Spin Physics Program in Jefferson Lab's Hall C

Oscar A. Rondón
INPP - University of Virginia

DIFFRACTION 2014 - 8th International Workshop on Diffraction in High-Energy Physics
Primošten, Croatia
September 13, 2014
Probing Nucleon Structure with Polarized Electromagnetic Scattering
Inelastic $e$-nucleon Scattering

- Inclusive EM scattering is described by hadronic and leptonic tensors.
- Symmetries reduce hadronic tensor to four structure functions (SF's):
  - Symmetric part: unpolarized $W_1$, $W_2$
  - Anti-symmetric part: spin-dependent $G_1$, $G_2$

\[
W^A_{\mu\nu} = 2\epsilon_{\mu\nu\lambda\sigma} q^\lambda \left[ M^2 S^\sigma G_1(\nu, Q^2) + [M \nu S^\sigma - p^\sigma S \cdot q] G_2(\nu, Q^2) \right]
\]

- $\gamma^*$ hadronic structure does not contribute for Bjorken $x > \sim 0.1$
  - JLab's domain is best region for illuminating nucleon structure

(http://www.desy.de/~gbrandt/feyn/)
Structure Functions in Inclusive DIS

- $G_1$, $G_2$, $W_1$, and $W_2$, contain all the information on nucleon structure that can be extracted from inclusive data.

- In high energy DIS, $g_1$ and $g_2$ scale like $F_1$ and $F_2$ (up to log violations):

\[
\begin{align*}
\lim_{Q^2, \nu \to \infty} M W_1(\nu, Q^2) &= F_1(x) \\
\lim_{Q^2, \nu \to \infty} \nu W_2(\nu, Q^2) &= F_2(x)
\end{align*}
\]

Bjorken $x = Q^2/(2M \nu)$

- In the quark parton model $g_1$ and $F_1$ are also related to parton distribution functions - PDF's:

\[
\begin{align*}
F_1(x) &= \frac{1}{2} \sum e_f^2 (q_f^+(x) + q_f^-(x)) \\
g_1(x) &= \frac{1}{2} \sum e_f^2 (q_f^+(x) - q_f^-(x))
\end{align*}
\]
Virtual Compton Asymmetries

- The spin SF's are also related to virtual photon cross-sections and spin asymmetries (SA)
  - the helicity of the virtual photon-nucleon system is $3/2$ or $1/2$ for transverse photons, $1/2$ for longitudinal ones

- $SA \ A_1$ is defined in terms of the difference for $3/2$ and $1/2$ helicity cross sections

- $A_2$ represents the interference between initial transverse and final longitudinal amplitudes
  - obeys Soffer-Teryaev bound

\[
A_1 = \frac{\sigma_{T}^{(3/2)} - \sigma_{T}^{(1/2)}}{\sigma_{T}^{(3/2)} + \sigma_{T}^{(1/2)}}
\]
\[
A_1 = \frac{1}{F_1} \left( g_1 - \gamma^2 g_2 \right); \quad \gamma = \frac{2xM}{\sqrt{Q^2}}
\]
\[
A_2 = \frac{\sigma_{TL}^{(1/2)}}{\sigma_{T}^{(3/2)} + \sigma_{T}^{(1/2)}} \leq \sqrt{\frac{A_1 + 1}{2}}\frac{1}{R} \leq \frac{\sigma_L}{\sigma_T}
\]
\[
A_2 = \frac{\gamma}{F_1} \left( g_1 + g_2 \right) = \frac{\gamma}{F_1} g_T
\]
Model Independent Extraction of Spin Structure Functions

- $G_1$ and $G_2$ can be separated by measuring cross section differences for opposite beam helicities with target spins parallel and transverse to the beam

$$\Delta \sigma (\theta, \theta_N, \phi) = \frac{4 \alpha^2 E'}{Q^2 E} \left[ (E \cos \theta_N + E' \cos \alpha) M G_1 + 2 E E' (\cos \alpha - \cos \theta_N) G_2 \right]$$

$$\cos \alpha = \sin \theta_N \sin \theta \cos \phi + \cos \theta_N \cos \theta, \quad (\theta, \phi: \text{final lepton angles})$$

