2 and R in resonance region (see E. Christy’s talk)

- Also can get $g_1, g_2$ directly from cross section differences:
  
  $F_2$ and $R$ not needed

- $g_1$ can be extracted from $A_\parallel$ and SSF model for $g_2$
• Raw Asymmetry, \( \epsilon = \frac{N^+ - N^-}{N^+ + N^-} \)
in which \( N^+ \), \( N^- \) are the number of counts normalized by the
charge and deadtime for opposite beam helicities.

• Parallel and perpendicular asymmetries

\[
A_{\parallel, \perp} = \frac{1}{C_N f_{rc}} \left( \frac{\epsilon}{f P_b P_t} - C_D \right) + A_{rc}
\]

- \( f = \) dilution factor; ratio of rates from polarized nucleons to all
  nucleons
- \( P_b, P_t = \) beam and target polarizations
- \( C_N, C_D = \) corrections of N in ammonia
- \( f_{rc}, A_{rc} = \) radiative corrections

Use code for polarized scattering in resonances
( I. Akusevich)
- Incident beam rastered in circular pattern with 2cm diameter.
- Before target, chicane magnets bend the beam to compensate for target field to make beam horizontal at target..
- Polarized target rotated so target field direction either parallel or perpendicular to beam direction.
Kinematic coverage

- Beam Energy = 5.755 GeV
- Electron scattering angle 13.15°
- HMS central momentum settings of 4.7 and 4.1 GeV/c
- $\langle Q^2 \rangle = 1.3 \text{ GeV}^2$ over $W$ range of 0.8 to 2.0 GeV.
Polarized Target

- Microwave Input
- NMR Signal Out
- Refrigerator
- Liquid Helium Magnet (inside coil)
- NMR Coil
- To Pumps
- LN2

Diagram:
- Electron Beam
- Target (inside coil)
- 1° K

Graph:
- Polarization (% Red=Top, Blue=Bottom)
- Proton
- Deuteron
- Run Number - 40000
Beam Characteristics

- Beam current
  - 150 - 200 nA for ND$_3$, C, He
  - 85 - 100 nA for NH$_3$

- Beam polarization measured in the Hall with Moller
$^{12}$C yield compared to Monte Carlo

Parallel field

Perpendicular field

Data at $p_{\text{cent}} = 4.7$ GeV/c
Monte Carlo
Data at $p_{\text{cent}} = 4.0$ GeV/c
Dilution factors

Preliminary assuming 50% packing fraction

- need to determine packing fraction for target cell (8 in total)
- Packing fraction between 0.5 to 0.6 determined by ratio on ammonia to carbon rates.
• Preliminary dilution factor (same packing fraction for all targets).

• Not applied: Radiative corrections, individual packing fractions, N asymmetry.
<table>
<thead>
<tr>
<th>Source</th>
<th>$^{15}NH_3$</th>
<th>$^{15}ND_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen polarization</td>
<td>&lt;1%</td>
<td>1%</td>
</tr>
<tr>
<td>Radiative corrections</td>
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<td>3%</td>
</tr>
<tr>
<td>Beam Polarization</td>
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<td>1.5%</td>
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<tr>
<td>Target polarization</td>
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<td>Dilution factor</td>
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<tr>
<td>Pions, deadtime</td>
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<td>1%</td>
</tr>
<tr>
<td>Errors from R and F2</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Total error</strong></td>
<td><strong>5.5%</strong></td>
<td><strong>6.8%</strong></td>
</tr>
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</table>
Extracted $A_{1p}$ and $g_{1p}$

Use hall C fit to $F_{2p}$ and $R$
Spin Asymmetries on the Nucleon Experiment

U. Basel, Florida International U., Hampton U., IHEP Protvino, Norfolk State U., Rensselaer Polytechnic I.,
Temple U., TJNAF, U. of Virginia, College of William & Mary, Yerevan Physics I.

Spokesmen: Oscar A. Rondon (U. of Virginia), Zein-Eddine Meziani (Temple U.) and Seonho Choi (Temple U.)

