The Spin Asymmetries of the Nucleon Experiment - SANE

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Probing the Nucleon 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 $G_1$, $G_2$

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

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

(http://www.desy.de/~gbrandt/feyn/)

Inclusive scattering: undetected final state
Structure Functions in Inclusive DIS

- In high energy DIS, $G_1$, $G_2$, $W_1$ and $W_2$, become scaling functions of only one variable, up to log violations.

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

- In the quark parton model, $g_1$ and $F_1$ can be related to parton distribution functions - PDF's:

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

(Index $f$ runs over active flavors)
Virtual Compton Asymmetries

• The spin SF's are also related to virtual photon absorption cross-sections and spin asymmetries (SA)

  • the helicity of the virtual photon-nucleon system is 3/2 or ½ for transverse photons, ½ for longitudinal ones

• $A_1$ is defined in terms of the difference for 3/2 and ½ helicity cross sections

\[ A_1 = \frac{\sigma_T^{3/2} - \sigma_T^{1/2}}{\sigma_T^{3/2} + \sigma_T^{1/2}} \]

\[ A_1 = \frac{1}{F_1} \left( g_1 - \gamma^2 g_2 \right); \quad \gamma = \frac{2xM}{\sqrt{Q^2}} \]

• $A_2$ represents the interference between initial transverse and final longitudinal amplitudes

\[ A_2 = \frac{\sigma_T^{1/2}}{\sigma_T^{3/2} + \sigma_T^{1/2}} \leq \sqrt{\frac{A_1 + 1}{2}} \quad R \leq R = \sqrt{\frac{\sigma_L}{\sigma_T}} \]

\[ A_2 = \frac{\gamma}{F_1} (g_1 + g_2) = \frac{\gamma}{F_1} g_T \]
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

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

- $G_1$ 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 $qgq$ is first step to understanding confinement
  - "Unique feature of spin-dependent scattering" (R. Jaffe)

(Comments NPP 19, 239 (1990))
Why is $g_2$ interesting?

- tests **twist-3** effects = *quark-gluon* correlations
- higher twist corrections to $g_1$ with 3$^\text{rd}$ moment's $d_2$ matrix element
- also test lattice QCD, QCD sum rules, quark models
- $d_2$ related to color Lorentz force on transverse polarized quark
  

  - sign of $d_2$ related to sign of transverse deformation (anomalous $\kappa^q$)

- polarizabilities of color fields (with twist-4 matrix element $f_2$)

  - magnetic $\chi_B = (4d_2 + f_2)/3$ and electric $\chi_E = (4d_2 - 2f_2)/3$.

- contains chiral odd twist-2 = quark transverse spin (mass term)

  - test quark masses (covariant parton models)
$g_2$ 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]

$$g_T(x) = \int d^2 \vec{k}_t \frac{k_t^2}{2M^2} g_{11}^q(x, \vec{k}_t^2) \frac{m}{M} h_1(x) + \tilde{g}_T(x)$$

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

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

Twist-3 for the nucleon (neglecting quark mass)

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

Proton world $A_{\parallel}, A_{\perp}$ data before SANE

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

Goal: Measure the proton spin structure function \( g_2(x, Q^2) \) and spin
asymmetry \( A_1(x, Q^2) \) for \( 2.5 \leq Q^2 \leq 6.5 \text{ GeV}^2 \) and \( 0.3 \leq x \leq 0.8 \)

Method: Measure parallel and near-transverse inclusive double spin asymmetries,
detecting the electrons with novel non-magnetic large solid angle telescope BETA
SANE Layout in JLab's Hall C

Hall C

High Momentum Spectrometer - HMS

Polarized Target

CEBAF South Linac

beam <p> ~ 73%

Big Electron Telescope Array

ΔΩ ~ 190 msr; Δθ = ± 10°

[1] Big Electron Telescope Array

(J. Maxwell)
BETA with DIS electron simulation

BigCal Pb glass Calorimeter [1]

