Nucleon Spin Physics Program in JLab's Hall C

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Nuclear Seminar
U. of Virginia
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Scattering and proton structure

- Charged point particles obey Rutherford scattering (non-relativistic)

- R. Hofstadter found proton was not a point particle using electron scattering at SLAC: deviations from Mott scattering (for relativistic spin $\frac{1}{2}$ point particles)
Electron (lepton) scattering

- Scattering high energy electrons makes short wavelength light
  - Coulomb scattering produces virtual photons (time-like, longitudinal, transverse)
  - *Bremsstrahlung* produces real photons (transverse only)
- Other "electron-like" particles (leptons) can also be used:
  - Muons and neutrinos
Examples of electron scattering

- Elastic, quasi-elastic scattering:
  - $e + A \rightarrow e' + A'$
  - $e + N \rightarrow e' + N'$

- Inclusive inelastic scattering
  - $e + A \rightarrow e' + X$ or $A(e,e')X$

- Deep Inelastic Scattering (DIS) of leptons probes inside the nucleon (protons and neutrons)

- Partonic ($q, g$) structure of the nucleon established from DIS
Scaling and DIS

- Parton, QCD predictions:
  - DIS scattering same at all energy scales
  - Scattering depends on one dimensionless parameter
    \[ x = \frac{Q^2}{2M_\nu} \]
  - \( Q^2 \) = four-momentum squared of virtual photon
  - \( \nu \) = energy of virtual photon
  - Deviations of \( F_2(x) \) from scaling: gluon radiation

\[
\frac{d^2 \sigma}{d \Omega dE'} \approx \left( \frac{d^2 \sigma}{d \Omega dE'} \right)_{\text{point}} f(E, E', \theta) F_2(x)
\]

\( F_2(x) \) = nucleon structure function
\( x \) = fraction of proton's \( |\vec{p}| \) carried by parton
Scaling and DIS

- Parton, QCD predictions:
  - DIS scattering same at all energy scales
  - Scattering depends on one dimensionless parameter
    \( x = \frac{Q^2}{2Mu} \)
  - \( Q^2 = \) four-momentum squared of virtual photon
  - \( u = \) energy of virtual photon
  - Deviations of \( F_2(x) \) from scaling: gluon radiation
Scaling and DIS

- Parton, QCD predictions:
  - DIS scattering same at all energy scales
  - Scattering depends on one dimensionless parameter
    \[ x = \frac{Q^2}{(2\mu v)} \]
  - \( Q^2 \) = four-momentum squared of virtual photon
  - \( \mu = \) energy of virtual photon
  - Deviations of \( F_2(x) \) from scaling: gluon radiation

Parton Distribution Functions - PDF's (Review of Particle Properties 2004)
Polarized photons

- Real and virtual photons can be polarized
  - real photons are transverse waves only; \( \mathbf{E} \) and \( \mathbf{B} \) fields perpendicular to motion
  - linear and circular polarization
  - virtual photons can have longitudinal polarization:
    photon spin \( \mathbf{J} = 1 \hbar, J_z = \pm 1, 0 \)
- virtual photon mass squared \(-Q^2 \neq 0\) allows \( J_z = 0 \)

Polarized light reveals features (stress patterns) not seen otherwise
Polarized photons

Tip: Looking for pictures? Try Google Images

Polarization of the Photon
... Polarization of the Photon. And what about the photon? ... We can use symbols and to describe linearly polarized photons in the x or y directions. ... beige.ovpit.indiana.edu/B679/node62.html - 10k - Cached - Similar pages

The polarization of photons
... A beam of light which is plane polarized in a certain direction is made up of a stream of photons each plane polarized in that direction. ... farside.ph.utexas.edu/teaching/qm/fundamental/node6.html - 10k - Cached - Similar pages

PHSC 1121 - Lab 6
... second, with each photon polarized in a different plane. This combination of randomly polarized photons is called unpolarized light. ... hp73.pvamu.edu/phsc/lab6.html - 8k - Cached - Similar pages

Re: Linearly polarized photons
... Re: Linearly polarized photons. Subject: Re: Linearly polarized photons; From: n._bates@my-deja.com; Date: Tue, 05 Dec 2000 01:50:04 GMT; ... www.lns.cornell.edu/spr/2000-12/msg00300008.html - 5k - Cached - Similar pages

