RSS and SANE

Oscar A. Rondón
University of Virginia

Spin Structure at Long Distance
Jefferson Lab
March 12, 2009
Hall C 6 GeV Spin Structure Program

- Spin Structure Functions at 6 GeV:
  - Inclusive measurements
    - SSF's in the Nucleon Resonances Region – RSS - Published
    - Proton SSF at high Bjorken $x$ – SANE - Completed
    - Precision Deuteron spin structure – $g_1^d/F_1^d$ - Pending
  - Semi-inclusive measurements
    - Flavor Decomposition of Nucleon Spin – SemiSANE - Pending
- Real Polarized Photons:
  - Polarized Compton Scattering – Pending
- Four experiments rated A or A-
**RSS - Resonances Spin Structure**

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

**TJNAF E01-006**


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 $Q^2 \approx 1.3 \text{ GeV}^2$ and $0.8 \leq W \leq 1.91 \text{ GeV}$

- Study $W$ dependence of asymmetries, onset of polarized local duality, twist-3 effects, using inclusive polarized scattering
**RSS Technique**

- **Equipment: TJNAF Hall C**
  - CEBAF polarized electron beam
    - 5.755 GeV- 66 to 71% polarization
    - 2 cm diameter raster at target
    - $I = 85-150$ nA
  - Target: polarized ammonia $\text{NH}_3$, $\text{ND}_3$.
    - Luminosity $\sim 10^{35}$ s$^{-1}$cm$^{-2}$
    - HMS electron detector
- **Kinematics**
  - Final state mass range:
    - $0.8 \text{ GeV} \leq W \leq 1.91$ GeV
  - $<Q^2> = 1.28$ [GeV/c]$^2$
Polarized Target

- Dynamic Nuclear Polarized ammonia (NH$_3$, $<P>$ ~ 70% in beam) and deuterated ammonia (ND$_3$, $<P>$ 20-30%)
  - Wide range of field orientations
- Target used in six experiments before SANE:
  - SLAC E143, E155, E155x ($g_2$)
  - JLab GEn98, GEn01, RSS
- Damaged coils successfully repaired in Nov. '08 by JLab staff with Oxford Inst. help
- Down but not out.
Measured asymmetries $A_{\parallel}, A_{\perp}$

$$A_{\parallel, \perp} = \left( \frac{\epsilon}{f P_b P_t C_N} + C_D \right) + A_{rc}$$

$$\epsilon = \frac{N^- - N^+}{N^- + N^+}$$

- $N^-, N^+ =$ charge normalized, dead time and pion corrected yields for +/- beam helicities
- $P_b, P_t =$ beam, target polarizations
- $f =$ dilution factor
- $C_N, C_D =$ polarized nucleons in $^{15,14}N$
  - proton $C_D = 0$, deuteron $C_N \approx 1$
- $A_{rc} =$ radiative correction

<table>
<thead>
<tr>
<th>Proton Elastic</th>
<th>$G_E/G_M$ Sensitivity</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\parallel}$</td>
<td>Low</td>
<td>$P_b P_t$</td>
</tr>
<tr>
<td>$A_{\perp}$</td>
<td>High</td>
<td>$G_E/G_M$</td>
</tr>
</tbody>
</table>

![Graph showing data points and a trend line with a caption indicating the reference PRC 74, 035201 (2006).]
**RSS goal: Spin Asymmetries $A_1, A_2$**

- Combine $A_{\parallel}, A_{\perp}$ to get virtual Compton absorption asymmetries:

  \[
  A_1 = \frac{1}{(E + E')D'} \left( (E - E' \cos \theta)A_{\parallel} - \frac{E' \sin \theta}{\cos \phi} A_{\perp} \right)
  \]

  \[
  A_2 = \frac{\sqrt{Q^2}}{2ED'} \left( A_{\parallel} + \frac{E - E' \cos \theta}{E' \sin \theta \cos \phi} A_{\perp} \right)
  \]

- $A_1, A_2$ have minimal model dependence
  - $D'(E,E',\theta,R)$ is function only of kinematics and $R = \sigma_L/\sigma_T$
    - Proton $R, F_1$ from fit to Hall C $e-p$ data (E. Christy)
    - Deuteron $R, F_1$ from fit to world data (P. Bosted)
Fit A1 and A2 independently
  - Four Breit-Wigner resonance shapes plus DIS background
  - Reduced $\chi^2 = 1.2 - 1.4$ for 12 d.o.f.
  - PRL 98, 132003 (2007)
**RSS Deuteron Spin Asymmetries**