- Transverse target spin $\theta_N$: comparable $G_1$, $G_2$ terms

$$\frac{d^2 \sigma^{(\uparrow \rightarrow)}}{d \Omega d E'} - \frac{d^2 \sigma^{(\downarrow \rightarrow)}}{d \Omega d E'} = \frac{4 \alpha^2 E'}{Q^2 E} E' \sin \theta \cos \phi \left[ M G_1 (\nu, Q^2) + 2 E G_2 (\nu, Q^2) \right]$$

- $G_1$ is twist-2 (plus corrections)

- $G_2$ has both twist-2 and twist-3 contributions
Transverse Polarized Scattering: Unlocking Twist-3

- Twist-2 and twist-3 operators contribute at same order in transverse polarized scattering
  - twist-2: handbag diagram
  - twist-3: $qgq$ correlations
- direct access to twist-3 via $g_2$:
  - interacting $qgq$, beyond asymptotically free partons, is first step to understanding confinement
  - "Unique feature of spin-dependent scattering" (R. Jaffe)
**$g_2$ and $g_T$ Spin Structure Functions**

Experimentally measured quantities

$$g_T(x) = g_1(x) + g_2(x) = \frac{1}{2} \sum e_q^2 g_T^q(x)$$

$g_T^q$ in terms of Transverse Momentum Dependent distributions \[1\]

$$g_T(x) = \int d^2 \vec{k}_i \frac{\vec{k}_i^2}{2 M^2} \frac{g_T^q(x, \vec{k}_i^2)}{x} + \frac{m}{M} \frac{h_1(x)}{x} + \tilde{g}_T(x)$$

**Twist-3 for the nucleon (neglecting quark mass)**

Applying twist-2 Wandzura-Wilczek approximation of $g_2$

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

$$\bar{g}_2 = \frac{1}{2} \sum e_q^2 \left[ \tilde{g}_T^q - \int_x^1 \frac{dy}{y} \left( \tilde{g}_T^q(y) - \tilde{g}_T^q(y) \right) \right]; \; \tilde{g}_T = qg \text{ term, } \hat{g}_T = \text{ Lorentz invariance} \ [2]$$

\[1\] hep-ph/9408305v1
\[2\] JHEP 0911 (2009) 093
Hall C Spin Experiments
Hall C Spin Structure Program

Spin Structure Functions at 6 GeV:

Inclusive measurements

SSF's in the Nucleon Resonances - RSS  (published)


Proton SSF at high Bjorken $x$ - SANE (preliminary results)

Precision Deuteron spin structure - $g_1^d/F_1^d$ (Hall B eg1/DVCS)

Semi-inclusive measurements

Flavor Decomposition of Spin - SemiSANE (12 GeV)

Real Polarized Photons:

Polarized Compton Scattering - WACS (12 GeV)
**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 $0.8 \leq W \leq 1.91 \text{ GeV}$

**Goals:** study $W$ dependence of asymmetries, onset of polarized local duality, and twist-3 effects
SANE - Spin Asymmetries of 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 the 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 $0.3 \leq x \leq 0.8$

Goal: Learn all we can about proton spin structure from an
inclusive double polarization measurement
Layout in JLab's Hall C: RSS
Layout in JLab's Hall C: SANE

[1] Big Electron Telescope Array
$\Delta\Omega \sim 190 \text{ msr}; \Delta\theta = \pm 10^\circ$
BETA with DIS electron simulation

[1] BigCal Collaboration
[5] UVA- JLab

(W. Armstrong)
Polarized Target

- Dynamic Nuclear Polarized ammonia NH$_3$, ND$_3$, at 5T and 1K
  - Proton $<P> \sim 70\%$ in beam
  - Deuteron $<P> \sim 20\%$ in beam
  - Proton luminosity $\sim 10^{35}$ Hz cm$^{-2}$
- Target used in multiple experiments:
  - SLAC: E143, E155, E155x ($g_2$)
  - JLab: GEn98, GEn01, RSS, SANE
# Hall C Spin Structure Program