Re: Linearly polarized photons
... Re: Linearly polarized photons. Subject: Re: Linearly polarized photons; From: baszn@galexy.ucr (John Basz); Date: 7 Dec 2000 10:43:41 GMT; ... www.lns.cornell.edu/spr/2000-12/msg0030038.html - 5k - Cached - Similar pages [ More results from www.lns.cornell.edu ]

Polarized Photon Beams
... Polarized Photon Beams: With such a cavity operating in the visible (515 nm), scattering against 4 GeV electrons would produce 0.5 GeV polarized photons. ... www.jlab.org/media_relations/nsac/paragraph3_6_2_9_2.html - 5k - Cached - Similar pages

The Physics with Linearly-Polarized Photons in Hall B of JLab
The Physics with Linearly-Polarized Photons in Hall B of JLab Dr. Philip Cole Idaho State University Department of Physics Constituent quark models, such as ... www.physics.isu.edu/colloquium/cole05.html - 3k - Cached - Similar pages

Photons For Sale
Low Priced Photons
Huge Selection! (aff)
ebay.com

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Making Polarized Virtual Photons

- Polarized leptons radiate polarized photons:
  - Helicity conservation requires transfer of the alignment of electron spin to the photon
  - Transfer not 100%, depends on electron, photon energies
  - Good for both real and virtual photons

Helicity: average probability of electrons' spin being parallel to their momenta

\[ h = \langle \sigma \cdot \hat{p} \rangle \]
Polarized lepton-nucleon scattering

- Polarized lepton beam ($e$ or $\mu$)
  - Leptons polarized along their momentum: helicity $\pm \frac{1}{2}$

- Polarized target:
  - Nuclei polarized parallel or perpendicular to beam

Nucleon spins **parallel** to beam
\[
\frac{d^2 \sigma^{(\uparrow \downarrow)}}{d \Omega \, dE'} - \frac{d^2 \sigma^{(\downarrow \uparrow)}}{d \Omega \, dE'} = \frac{4 \alpha^2 E'}{Q^2 E} \left[ (E + E' \cos \theta) M G_1(\nu, Q^2) - Q^2 G_2(\nu, Q^2) \right]
\]

Nucleon spins **perpendicular** to beam
\[
\frac{d^2 \sigma^{(\uparrow \rightarrow)}}{d \Omega \, dE'} - \frac{d^2 \sigma^{(\downarrow \leftarrow)}}{d \Omega \, dE'} = \frac{4 \alpha^2 E'}{Q^2 E} E' \sin \theta \left[ M G_1(\nu, Q^2) + 2 E G_2(\nu, Q^2) \right]
\]
Spin Structure Functions (SSF)

- Two structure functions that depend on the nucleon's polarization: $G_1$ and $G_2$
  - $G_1$ dominates parallel scattering, $G_2$ is mainly perpendicular
  - At very high energy they are expected to scale (like $F_2$):
    \[
    \lim_{Q^2, \nu \rightarrow \infty} \left( M^2 \nu \right) G_1(\nu, Q^2) = g_1(x)
    \]
  - $g_1(x)$ can be interpreted in the parton model as the helicity (=spin) distribution of the quarks in the nucleon:
    \[
    g_1(x) = \frac{1}{2} \sum e_i^2 (q_i^\uparrow(x) - q_i^\downarrow(x)), \quad i = \text{index of quark flavor: } u, \bar{u}, d, \bar{d}, \ldots \text{etc.}
    \]
Spin Asymmetry (SA)

- SF's at Low Energy (e.g. Resonances): forward virtual Compton scattering $\sigma$

$$A_1(Q^2, \nu) = \frac{\sigma_{1/2}^T - \sigma_{3/2}^T}{\sigma_{1/2}^T + \sigma_{3/2}^T} = \frac{M \nu G_1(Q^2, \nu) - Q^2 G_2(Q^2, \nu)}{W_1(Q^2, \nu)}$$

- SF's in DIS: Parton model and QCD's Operator Product Expansion - OPE

$$A_1(x) \approx \frac{g_1(x)}{F_1(x)} = \sum e_i^2 \Delta q_i \frac{\sum e_i^2 q_i}{\sum e_i^2 q_i}$$
Early Spin Structure Results