- Fit deuteron $A_1$ with three B-W resonances plus linear DIS
- Fit deuteron $A_2$ with constant: $A_2 = 0.083 \pm 0.017$
**RSS Spin Structure Functions**

- Use measured unpolarized $F_1$
- High precision, high resolution measurement
  - Extracting neutron SF's requires polarized proton smearing (Kulagin & Melnitchouk, PRC 77, 015210 (2008))

\[
g_1 = \frac{F_1}{1+\gamma^2} \left( A_1 + \gamma A_2 \right)
\]
\[
g_2 = \frac{F_1}{1+\gamma^2} \left( \frac{A_2}{\gamma} - A_1 \right); \quad \gamma = \frac{2 x M}{\sqrt{Q^2}}
\]
**RSS goal Bloom-Gilman Local Duality for $g_1^p$**

- Polarized (B-G) Local Duality: Ratio of integrals (at constant $Q^2$) = 1
  - $g_1$ fit over $A_1$ fit resonances
  - $g_1$ from PDF's evolved to same $\langle Q^2 \rangle = 1.28$ GeV$^2$, with target mass corrections

- Polarized global duality seems to work above $Q^2 \approx 1.8$ GeV$^2$
$g_2$ Spin Structure Functions

- First world data for $g_2^{p,d}$ in the resonances
- Clear higher-twist in $g_2^p(x > 0.4)$
- $g_2^{ww}$ computed using RSS fit to $g_1$ point by point

$$g_2(x, Q^2) = g_2(x, Q^2) - g_2^{ww}(g_1(x, Q^2))$$

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

- First moment of $g_1$ (extended GDH or Ellis-Jaffe sum rule)

$$\bar{F}_1(Q^2) = \int_0^{1-\epsilon_l} g_1(x, Q^2) dx$$

$$= \frac{1}{36} ((a_8 + 3a_3)C_{NS} + 4a_0C_S)$$

arXiv:0812.00131
Sum Rules

- First moment of $g_2$ (Burkhardt-Cottingham S. R.)

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

- Free of QDC radiative and target mass corrections (Kodaira et al. PLB345(1995) 527)
  - RSS full (solid), measured (open)
  - Hall A E01—012 (very preliminary) \(E97-110, E94-010\)
  - SLAC E155x
    - (From K. Slifer)
Nachtmann moments and quark matrix elements

- Matrix elements representing interactions (higher twists) between quarks and gluons can be expanded in terms of Nachtmann moments
  - Free of target mass effects to $O(M^8/Q^8)$: dynamic higher twists can be extracted
  - Both $g_1$ and $g_2$ SSF's are needed: transverse asymmetry data (e.g. RSS, SANE)
  - Nachtmann moments reduce to conventional Cornwall-Norton (C-N) at high $Q^2$
  - Required at low momentum transfers: $Q^2 < \sim 5$ GeV$^2$ and for the higher moments dominated by high $x$ contributions: $d_2^{\text{Nacht.}}(Q^2)$, $a_2^{\text{Nacht.}}(Q^2)$

$$d_2^{\text{Nacht.}}(Q^2) = \int_0^1 dx \xi^2 \left( \frac{2 \xi}{x} g_1 + 3 \left( 1 - \frac{\xi^2 M^2}{2 Q^2} \right) g_2 \right) \Rightarrow Q^2 \to \infty \int_0^1 dx x^2 (2 g_1 + 3 g_2)$$

$$a_2^{\text{Nacht.}}(Q^2) = 2 \int_0^1 dx \left( \frac{\xi^3}{x} \left[ 1 - \frac{9}{25} \frac{\xi^2 M^2}{Q^2} \right] g_1 - \frac{12}{5} \frac{x \xi M^2}{Q^2} g_2 \right) \Rightarrow Q^2 \to \infty 2 \int_0^1 dx x^2 g_1$$

$$\xi = 2 x / \left[ 1 + \sqrt{1 + (2 x M^2 / Q^2)} \right]$$

Twist-3 (proton)

- The twist-3 matrix element $d_2$ represents $q-g$ correlations

$RSS$ inelastic ($0 < x <$ inelastic threshold); $\overline{d}_2(x<0.316) = 0$, extrapolated from data

$d_2^{C-N}(1.3 \text{ GeV}^2) = 0.0057 \pm 0.0013$ (published)

$d_2^{Nachtmann} = 0.0037 \pm 0.0010$ (total error): clean twist-3 to $> 3$ sigmas
**Twist-3 (deuteron, etc.)**