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detector</th>
<th>Detected particle</th>
<th>Scattering Type</th>
<th>Beam Energy [GeV]</th>
<th>Field Direction</th>
<th>Target</th>
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<tbody>
<tr>
<td>RSS</td>
<td>HMS</td>
<td>e-</td>
<td>Inclusive inelastic &amp; elastic</td>
<td>5.76</td>
<td>180°, 90°</td>
<td>NH3, ND3, C, LHe [1]</td>
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<tr>
<td>SANE</td>
<td>BETA</td>
<td>e, π⁰</td>
<td>Inclusive inelastic</td>
<td>5.9, 4.7</td>
<td>180°, 80°</td>
<td>NH3</td>
</tr>
<tr>
<td></td>
<td>HMS</td>
<td>e</td>
<td>Inclusive inelastic</td>
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<tr>
<td>BETA - HMS</td>
<td></td>
<td>e - p</td>
<td>Coincidence elastic</td>
<td>5.9</td>
<td>80°</td>
<td>NH3</td>
</tr>
</tbody>
</table>

[1] Unpolarized, for dilution factor
BETA and HMS data

- $Q^2 - x$ phase space of BETA's 80° data (SANE)
  - cut on $E' \geq 1.3$ GeV

- Central kinematics of HMS inclusive asymmetry data
  (RSS and SANE)
Measured Asymmetries $A_\parallel, A_\perp$ (RSS)

$$A_m = \frac{\epsilon}{f P_b P_t C_N} + C_D; \quad \epsilon = \frac{N^- - N^+}{N^- + N^+}$$

$$A_{phys} = \frac{A_m}{f_{rc}} + A_{rc}$$

- $N^{+,-} = \text{charge normalized, dead time corrected yields}$
- $P_b, P_t = \text{beam, target polarizations}$
- $f = \text{polarized dilution factor}$
- $C_N, C_D = N \text{ polarization corrections}$
- $A_{rc}, f_{rc} = \text{radiative corrections}$

(Proton: PRL 98, 132003 (2007))

9/13/14
Measured Asymmetries $A(80^\circ), A(180^\circ)$

\[ A_m = \frac{\epsilon}{f \, P_b \, P_t \, C_N} ; \quad \epsilon = \frac{N^- - N^+}{N^- + N^+} \]

\[ A_{phys} = \frac{1}{f_{rc}} \left( \frac{A_m - f_b \, A_b}{1 - f_b} \right) + A_{rc} \]

- $N^{+,-}$ = charge normalized, dead time corrected yields
- $P_b, P_t$ = beam, target polarizations
- $f$ = polarized dilution factor
- $C_N$ = N polarization corrections
- $A_{rc}, f_{rc}$ = radiative corrections
- $A_b, f_b$ = background corrections

\[ A_\perp = (A_{180} \cos 80^\circ + A_{80}) / \sin 80^\circ \]
Sample of Normalizations and corrections
Results
Spin Asymmetries $A_1$ and $A_2$

- HMS single arm data in the resonances, $\langle Q^2 \rangle \sim 1.3 \text{ GeV}^2$
  - Model independent separation from measured asymmetries

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

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

9/13/14
Spin Asymmetries $A_1$ and $A_2$

- HMS single arm data in the resonances, $<Q^2> \sim 1.8$ GeV$^2$
  - Model independent separation from measured asymmetries

\[
A_1 = \frac{1}{D'} \left( \frac{E - E' \cos \theta}{E + E'} A_{180} + \frac{E' \sin \theta}{(E + E') \cos \phi} \frac{A_{180} \cos 80^\circ + A_{80}}{\sin 80^\circ} \right)
\]

\[
A_2 = \frac{1}{D'} \frac{1}{2E} \left( \sqrt{Q^2} A_{180} - \sqrt{Q^2} \frac{E - E' \cos \theta}{E' \sin \theta \cos \phi} \frac{A_{180} \cos 80^\circ + A_{80}}{\sin 80^\circ} \right)
\]
DIS Spin Asymmetry $A_1$

- BETA data - Statistical errors only
- CLAS data of same $W$ but different $Q^2$ are merged in $A_1^p(W)$
$g_2$ Spin Structure Functions

- First world data for $g_2^{p,d}$ in the resonances
- Twist-2 $g_2^{ww}$ computed using RSS fit to $g_1$ point by point
- Clear difference between proton data and twist-2 part
$g_2$ in DIS and Resonances