- First measurements of SSF's at SLAC E80 (1978)
  - Measured $A_1^{\text{proton}} \approx g_1/F_1$

- Improved measurement at CERN EMC experiment:
  - Quarks not carrying all of the proton's spin

$$\int_0^1 dx \, g_1(x) = \frac{1}{2} \sum e_i^2 \Delta q_i = \frac{1}{18} (4 \Delta u + \Delta d + \Delta s)$$

Quark component of spin $\frac{1}{2} \sum q = \Delta u + \Delta d + \Delta s \neq \frac{1}{2}$
Final Results from SLAC, CERN, DESY

July 2000

- Bjorken sum rule \( \int_0^1 (g_1^p - g_1^n) \, dx = g_A / 6 \times C_{ns} \) (QCD) verified to ~10%
- Quark spin (SLAC E155 global fit): \( \sum q = 0.229 \pm 0.041 \pm 0.057 \)
- Quarks: only 23% of spin! What carries the remainder? \textit{gluons}? \( L \)?

![Graphs showing the results of the measurements.](Image)
Polarized PDF's - Gluon Spin

- Gluon contribution not yet established by experiment
- Few data, seem to favor 0 gluon spin
  - (N. Saito plenary talk, PANIC 2005)

(Review of Particle Properties 2004)
Transverse Spin Structure Functions

- Transverse $g_T$ measures spin distribution normal to virtual photon
  \[ g_T = g_1 + g_2 \]
- No simple parton interpretation for transverse SSF's.
- $g_2$ is combination of twist-2 ($q$-$q$) and twist-3 ($q$-$g$) components:
  \[ g_2(x, Q^2) = g_2^{WW}(x, Q^2) + g_2(x, Q^2) \]
  \[ = - g_1(x, Q^2) + \int_{x}^{1} g_1(x', Q^2) \frac{dx'}{x'} - \int_{x}^{1} \frac{\partial}{\partial x'} \left[ \frac{m}{M} h_T(x', Q^2) + \xi(x', Q^2) \right] \frac{dx'}{x'} \]
- $g_2^{WW}$ (Wandzura-Wilczek) part depends on $g_1$; $h_T$ is transversity SSF
- $\xi$ represents twist-3 quark-gluon correlations.
Results for $xg_2$ vs $x$

- E155x: solid red
- E143: open green
- E155: crosses
- Black curve: $xg_2^{ww}$
- Models
  - Magenta: Stratmann
  - Light-blue: Weigel et al.
  - Green: Wakamatsu
  - Blue dots: Song
Transverse Spin Structure Sum Rules

- Operator-Product Expansion (OPE):
  - connection between $g_1$, $g_2$ moments with twist-2 ($a_N$), twist-3 ($d_N$) matrix elements

\[
\int_0^1 x^N g_1(x, Q^2) dx = \frac{1}{2} a_N + O(M^2/Q^2), \quad N = 0, 2, 4, ...
\]
\[
\int_0^1 x^N g_2(x, Q^2) dx = \frac{N}{2(N+1)} (d_N - a_N) + O(M^2/Q^2), \quad N = 2, 4, ...
\]

- $d_N$ measure twist-3 (for $m \ll M$ and $h_T$ not too large)

\[
d_N(Q^2) = \frac{2(N+1)}{N} \int_0^1 x^N g_2(x, Q^2) dx
\]
Twist-3 $d_2$: Theory and Experiment

$$d_2(Q^2) = 3 \int_0^1 x^2 g_2(x, Q^2) \, dx$$

Models and Data

- **Bag**: 1-Song, 2-Stratmann, 3-Ji & Unrau
- **QCD Sum Rules**: 4-Stein et al., 5-Balitsky et al., 6-Ehrnsperger & Schaefer
- **Lattice QCD**: 7-Goeckeler et al.
- **Chiral Quark Soliton**: 8-Weigel et al.
- **E155, E155x, E142, E143, E154**
DIS and Beyond - JLab Spin Physics

- **DIS** does not exhaust possibilities of spin structure physics
- New player in spin physics: TJNAF or JLab
- Lower energy than SLAC but very high intensity
- Three experimental halls:
  - A, B and C (!)
JLab Polarized Electron Beam

- CEBAF recirculating linear accelerators: final energy $\propto$ number of passes
  - $E_{\text{maximum}} = 5.78$ GeV
  - $I_{\text{maximum}} = 140$ $\mu$A