**RSS** inelastic (0 < \(x\) < inelastic threshold), \(\overline{d}_2 (x < 0.316) = 0\), extrapolated from data

**Deuteron** \(d_2^{C-N}\) = 0.0082 ± 0.0019 (all total errors)

**Nachtmann** \(d_2^{Nachtmann}\) = 0.0048 ± 0.0015: clean twist-3 to 3 sigmas

**Neutron** \(d_2^{Nachtmann}\) = 0.0015 ± 0.0019  **Non-Singlet** \(d_2^{Nachtmann}\) = 0.0022 ± 0.0026

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**Y. B. DONG**

**PHYSICAL REVIEW C 77, 015201 (2008)**

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**FIG. 1.** Ratio \(R(Q^2)\).
## Credits

### Analysis Team
- Karl Slifer
- Shigeyuki Tajima
- Frank Wesselmann
- Peter Bosted
- Eric Christy
- Paul McKee
- Hongguo Zhu
- Mark Jones
- Oscar Rondon

### Special Thanks
- Don Crabb
- Donal Day
- Mahbub Khandaker
- Hamlet Mkrtchyan
- JLab Hall C
- JLab Target group
SANE
Spin Asymmetries on the Nucleon Experiment
(TJNAF E07-003)

SANE Collaboration
Argonne National Lab., Christopher Newport U., Florida International U.,
Hampton U., Jefferson Lab., U. of New Hampshire, Norfolk S. U.,
North Carolina A&T S. U., Mississippi S. U., Ohio U., IHEP - Protvino, U. of Regina,
Rensselaer Polytechnic I., Rutgers U., Seoul National U., Southern U. New Orleans,
Temple U., Tohoku U., U. of Virginia, Yerevan Physics I., Xavier U.

Spokespersons:
S. Choi (Seoul), M. Jones (JLab), Z-E. Meziani (Temple), O. A. Rondon (U. of Virginia)

- Measure **proton** spin structure function $g_2(x, Q^2)$ and spin asymmetry $A_1(x, Q^2)$ for $2.5 \leq Q^2 \leq 6.5$ GeV$^2$ and $0.3 \leq x \leq 0.8$

- **SANE meets DOE 2011 Milestone for Proton Spin Structure**
SANE Physics

• Goal is to learn all we can about proton SSF's from an inclusive double polarization measurement:
  – twist-3 effects from moments of $g_2$ and $g_1$
  
  $d_2$ matrix element $= \int_0^1 x^2 (3 g_2 + 2 g_1) \, dx$
  
  – comparisons with Lattice QCD, QCD sum rules, bag models, chiral quarks
  – Study $x$ dependence (test nucleon models) and $Q^2$ dependence (evolution)
  – Exploration of "high" $x$ region: $A_1$'s approach to $x = 1$
  – Test polarized local duality for final state mass $W > 1.4$ GeV

• Method:
  
  – Measure inclusive spin asymmetries for two orientations of target spin relative to beam helicity (anti-parallel and near-perpendicular)
  
  – Detect electrons with novel large solid angle electron telescope BETA
World data on $A_\parallel$, $A_\perp$ and SANE kinematics

- Two beam energies: 5.9 GeV, 4.7 GeV
- Very good high $x$ coverage with detector at 40°
SANE Layout

BETA (40°)

- BigCal w. Gain Monitor
- Lucite Hodoscope
- Gas Cherenkov
- Forward Hodoscope

HMS (15°-42°) calibrations, backgd.
- Polarized Target
- Target Beam position monitor
- Beam Line

B at 80° or 180°
Big Electron Telescope Array – BETA

- **BigCal** lead glass calorimeter: main detector used in *GEp-III*.
- Tracking **Lucite hodoscope**
- **Gas Cherenkov**: pion rejection
- Tracking fiber-on-scintillator **forward hodoscope**
- BETA's characteristics
  - Effective solid angle = 0.194 sr
  - Energy resolution 8%/√$E$(GeV)
  - 1000:1 pion rejection
  - Vertex resolution ~ 5 mm
  - Angular resolution ~ 1 mr
- Target field sweeps low $E$ background
  - 180 MeV/c cutoff
**Big Electron Telescope Array – BETA**

- **BigCal** lead glass calorimeter: main detector used in *GEp-III*.
- Tracking **Lucite hodoscope**
- **Gas Cherenkov**: pion rejection
- Tracking fiber-on-scintillator **forward hodoscope**
- **BETA's characteristics**
  - Effective solid angle $= 0.194 \text{ sr}$
  - Energy resolution $8\%/\sqrt{E(\text{GeV})}$
  - 1000:1 pion rejection
  - Vertex resolution $\sim 5 \text{ mm}$
  - Angular resolution $\sim 1 \text{ mr}$
- **Target field sweeps low $E$ background**
  - 180 MeV/c cutoff
SANE Expected Results (I)