- BETA proton data
  - DIS and resonances
    $0.3 < x < 0.8, 2.5 < Q^2 < 6.0, E' \geq 1.3$ GeV (more data available down to 0.9 GeV)
  - Twist-2 $g_2^{ww}(4 \text{ GeV}^2)$ from PDF's
- SLAC E143, E155, E155x DIS data

(W. Armstrong)
DIS Transverse Spin SF $g_T^p$

- $g_T^p = F_1 A_2 / \gamma$ measures spin distribution normal to $\gamma^*$
- SANE $<g_T^p(x > .3)> = 0.023 \pm 0.006$

- Bag Model (1990's)
  - Data scaled $\times 2.5$
  - Model updates needed
Operator Product Expansion for Spin SF's

- OPE connects SF's Cornwall-Norton moments to twist-2, twist-3 matrix elements $a_N$, $d_N$

$$\int_0^1 x^N g_1(x, Q^2) dx = \frac{a_N}{2} + tmc, \quad N = 0, 2, 4, \ldots$$

$$\int_0^1 x^N g_2(x, Q^2) dx = \frac{N(d_N - a_N)}{2(N+1)} + tmc, \quad N = 2, 4, \ldots$$

(tmc: target mass corrections)

- $d_2$ is mean color-magnetic field along spin

- Nachtmann moments needed to get twist-3 free of tmc

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

Moments at $<Q^2> = 1.3 \text{ GeV}^2$

- measured range $0.32 < x < 0.8$
  plus elastic (quasi-elastic for deuteron)

- unmeasured low $x < 0.32$
  suppressed by $x^2$ weight

(OPE valid to $N=2 < Q^2/M_0^2 \sim 1.3/0.5^2$
per DIS – resonances duality)

(Ji & Unrau, PR D52 (1995) 72)
Operator Product Expansion for Spin SF's

- OPE connects SF's Cornwall-Norton moments to twist-2, twist-3 matrix elements $a_N$, $d_N$

\[
\int_0^1 x^N g_1(x, Q^2) \, dx = \frac{a_N}{2} + tmc, \quad N = 0, 2, 4, \ldots
\]

\[
\int_0^1 x^N g_2(x, Q^2) \, dx = \frac{N(d_N - a_N)}{2(N+1)} + tmc, \quad N = 2, 4, \ldots
\]

(tmc: target mass corrections)

- $d_2$ is mean color-magnetic field along spin

- Nachtmann moments needed to get twist-3 free of tmc

\[
d_2(Q^2) = \int_0^1 dx \xi^2 \left( 2g_1 - \frac{\xi^2 M^2}{2Q^2} g_2 \right) \Rightarrow Q^2 \rightarrow \infty \int_0^1 dx x^2 \left( 2g_1 + 3g_2 \right)
\]

Only projected error shown.)

SANE's measured C-N $d_2$

(All data $E' > 1.3$ GeV, $W > 2$ GeV.)
Operator Product Expansion for Spin SF's

- OPE connects SF's Cornwall-Norton moments to twist-2, twist-3 matrix elements $a_N$, $d_N$

$$\int_0^1 x^N g_1(x, Q^2) \, dx = \frac{a_N}{2} + tmc, \quad N = 0, 2, 4, \ldots$$

$$\int_0^1 x^N g_2(x, Q^2) \, dx = \frac{N (d_N - a_N)}{2 (N+1)} + tmc, \quad N = 2, 4, \ldots$$