- Electrons emitted by photoelectric effect with polarized laser light
  - Maximum source polarization $\sim 75$-$85\%$
Hall C Facility

- Three spectrometers
  - All purpose High Momentum Spectrometer (HMS) is used for Spin Physics
  - Short Orbit Spectrometer (SOS) and experiment G0
HMS

- Quadrupole magnets focus particles
- Dipole disperses particles by momentum
- Detectors
  - Drift chambers for tracking
  - Cherenkov and shower calorimeter for particle ID
  - Scintillators for timing
Polarized Target

- Dynamic Nuclear Polarization
  - hyperfine transitions induced by microwave pumping
- Typical characteristics:
  - very high magnetic field
    - $B > 2.5$ Tesla ($5$ T common)
  - low temperature $\leq 1\text{K}$
  - frozen solids: $\text{NH}_3$, $\text{LiD}$
  - NMR to measure polarization
  - maximum $I_{\text{beam}} \approx 200$ nA
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  - NMR to measure polarization
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Hall C Spin Structure Program

- Spin Structure Functions at 6 GeV:
  - Inclusive measurements
    - SSF's in the Nucleon Resonances Region - RSS
    - SSF's at high Bjorken $x$ (proton) - SANE
  - Semi-inclusive measurements
    - Flavor Decomposition of Nucleon Spin - SemiSANE
- Real Polarized Photons:
  - Polarized Compton Scattering
- Spin Structure Functions at 11 GeV: Inclusive, semi-inclusive and exclusive up to $Q^2 \sim 10$ GeV$^2$
JLab E01-006: Resonances Spin Structure

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 four-momentum transfer $Q^2 \approx 1.3 \text{ GeV}^2$ and invariant mass $0.8 \leq W \leq 2 \text{ GeV}$
- Study $W$ dependence, onset of polarized local duality, twist-3 effects, using inclusive polarized scattering
$A_{\parallel}$ and $A_{\perp}$ data on protons and deuterons

- Spin Structure $g_1$ and $g_2$
  obtained from $A_{\parallel}$ and $A_{\perp}$

\[
A_{\parallel} = \frac{\sigma^{(\uparrow\downarrow)} - \sigma^{(\downarrow\downarrow)}}{\sigma^{(\uparrow\downarrow)} + \sigma^{(\downarrow\downarrow)}}, \quad A_{\perp} = \frac{\sigma^{(\uparrow\rightarrow)} - \sigma^{(\downarrow\leftarrow)}}{\sigma^{(\uparrow\rightarrow)} + \sigma^{(\downarrow\leftarrow)}},
\]

- Few $A_{\perp}$ data for $W<2$ GeV

- JLab E01-006 (RSS) first complete measurement on \textit{protons} and \textit{deuterons} in the resonances

Central kinematics of world's $p, d$ data
($Q^2 < 10$ GeV$^2$; upper $Q^2$ limit for Hall B)
## Resonances SSF Experiments

<table>
<thead>
<tr>
<th>Lab</th>
<th>Experiment</th>
<th>Target</th>
<th>$Q^2$ [GeV/c]$^2$</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC</td>
<td>E143 (E80)</td>
<td>NH$_3$ p(rotons) &amp; d (eutrons)</td>
<td>0.5 1.3</td>
<td>A$_\parallel$</td>
</tr>
<tr>
<td>JLab</td>
<td>Hall A 94-010</td>
<td>$^3$He</td>
<td>0.1 to 0.9 (6 values)</td>
<td>A$<em>\parallel$,A$</em>\perp$</td>
</tr>
<tr>
<td></td>
<td>CLAS eg1a-b</td>
<td>NH$_3$ p &amp; d</td>
<td>0.2 to 5 (over 12 values)</td>
<td>A$_\parallel$</td>
</tr>
<tr>
<td></td>
<td>Hall C RSS</td>
<td>NH$_3$ p &amp; d</td>
<td>1.3</td>
<td>A$<em>\parallel$,A$</em>\perp$</td>
</tr>
<tr>
<td></td>
<td>Hall A 01-012</td>
<td>$^3$He</td>
<td>~1. to ~4.</td>
<td>A$<em>\parallel$,A$</em>\perp$</td>
</tr>
</tbody>
</table>
RSS Technique