- Measure inclusive electron scattering spin asymmetries, $A_{\parallel}$ and $A_{\perp}$, on $NH_3$ target. Two beam energies: 4.8 and 6 GeV so large kinematic range
  - $2.5 < Q^2 < 6.5$ GeV$^2$
  - $0.3 < x < 0.8$

- Extract proton $g_2(x, Q^2)$ and $A_1(x, Q^2)$

- Study $x$ and $Q^2$ dependence, twist-3 effects, moments of $g_2$ and $g_1$,
  comparison with Lattice QCD predictions,
  test polarized local duality for $W > 1.4$ GeV.
Experimental Setup

**Target**
- UVa NH3 target
- 5 T field

**Beamline**
- Chicanes
- SEM
- He Bag

**Electron Arm**
- BETA

**Background Studies**
- HMS

\[ \theta_{\text{BETA}} = 40^\circ \]
\[ \theta_N = 80^\circ \]
\[ \theta_N = 180^\circ \]
\[ \theta_{\text{HMS}} = 35-45^\circ \]
Big Electron Telescope Array (BETA)

- Lead Glass Calorimeter
  - $\Delta E/E = 5\%/\sqrt{E}$
  - Large solid angle (194msr)
  - Highly segmented, 1744 blocks (4 x 4 x 40cm)

- Gas Cerenkov
  - $\pi/e$ separation, 1000:1 rejection factor

- Lucite hodoscope array
  - Redundant PID, Tracking info when combined with Calo.
Kinematic coverage with two beam energies
Expected Results for proton $g_2$ and $A_1$
Expected Results $x$ and $Q^2$ dependence
Semi-Inclusive Spin Asymmetries on the Nucleon Experiment

Spokesmen: P. Bosted (Jlab), D. Day (U. of Virginia), X. Jiang (Rutgers); M. Jones (JLab)

- Measure proton and deuteron semi-inclusive longitudinal spin asymmetries in polarized DIS reactions $p(e, e'h)$ and $d(e, e'h)$ for $h = \pi^\pm, K^\pm$ at $1.2 < Q^2 < 3.1$ GeV$^2$, $0.12 < x < 0.43$, with hadrons carrying $0.5 < z(= E_h/\nu) < 0.7$ of the energy transfer $\nu$

- Spin flavor decomposition with special emphasis on NLO spin flavor decomposition to extract $\Delta u_v, \Delta d_v$ and $\Delta \bar{u} - \Delta \bar{d}$ based on measurement of combined asymmetry, $A_{1N}^{\pi^+ - \pi^-}$. Christova and Leader PLB 468 (1999), NPB 607 (2001)

- Examine deviation from factorization by comparing combined asymmetry, $A_{1N}^{\pi^+ + \pi^-}$ with the inclusive asymmetry, $A_{1N}$. 
- Electrons detected in BETA at 30°
- Hadrons detected in HMS at 10.8° and $p_{cent} = 2.7$ GeV/c
  - HMS had ± 10% momentum bite
  - Kaon PID by hit in aerogel but not gas cerenkov
  - Pion PID by hit in aerogel and gas Cerenkov
  - Positrons eliminated by energy in HMS calorimeter.
- Longitudinally polarized target of NH$_3$ and LiD.
Kinematic coverage
In leading order, the hadron production cross sections factorize

\[ A^h_{1N}(x, Q^2, z) = \frac{\sum_f e_f^2 \Delta q_f(x, Q^2) \cdot D^h_f(z, Q^2)}{\sum_f e_f^2 q_f(x, Q^2) \cdot D^h_f(z, Q^2)}. \]

In well defined \( z \)-bin, then each asymmetry can be related to quark polarization, e.g.:

\[ A^\pi_{1p}(x, z) = \frac{4\Delta u + \Delta d + (4\Delta \bar{u} + \Delta d) \lambda_\pi + 2\Delta s \xi_\pi}{4u + d + (4\bar{u} + d) \lambda_\pi + 2s \xi_\pi} \]

\[ \lambda_\pi(z) = \frac{D^-_\pi(z)}{D^+_\pi(z)} \]

\[ \xi_\pi(z) = \frac{D^\pi_s(z)}{D^\pi_\pi(z)} \]

are ratios of fragmentation functions (FF).

- Ratios of FF better known than FF themselves.