$(tmc$: target mass corrections$)$

- $d_2$ is mean color-magnetic field along spin

- Nachtmann moments needed to get twist-3 free of $tmc$

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

- SANE analysis near final version

- Publication in preparation
Hall C 12 GeV Spin Physics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Title</th>
<th>Beam days</th>
<th>Rating</th>
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<tbody>
<tr>
<td>E12-06-101</td>
<td>Measurement of the Charged Pion Form Factor to High Q2</td>
<td>40</td>
<td>A-</td>
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<tr>
<td>E12-06-104</td>
<td>Measurement of the Ratio R=σl/σt in Semi-Inclusive Deep-Inelastic Scattering</td>
<td>52</td>
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<tr>
<td>E12-06-105</td>
<td>Inclusive Scattering from Nuclei at 3x &gt; 15 in the quasielastic and deeply inelastic regimes</td>
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<tr>
<td>E12-06-107</td>
<td>The Search for Color Transparency at 12 GeV</td>
<td>26</td>
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<td>E12-06-109</td>
<td>Measurement of Neutron Spin Asymmetry A1n in the Valence Quark Region Using an 11 GeV Beam and a Polarized 3He Target in Hall C</td>
<td>36</td>
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<tr>
<td>E12-06-121</td>
<td>Measurement of the Ratio R=σl/σt in Semi-Inclusive Deep-Inelastic Scattering</td>
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<td>E12-10-002</td>
<td>Precision measurements of the F_2 structure function at large x in the resonance region</td>
<td>13</td>
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<tr>
<td>E12-10-003</td>
<td>Deuteron Electro-Disintegration at Very High Missing Momentum</td>
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<td>E12-10-008</td>
<td>Detailed studies of the nuclear dependence of F2 in light nuclei</td>
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<td>E12-11-002</td>
<td>Proton Recoil Polarization in 4He(e,e'p)3H, 2H(e,e'p)n, and 1H(e,e'p) Reactions</td>
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<td>E12-11-009</td>
<td>The Neutron Electric Form Factor at Q^2 up to 7 (GeV/c)^2 from the Reaction d(e,e'n)p via Recoil Polarimetry</td>
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<td>E12-07-105</td>
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<td>E12-12-002</td>
<td>Precision Measurement of p^+/-p Ratios in Semi-Inclusive Deep Inelastic Scattering Part1: Charge Symmetry violating Quark Distributions</td>
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<td>E12-09-011</td>
<td>Studies of the L-T Separated Kaon Electroproduction Cross Section from 5-11 GeV</td>
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<td>E12-11-107</td>
<td>In Medium Nucleon Structure Functions, SRC, and the EMC effect</td>
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<td>E12-13-007</td>
<td>Measurement of Semi-Inclusive A→e Production as Validation of Factorization</td>
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<td>E12-13-010</td>
<td>Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C</td>
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<td>E12-13-011</td>
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<td>E12-14-002</td>
<td>Precision Measurements and Studies of a Possible Nuclear Dependence of R</td>
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<tr>
<td>E12-14-003</td>
<td>Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies</td>
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<tr>
<td>E12-14-005</td>
<td>Wide Angle Exclusive Photoproduction of pi-zero Mesons</td>
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<td>E12-14-006</td>
<td>Initial State Helicity Correlation in Wide Angle Compton Scattering</td>
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<td>B</td>
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</table>

Total Spin Physics days: 95
Extras
\( \frac{G_E^p}{G_M^p} \) from inclusive and coincidence data

Ratio from:

- **SANE inclusive HMS data at** \( Q^2 = 2.06 \text{ GeV}^2 \)
  - \( A_{\text{el}}^p = -0.20 \pm 0.02 \)
  - \( \frac{G_E^p}{G_M^p} = 0.60 \pm 0.18 \pm 0.06 \) \( \text{(statistical + systematic error)} \)

- **BETA–HMS \( e-p \) coincidences at** \( Q^2 = 5.66 \text{ GeV}^2 \)
  - \( \frac{G_E^p}{G_M^p} = 0.67 \pm 0.36 \) \( \text{(statistical error only)} \)
SANE Collaboration (E-07-003)

P. Solvignon
Argonne National Laboratory, Argonne, IL

E. Brash, P. Carter, A. Puckett, M. Veilleux
Christopher Newport University, Newport News, VA

W. Boeglin, P. Markowitz, J. Reinhold
Florida International University, Miami, FL

Hampton University, Hampton, VA

Thomas Jefferson National Accelerator Facility, Newport News, VA

J. Dunne, D. Dutta, A. Narayan, L. Ndukum, Nuruzzaman
Mississippi State University, Jackson, MI

A. Ahmadouch, S. Danagoulian, B. Davis, J. German, M. Jones
North Carolina A&T State University, Greensboro, NC

M. Khandaker
Norfolk State University, Norfolk, VA

A. Daniel, P.M. King, J. Roche
Ohio University, Athens, OH

A.M. Davidenko, Y.M. Goncharenko, V.I. Kravtsov, Y.M. Melnik, V.V. Mochalov, L. Soloviev, A. Vasiliev
Institute for High Energy Physics, Protvino, Moscow Region, Russia