- **Equipment: TJNAF Hall C**
  - CEBAF polarized electron beam
    - 2 cm diameter raster at target
    - \( I = 85-150 \text{ nA} \)
  - Target: polarized ammonia \( \text{NH}_3, \text{ND}_3 \).
    - Luminosity \( \sim 10^{35} \text{ s}^{-1}\text{cm}^{-2} \)
  - HMS electron detector
- **Data run: Jan.-Feb. 2002**
  - 160 M proton,
  - 350 M deuteron triggers
**RSS Kinematics**

- Beam energy 5.755 GeV
- HMS angle 13.15°
- HMS central momenta:
  - 4.71 GeV/c
  - 4.08 GeV/c
- Final state mass range:
  - 0.8 GeV ≤ \( W \) ≤ 2.0 GeV
- \( <Q^2> = 1.3 \text{ [GeV/c]}^2 \)
Measured asymmetries $A_{\parallel}$, $A_{\perp}$

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

$$\epsilon = \frac{(N^- - N^+)/N^- + N^+)}{N^- + N^+}$$

- $N^-$, $N^+ = \text{charge normalized, dead time and pion corrected yields for +/− beam helicities}$
- $P_b$, $P_t = \text{beam, target polarizations}$
- $f = \text{dilution factor}$
- $C_N, C_D = \text{corrections for } ^{15,14}\text{N proton}$
  - $C_D = 0$, deuteron $C_N \approx 1$
- $f_{rc}, A_{rc} = \text{radiative corrections}$
Measured asymmetries $A_\parallel$, $A_\perp$

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

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

- $f$ = fraction of rate from polarized H, $^2\text{H}$
  - Monte Carlo radiated rates
- Effective ammonia thickness (packing fraction) is cell specific - 8 cells total
  - obtained from data-MC comparison
  - packing fraction range: 0.52 - 0.61
Measured asymmetries $A_{\parallel}, A_{\perp}$

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

$$\epsilon = (N^- - N^+)/N^- + N^+)$$

- $N^-, N^+ =$ charge normalized, dead time and pion corrected yields for $+/-$ beam helicities
- $P_b, P_t =$ beam, target polarizations
- $f =$ dilution factor
- $C_N, C_D =$ corrections for $^{15,14}$N proton
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- $P_b, P_t$ = beam, target polarizations
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- $N^-, N^+ =$ charge normalized, dead time and pion corrected yields for +/- beam helicities
- $P_b, P_t =$ beam, target polarizations
- $f =$ dilution factor
- $C_N, C_D =$ corrections for $^{15,14}N$ proton
  - $C_D = 0,$ deuteron $C_N \approx 1$
- $A_{rc} =$ radiative correction ($p$ only)
How to get $A_1$, $A_2$

- Combine $A_{\parallel}$, $A_{\perp}$ to get $A_1$, $A_2$:

\[
A_1 = \frac{1}{(E + E')D'}\left((E - E' \cos \theta)A_{\parallel} - \frac{E' \sin \theta}{\cos \phi}A_{\perp}\right)
\]
\[
A_2 = \frac{\sqrt{Q^2}}{2ED'}\left(A_{\parallel} + \frac{E - E' \cos \theta}{E' \sin \theta \cos \phi}A_{\perp}\right)
\]

- $D'(E,E',\theta,R)$ is function of kinematics and $R = \sigma_L / \sigma_T$

- Proton $R$, $F_2$ unpolarized S.F.s from E. Christy's fit to JLab Hall C $e-p$ data
Spin Asymmetry results

- $A_1, A_2$ for proton, deuteron in resonances are unique:
  - $RSS$ is only experiment that can separate $A_1, A_2$
- Proton (near) final results
- Deuteron radiative corrections not applied yet
**RSS Fit to the SA's**

- Four Breit-Wigner resonance shapes plus DIS background
- Fit $A_1$ and $A_2$ independently
- Reduced $\chi^2 \sim 1.3 - 15$ for 12 d.o.f.
• $A_1$: highest precision and resolution at $Q^2 \sim 1.3$ GeV$^2$