- Measure 10 double-spin asymmetries

\[ \vec{A} = \left( A^\pi_{1p}, A^\pi_{1d}, A^K_{1p}, A^K_{1d}, A_{1p}, A_{1d} \right) \]

and the extract 5 quark polarization

\[ \vec{Q} = \left( x\Delta u, x\Delta d, x\Delta \bar{u}, x\Delta d, xs \right) \]
Flavor Decomposition

- GRSV 2000
- BB
- Positivity limit

Data points:
- Projected JLab data
\[ A_{1p}^{\pi^+\pm\pi^-}(x, Q^2, z) = \frac{\Delta \sigma_p^{\pi^+}}{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}} \pm \frac{\Delta \sigma_p^{\pi^-}}{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}} \]

\[ A_{1d}^{\pi^+\pm\pi^-}(x, Q^2, z) = \frac{\Delta \sigma_d^{\pi^+}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} \pm \frac{\Delta \sigma_d^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} \]

Polarized light sea asymmetry

\[
\begin{align*}
A_{1p}^{\pi^+ - \pi^-} &= \frac{\Delta \sigma_{p}^{\pi^+} - \Delta \sigma_{p}^{\pi^-}}{\sigma_{p}^{\pi^+} - \sigma_{p}^{\pi^-}} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}, \\
A_{1d}^{\pi^+ - \pi^-} &= \frac{\Delta \sigma_{d}^{\pi^+} - \Delta \sigma_{d}^{\pi^-}}{\sigma_{d}^{\pi^+} - \sigma_{d}^{\pi^-}} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}.
\end{align*}
\]

Therefore:

\[
\begin{align*}
(\Delta u_v)_{LO} &= \frac{1}{5} \left[ (4u_v - d_v) \cdot A_{1p}^{\pi^+ - \pi^-} + (u_v + d_v) \cdot A_{1d}^{\pi^+ - \pi^-} \right] , \\
(\Delta d_v)_{LO} &= \frac{1}{5} \left[ 4 (u_v + d_v) \cdot A_{1d}^{\pi^+ - \pi^-} - (4u_v - d_v) \cdot A_{1p}^{\pi^+ - \pi^-} \right] , \\
(\Delta u_v - \Delta d_v)_{LO} &= \frac{1}{5} \left[ 2 (4u_v - d_v) \cdot A_{1p}^{\pi^+ - \pi^-} - 3(u_v + d_v) \cdot A_{1d}^{\pi^+ - \pi^-} \right].
\end{align*}
\]

From the inclusive DIS data, we have:

\[
g_1^p(x, Q^2) - g_1^n(x, Q^2) = \frac{1}{6} \Delta q_3(x, Q^2) \big|_{LO},
\]

the non-singlet \( \Delta q_3 \) is defined as:

\[
\Delta q_3(x, Q^2) \equiv (\Delta u + \Delta \bar{u}) - (\Delta d + \Delta \bar{d}).
\]

The polarized light sea asymmetry can be extracted through:

\[
(\Delta \bar{u} - \Delta \bar{d}) \big|_{LO} = 3(g_1^p - g_1^n) \big|_{LO} - \frac{1}{2} (\Delta u_v - \Delta d_v) \big|_{LO}.
\]

A similar relation holds at the NLO.
Polarized light sea asymmetry

\[ x \Delta u_v \]
\[ x \Delta d_v \]
\[ x (\bar{u} + \bar{d}) \text{ CTEQ5M} \]

HERMES $Q^2 = 2.5 \text{ GeV}^2$
SMC $Q^2 = 10.0 \text{ GeV}^2$

This experiment
fixed-$z$ purity
sys. err. C.-L.
Christova-Leader
AAC-03
$Q^2 = 2.5 \text{ GeV}^2$
Comparison between Inclusive and Semi-Inclusive
Summary of Hall C spin program

- RSS experiment measured $A_\parallel$ and $A_\perp$ in inclusive electron scattering on protons and deuterons
  - Extract $g_1$ and $g_2$ at $Q^2 = 1.3$ GeV$^2$ and $0.8 < W < 2.0$
  - Finished analysis by end of 2004

- Approved experiment to measure $A_\parallel$ and $A_\perp$ in inclusive electron scattering on proton with large acceptance detector (BETA)
  - Extract $g_1$ and $g_2$ in range $2.5 < Q^2 < 6.5$ and $0.3 < x < 0.8$
  - Tentatively scheduled to run at end of 2006

- Proposed experiment to measure $A_{1N}^{h\pm}$ for SIDIS reactions $p(e, e'h)$ and $d(e, e'h)$ for $h = \pi^\pm, K^\pm$ for protons and deuterons.
  - $1.2 < Q^2 < 3.1$ GeV$^2$, $0.12 < x < 0.43$, $0.5 < z < 0.7$
  - Spin flavor decomposition
  - “Test” of validity of factorization by checking if $A_{1N}^{\pi^+ + \pi^-}$ equals the inclusive asymmetry, $A_{1N}$. 