C. Butuceanu, G. Huber
University of Regina, Regina, SK

V. Kubarovsky
Rensselaer Polytechnic Institute, Troy, NY

L. El Fassi, R. Gilman
Rutgers University, New Brunswick, NJ

S. Choi, H-K. Kang, H. Kang, Y. Kim
Seoul National University, Seoul, Korea

M. Elaasar
State University at New Orleans, LA

W. Armstrong, D. Flay, Z.-E. Meziani, M. Posik, B. Sawatzky, H. Yao
Temple University, Philadelphia, PA

O. Hashimoto, D. Kawama, T. Maruta, S. Nue Nakamura, G. Toshiyuki
Tohoku U., Tohoku, Japan

K. Slifer
University of New Hampshire

University of Virginia, Charlottesville, VA

L. Pentchev
College of William and Mary, Williamsburg, VA

F. Wesselmann
Xavier University, New Orleans, LA

A. Asaturyan, A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan
Yerevan Physics Institute, Yerevan, Armenia

Ph.D. student, M.S. Student, Student
E01–006, Resonances Spin Structure

RSS Collaboration

Institute of Nuclear and Particle Physics
Department of Physics, University of Virginia
Charlottesville, VA 22901

Departmentent für Physik und Astronomie der Universität Basel
CH-4056, Basel, Schweiz

Thomas Jefferson National Accelerator Facility
Newport News, VA 23606

W. Boeglin, L. Coman, L. Kramer, P. Markowitz, B. Rauz, J. Reinhold
Department of Physics, Florida International University
Miami, FL 33199

B. Hu, E. Christy, L. Cole, A. Gasparian, Y. Liang
C. Keppel, L. Tang, L. Yuan
Department of Physics, Hampton University
Hampton, VA 23668

M. Katramatou, G. Petrotas
Kent State University
Kent, OH 44444

P. Bosted
University of Massachusetts at Amherst
Amherst, MA 01000

J. Dunne, J. Cha
Department of Physics, Mississippi State University
Mississippi State, MS 39762

M. Khandaker
Department of Physics, Norfolk State University
Norfolk, VA 23504

A. Ahmidouch, S. Danagoulian
Department of Physics, North Carolina A & T State University
Greensboro, NC 27411

A. Klein
Department of Physics, Old Dominion University
Norfolk, VA 23529

M. Elaasar
Southern University at New Orleans
New Orleans, LA 70126

J. Lichtenstadt
Tel Aviv University
Tel Aviv, Israel

J. Yun
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

T. Averett
College of William & Mary
Williamsburg, VA 23185

A. Agalaryan, R. Asatryan, H. Mkrichyan, S. Stepanyan
Yerevan Physics Institute
Yerevan, Armenia
Why is $g_2$ interesting?

- tests twist-3 effects = quark-gluon correlations
- higher twist corrections to $g_1$ with 3$^{\text{rd}}$ moment $d_2$ matrix element
- test of lattice QCD, QCD sum rules, quark models from moments
- polarizabilities of color fields (with twist-4 matrix element $f_2$)
  - magnetic $\chi_B = (4d_2 + f_2)/3$ and electric $\chi_E = (4d_2 - 2f_2)/3$.
- 3$^{\text{rd}}$ moment related to color Lorentz force on transverse polarized quark (M. Burkardt, AIP Conf.Proc. 1155 (2009) 26)
  - sign of $d_2$ related to sign of transverse deformation (anomalous $\kappa^q$)
- contains chiral odd twist-2 = quark transverse spin (mass term)
  - test quark masses (covariant parton models)
**RSS Spin Structure Functions** $g_1^{p,d}$

F. Wesselmann *et al.*, Phys.Rev.Lett. 98, 132003 (2007) (including spin asymmetries $A_1$, $A_2$)

In preparation
**RSS Proton Spin Asymmetries**

Fit $A_1$ and $A_2$ independently
- Four Breit-Wigner resonance shapes plus DIS background
- Reduced $\chi^2 = 1.2 - 1.4$ for 12 d.o.f.
$g_2$ in DIS and Resonances