• $A_2$: first measurement on proton in the resonances
Spin Structure Functions

- Use unpolarized $F_1$

$$g_1 = \frac{F_1}{1 + \gamma^2} (A_1 + \gamma A_2)$$
$$g_2 = \frac{F_1}{1 + \gamma^2} \left( \frac{A_2}{\gamma} - A_1 \right); \quad \gamma = \frac{2xM}{\sqrt{Q^2}}$$

- High precision, high resolution measurement

- First world data for $g_2^p$ in the resonances

- Clear higher-twist in $g_2^p$
RSS Proton $g_1$ results in context

- RSS results should help improve SSF models
- Fit to $A_1$, $A_2$ gives excellent description of $g_1$
Local Duality (Bloom-Gilman 1971)

- Integral of proton $W_2(\nu,Q^2) = \text{integral of scaling } F_2(\omega') \equiv \nu W_2(\omega')$
  - fixed $Q^2$, definite ranges of $\nu$ from 1.072 GeV $\leq W \leq \sim 2$ GeV

- Ratio of integrals vs $Q^2$
  - $\sim 1$ for all mass ranges
  - independent of $Q^2$ above a low ("precocious") value $\sim 1$ GeV^2
  - Hall C resonances data
  - NMC $F_2$ and Hall C fit

\[
2 \frac{M}{Q^2} \int_{\nu_a}^{\nu_b} d\nu \nu W_2(\nu,Q^2) = \int_{\omega'_a}^{\omega'_b} d\omega' F_2(\omega')
\]

\[
\nu_{a,b} = \frac{W_{a,b}^2 - M^2 + Q^2}{2M} \quad \omega'_{a,b} = 1 + \frac{W_{a,b}^2}{Q^2}
\]
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Local Duality for $g_1$

- Integrate (at mean $Q^2 = 1.28 \text{ GeV}^2$)
  - $g_1$ fit over $A_1$ fit resonances
  - $g_1$ from PDF's evolved to same $Q^2$, with target mass corrections

- Polarized Local Duality:
  - ratio of integrals = 1

- Only approximate Global Duality

- Large $x$ resummations increase discrepancy by 1.2 (S. Liuti)
Higher-twist in $g_2^p$

- $g_2$: combination of twist-2 $(q-q)$ and twist-3 $(q-g)$

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$

- OPE matrix elements $d_N$ measure twist-3

$$d_2(Q^2) = 3 \int_0^1 x^2 \bar{g}_2(x, Q^2) \, dx$$

- Measured $d_2$:
  - elastic not included
Next: Neutron Spin Structure

- Extract neutron from $p$ and $d$
- Bodek-Ritchie version of Atwood-West smearing
  - generate smeared proton $A_{\parallel}$, $A_{\perp}$ from $g_1$, $g_2$
  - subtract from deuteron $A_{\parallel}$, $A_{\perp}$ to form smeared neutron quantities
  - unsmear neutron using iterated fit to model
Credits

Analysis Team

- Mark Jones
- Karl Slifer
- Shigeyuki Tajima
- Frank Wesselmann
- Eric Christy
- Paul McKee
- Hamlet Mkrtchyan
- Junho Yun
- Hongguo Zhu
- Oscar Rondon

Special Thanks

- Peter Bosted
- Don Crabb
- Donal Day
- Mahbub Khandaker
- JLab Hall C
- JLab Target group
SANE
Spin Asymmetries on the Nucleon Experiment
(TJNAF E-03-109)

SANE Collaboration
U. Basel, Florida International U., Hampton U., Norfolk S. U., North Carolina A&T S. U.,
IHEP-Protvino, Kent S. U., U. of Regina, Rensselaer Polytechnic I., St. Norbert College,
Temple U., TJNAF, U. of Virginia, College of William & Mary, Yerevan Physics I.

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

- Measure proton $g_2(x, Q^2)$ and $A_1(x, Q^2)$
  - $2.5 \leq Q^2 \leq 6.5$ GeV$^2$ and $0.3 \leq x \leq 0.8$
- Goals:
  - $x$ and $Q^2$ dependence of spin structure functions
  - Twist-3 from moments of $g_2$ and $g_1$, compare with Lattice QCD
  - "High $x$" region: $A_1$ approach to $x = 1$
  - Test polarized local duality for $W > 1.4$ GeV
- Method:
  - Inclusive parallel and near-perpendicular spin asymmetries
  - Detector: large solid angle electron telescope BETA
SANE Kinematics