B field: 80°, 180° (W. Armstrong)

[1] BigCal Collaboration
[5] UVA- JLab
Polarized Target

- Dynamic Nuclear Polarized ammonia $^{14}\text{NH}_3$ at 5T and 1K
  - $\langle P \rangle \sim 70\%$ 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

(UVA polarized target group)
Data
## DATA

<table>
<thead>
<tr>
<th>Detector</th>
<th>Detected particle</th>
<th>Scattering Type</th>
<th>Beam Energy [GeV]</th>
<th>Field Direction</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>BETA</td>
<td>e, $\pi^0$</td>
<td>Inclusive inelastic</td>
<td>5.9, 4.7</td>
<td>180°, 80°</td>
<td>NH3</td>
</tr>
<tr>
<td>HMS</td>
<td>e</td>
<td>Inclusive inelastic</td>
<td>5.9, 4.7</td>
<td>180°, 80°</td>
<td>NH3, C, LHe [1]</td>
</tr>
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<tr>
<td>BETA - HMS</td>
<td>e - p</td>
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<td>5.9</td>
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<td>NH3</td>
</tr>
</tbody>
</table>

[1] Unpolarized, for dilution factor

- **Data taken in January - March 2009**
BETA and HMS data

- $Q^2 - x$ phase space of BETA's 80° data
- Central kinematics of HMS inclusive asymmetry data
- cut on $E' \geq 1.3$ GeV
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
- $C_N = ^{14}\text{N}$ polarization correction
- $A_b, f_b$ = background corrections
- $A_{rc}, f_{rc}$ = radiative corrections

\[ A_\perp = \frac{(A_{180}\cos 80 + A_{80})}{\sin 80} \]
Preliminary Results
Spin Asymmetries $A_1$ and $A_2$

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

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

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

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\]

4/10/15

HMS single arm data in the resonances, $<Q^2> \sim 1.3$ GeV$^2$

- Model independent separation from measured asymmetries

4/10/15

(H.-y. Kang)
DIS Spin Asymmetry $A_1$

- $A_1(W)$ shows clear decreasing trend
- SANE BETA data
  - statistical errors only
- SLAC data plotted for individual spectrometers
  - very broad $Q^2$ range
- CLAS data at same $W$ but different $Q^2$ merged for clarity

(W. Armstrong)
\( g_1 \) and \( g_2 \) in DIS and Resonances

- BETA proton data
  - DIS and Resonances
  - \( g_1, g_2^{ww} \) curves from PDF's at 4 GeV\(^2\)
  - \( E' \geq 0.6 \) GeV
  - more data at 1.6 GeV\(^2\) coming
- SLAC E143, E155, E155x, SMC and HERMES DIS data

(W. Armstrong)
$g_1$ and $g_2$ in DIS and Resonances

- **BETA proton data**
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\[ x^2 g_2 \]
Operator Product Expansion for Spin SF's

- OPE relates Cornwall-Norton moments to matrix elements of twist-2 \( a_N \) and twist-3 \( d_N \)

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

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

\( (tmc: \text{target mass corrections}) \)

- \( d_2 \) is mean color-magnetic field along spin

- Nachtmann moments needed to get twist-3 free of \( tmc \)

\[
d_2(Q^2) = \int_0^1 dx \xi^2 \left( 2 \frac{\xi}{x} g_1 + 3 \left( 1 - \frac{\xi^2 M^2}{2 Q^2} \right) g_2 \right) \Rightarrow Q^2 \to \infty \int_0^1 dx x^2 \left( 2 g_1 + 3 g_2 \right)
\]
Operator Product Expansion for Spin SF's

- OPE relates Cornwall-Norton moments to matrix elements of twist-2 $a_N$ and twist-3 $d_N$

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

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

($tmc$ : target mass corrections)

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

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

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

- SANE analysis final version
- Publications in preparation

(W. Armstrong)
$G_E^p / G_M^p$ from inclusive and coincidence data

Ratio from:

- **SANE inclusive HMS data at $Q^2 = 2.06 \text{ GeV}^2$**
  
  - $A_{el}^p = -0.20 \pm 0.02$
  
  - $G_E^p / G_M^p = 0.60 \pm 0.18 \pm 0.06$

  (statistical + systematic error)

- **BETA–HMS $e–p$ coincidences at $Q^2 = 5.66 \text{ GeV}^2$**

  - $G_E^p / G_M^p = 0.67 \pm 0.36$

  (statistical error only)
Extras
**DIS Transverse Spin SF** $g_T^p$

- $g_T^p = F_1 A_2 / \gamma$ measures spin distribution normal to $\gamma^*$
- SANE $\langle g_T^p(x > 0.3) \rangle = 0.023 \pm 0.006$

- **Bag Model (1990's)**
  - Data scaled $\times 2.5$
  - Model updates needed
Sample of Normalizations and corrections
Pair-symmetric background - I

• BigCal detects both charge signs
  - Significant background from $e^+e^-$ from $\pi^0$ decays
  - Partial control with cut on $E' \geq 1.3$ GeV; worst dilution $< \sim 0.2$
  - Estimate with GEANT simulation of $\pi^0$ production
  - Need inclusive pion photo- and electro-production cross sections
  - Existing D. Wiser parametrization only for H, D targets
  - Parameterized Yerevan pion photoproduction data on C at 4.5 GeV
    • Cross section scales with pion $P_T$: use simple exponential scaling fit
    • Included fit in J. O'Connell EPC code for single arm hadron photo and electroproduction
    • Compared with DESY electroproduction on C at 5 GeV
Pair-symmetric background - II

K. Alanakian et al., JETP Lett. 32 (1980) 652

- Fitted $\pi^+$, $\pi^-$ data at 20°, 40°, 60° to $\sigma(P_T) = a e^{-bP_T}$
- $\pi^0$ fit from average of $\pi^+$ and $\pi^-$
- Wiser $\pi^-$ data on H, scaled 12×, along with $\pi^-$ data on C and scaling fit to C data.
Pair-symmetric background - III

- Test of scaling fit with DESY C(e,π⁻) data at 5 GeV, 13°

Jefferson Angular Momentum – JAM Collaboration

- Joint theorists and experimentalists effort to “study the quark and gluon spin structure of the nucleon by performing global fits of PDFs”.
- JAM's spin PDFs are tailored for studies at large Bjorken $x$, as well as the resonance-DIS transition region at low and intermediate $W$ and $Q^2$.

http://wwwold.jlab.org/theory/jam/
Big Electron Telescope Array – BETA

- **BETA specs**
  - Effective solid angle 0.194 sr
  - Energy resolution
    $10\% / \sqrt{E(\text{GeV})}$
  - 1000:1 pion rejection
  - Angular resolution $\sim 1 \text{ mr}$
- **Non-magnetic detector**
  - Detects DIS $e$ and $e^+ e^-$ pairs: need to cut on minimum $E'$
  - Target field helps sweep lowest $E$ background (180 MeV/c cutoff)
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>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Target} \downarrow \setminus \text{quark} \rightarrow )</td>
</tr>
<tr>
<td>( U )</td>
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<td>( L )</td>
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Longitudinal SSF (leading twist)
\[
g_1(x) = \sum g_i^q(x) = \sum \int d^2 \vec{k}_t g_{1L}(x, \vec{k}_t^2)
\]

Transverse SSF (twist-3)
\[
g_{1T}^{(1)}(x) = \sum g_{1T}^{q(1)}(x) = \sum \int d^2 \vec{k}_t \frac{\vec{k}_t^2}{2M^2} g_{1T}^q(x, \vec{k}_t^2)
\]
\[
g_7(x) = g_1(x) + \frac{d}{dx} g_{1T}^{(1)} = g_1(x) + g_2(x)
\]