- Proton (NH$_3$)
  - Hall C SANE (E07-003)
    - $0.3 < x < 0.8$  $2.5 < Q^2 < 6.5$
- SLAC $x g_2 (2 < Q^2 < 6 \text{ GeV}^2)$
- Total errors SANE & E143, statistical only E155x

9/13/14
DIS Spin Asymmetry $A_2$

- DIS $A_2^p$ not zero is signal of parton transverse momentum

- connection to transverse twist-3 TMD $g_{1T}^{\perp}$:
  \[ g_{2}^{\perp}(x) = \frac{d}{dx} g_{1T}^{(1)}(x) + \hat{g}_{T}(x) \]
Nucleon Spin beyond $G_1$ and $G_2$

- Need to go beyond $a_0$ to understand nucleon spin
  - Orbital angular momentum (OAM) $L$ is needed.
- Partons have transverse momentum, implies OAM
  - Muller, Ji, Radyushkin, Generalized Parton Distributions – GPDs
  - functions of Mandelstam $t$, light cone momentum $\xi$
  - exclusive scattering, DV Compton, meson

\[
\begin{align*}
H(x, \xi=t=0) &= q(x) = f_1(x) \\
\tilde{H}(x, \xi=t=0) &= \Delta q(x) = g_1(x) \\
E(x, \xi, t), \quad \tilde{E}(x, \xi, t) \\
&\text{(no partonic analogs)} \\
J_q &= \frac{1}{2} \int_{-1}^{1} dx \ x \left[H^q(x, \xi, t=0) + E^q(x, \xi, t=0)\right] \\
&\text{(Ji's sum rule)} \\
\sum J_q &= \sum \Delta q + L_q
\end{align*}
\]
Nucleon Spin beyond $G_1$ and $G_2$

- Need to go beyond $a_0$ to understand nucleon spin
  - Orbital angular momentum (OAM) $L$ is needed.
- Partons have transverse momentum, implies OAM
  - Mulders et al., Transverse Momentum dependent Distributions – TMDs
  - functions of $x$ and $k_t$
  - Semi-inclusive scattering (detect final $e$, one hadron)

<table>
<thead>
<tr>
<th>Transverse Momentum Distributions by Polarization</th>
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<tbody>
<tr>
<td>Target ↓ \ quark →</td>
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<tr>
<td>$U$</td>
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<tr>
<td>$L$</td>
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<td>$T$</td>
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Longitudinal SSF (leading twist)
\[ g_1(x) = \sum g_i^q(x) = \sum \int d^2 \vec{k}_i \ g_{1L}(x, \vec{k}_i^2) \]

Transverse SSF (twist-3)
\[ g_{1T}^{(1)}(x) = \sum g_{1T}^{q(1)}(x) = \sum \int d^2 \vec{k}_i \ \frac{\vec{k}_i^2}{2M^2} g_i^{q(1)}(x, \vec{k}_i^2) \]
\[ g_T(x) = g_1(x) + \frac{d}{dx} g_{1T}^{(1)} = g_1(x) + g_2(x) \]
Double Spin SIDIS $A_{LT}$

- $g_{1T}^\perp(x, k_t)$ is chiral-even TMD for quarks with longitudinal helicity in a transverse polarized target.
- Weighted by $k_t^2/2M^2$ and integrated over $k_t$, generates a $\cos(\phi-\phi_s)$ azimuthal $A_{LT}$, measurable in SIDIS.

\[
A_{LT}(x, y, z) = \frac{C(x, y) \sum e^2 g_{1T}^{(1)(x)} D^h(z)}{(|P_T|/M) \cos(\Phi-\Phi_s)} = \frac{C'(x, y) \sum e^2 f_1(x) D^h(z)}{C'(x, y) \sum e^2 f_1(x) D^h(z)}
\]

Hall A E06-010, PRL 108 (2012) 05200
Duality in $g_1$

- Bloom – Gilman duality for spin SF's
  - Local Duality only above $\Delta(1232)$
  - Global duality (for $W > \pi$ threshold, or from elastic) obtains above $Q^2 > 1.8$ GeV$^2$
  - seen in $p$, $d$, and $^3$He
  - DIS SSF's from PDF's extrapolated with target mass corrections
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