- SANE expected statistical errors for \( \overline{d}_2 = \int_{x_{\text{min}}}^{x_{\text{max}}} x^2 (2g_1 + 3g_2) dx \)

<table>
<thead>
<tr>
<th>( Q^2 )</th>
<th>( \Delta x ) Proposal</th>
<th>( \Delta x ) Projected</th>
<th>( \delta d_2/d_2 ) Proposal</th>
<th>( \delta d_2/d_2 ) Projected</th>
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</thead>
<tbody>
<tr>
<td>2.5 - 3.5</td>
<td>0.29</td>
<td>0.85</td>
<td>0.29</td>
<td>0.71</td>
</tr>
<tr>
<td>3.5 - 6.5</td>
<td>0.41</td>
<td>0.96</td>
<td>0.41</td>
<td>0.84</td>
</tr>
</tbody>
</table>
SANE Expected Results (Ia)
SANE Expected Results (II)

- \( x \) dependence at constant \( Q^2 \) and \( Q^2 \) dependence at fixed \( x \) (illustrative binning only)

- data are concentrated in the region most sensitive to \( x^2 g_{2,1} \)
  - (estimates based on 75% beam and target polarization, and 85 nA beam current)
SANE Expected Results (III)

- Constrain extrapolations of $A_1^p$ to $x = 1$ within +/- 0.1 (using duality)
- Both $A_\parallel$ and $A_\perp$ are required to get accurate, model-free $A_1$: $A_2 > 0$
- SANE's measured $A_2$ will contribute to improve world's $A_1$ data set
# Beam Time

<table>
<thead>
<tr>
<th>Calibration Production</th>
<th>Energy (GeV)</th>
<th>( \theta_N )</th>
<th>Time (Proposal FOM h)</th>
<th>Proposal</th>
<th>Actual</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.4</td>
<td>off, 0, 180</td>
<td>47</td>
<td>25</td>
<td>53%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>180</td>
<td>70</td>
<td>20*</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>80</td>
<td>130</td>
<td>98</td>
<td>75%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>80</td>
<td>200</td>
<td>143</td>
<td>72%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>180</td>
<td>100</td>
<td>( \geq 35 )</td>
<td>( \geq 35% )</td>
<td></td>
</tr>
</tbody>
</table>

**Commissioning** [ calendar days] 14.0 99

**Total** [ calendar days] 70.0 141

* At 30% efficiency until 3/16/09
Twist-3 operators

- The number of twist-3 operators increases with the order of the moment

- $d_n$ notation is shorthand for

  $$\tilde{d}_n = \sum_i d_i^n(\mu^2) E_{i,3}^n(Q^2/\mu^2, \alpha_s(\mu^2))$$

  - $d_i^n$ are the matrix elements, $i$ is the spin index, $n$ is the moment order
  - $E_{i,3}^n$ are twist-3 Wilson coefficients

- There is only one $d_1^2$, the one usually labeled $d_2$

- There are three $d_{i=1,2,3}^4$ operators associated with the fifth moment
  - with precise data are available over a wide range of $Q^2$ the evolution equations for the 5th. moments could be solved to extract these higher spin twist-3 matrix elements (Ji and Chou, PRD 42, 3637 (1990))
  - 5th. moment dominated by high $x$ data: Nachtmann moments required
Twist-2 and Twist-4

- **TOP:**
  - Ratio of Nachtmann to CN moments of twist-2 $a_2$ matrix element: proton and deuteron sensitive to kinematic twists

- **BOTTOM**
  - Difference between the extracted values of the twist-4 $f_2$ matrix element using Nachtmann vs CN moments: twist-4 is insensitive to target mass
Twist-3 in $g_2^p$
Magnet Circuit Damage

- Diagnostics with the magnet cold indicated need to open it for repair.
- Extensive testing (B. Vulcan, J. Beaufait and others) found multiple burned out wires connecting sections of one of the main coils.
- A protection diode for one coil was also found to be broken.
Magnet Repairs

- Oxford specialist Paul Brodie and J. Beaufait reconnected wires with ~1" superconducting joints and ~3" copper to copper contacts
- Replacement diodes were mounted on circuit board
- Magnet operation after repairs is delicate, prone to quench
- Protection circuits working