- Two beam energies:
  - 6 GeV, 4.8 GeV
- Very good high $x$ coverage
SANE Layout

- Target field aligned to measure Parallel and near-Perpendicular asymmetries
Big Electron Telescope Array - BETA

- BigCal lead glass calorimeter: main detector, being built for GEp-III.
- Gas Cherenkov: additional pion rejection
- Tracking Lucite hodoscope (Cherenkov)
- Target field sweeps low $E$ background
- BETA's characteristics
  - Effective solid angle = 0.194 sr
  - Energy resolution $5%/\sqrt{E}(\text{GeV})$
  - Angular resolution = 2°
  - 1000:1 pion rejection
- Added: front quartz hodoscope
  - Vertex resolution ~ 4 mm (geometric)
  - Angular resolution ~ 1 mr
SANE Current Design (1/06)

BETA

BigCal

Lucite Hodoscope

Gas Cherenkov

Quartz Hodoscope

HMS

Polarized Target

Target Beam position monitor

Beam Line
SANE Expected Results

- DIS data for $x$ up to 0.6 (with 6 GeV)
  - Constrain extrapolations of $A_1^p$ to $x = 1$ within +/- 0.1 (using duality)
SANE Expected Results (II)

- $x$ dependence at constant $Q^2$ and $Q^2$ dependence at fixed $x$
- data are concentrated in the region most sensitive to $x^2g_{2,1}$
SANE Expected Results (III)

- Twist-3 matrix element
  \[
  d_2 = \int_0^1 x^2 (2g_1 + 3g_2) \, dx
  \]
  calculable in Lattice QCD

- SANE expected error on
  \[
  d_2 (Q^2 = 2.5 \text{ to } 6.5 \text{ GeV}^2) = 0.0009 \] (½ the current world error)
SANE Status - Organization

- Conditional approval by PAC24 for 27 days in Hall C with A- rating
  - SANE addresses DOE performance milestone for 2011:
    - Nine collaboration meetings since Nov. 2003, most recent Dec. '05.
    - Seven new collaborator groups joined since PAC
    - Hall C schedule:
      - SANE tentatively to run in 2008, followed by Semi-SANE and Polarized Wide Angle Compton Scattering (All three experiments with UVa spokespeople, using UVa polarized target)
- SANE Web site: http://www.jlab.org/~rondon/sane/
Beyond Inclusive Scattering

- Eight quark distribution functions:
  - $k_\perp$ independent (leading twist)
    - $F_1, g_1$: inclusive
    - $\delta$: transversity ($h_T$)
  - $k_\perp$ dependent
    - $g_T = g_1 + g_2$: inclusive, mixed twist
    - $h_{1L}^\perp, h_{1T}^\perp$: semi-inclusive, $T$-even
    - $f_{1T}^\perp, h_1^\perp$: semi-inclusive, $T$-odd
- Spin Dependent Fragmentation: Semi-Inclusive Leptoproduction
  - Detect hadron ($\pi, K, ..$)-lepton in coincidence
  - Semi-inclusive Asymmetry

$$A^h_i(x, z, Q^2) = \sum e_f^2 q_f(x, Q^2) D_f^h(z, Q^2)$$

- Spin Dependent Exclusive Scattering: Generalized Parton Distributions
Flavor Decomposition of Nucleon Spin

TJNAF Experiment 04-113

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

• Measure proton and deuteron semi-inclusive spin asymmetries in polarized DIS reactions $p(e,e' h)$ and $d(e,e' h)$: Semi-SANE
  – $h = \pi^+, K^+, 1.2 \leq Q^2 \leq 3.2 \text{ GeV}^2, 0.12 \leq x \leq 0.43$, for hadrons with $0.5 \leq z \leq 0.7$
  – Extract the $\Delta u, \Delta d, \Delta s$, and anti-quark spin components
  – Test factorization comparing $A^{\pi^+ \pi^-}_{1N}$ to inclusive $A_{1N}$
  – Detect electrons with BETA and hadrons with HMS
Method and Sample of Expected Results

- Form $A_{1N}^{\pi^+ - \pi^-}$ to get valence quark helicities
  - combine with inclusive data to probe polarized light sea flavor asymmetry
- Compare $A_{1N}^{\pi^+ + \pi^-}$ with inclusive result to test factorization
- Expected results for the $u$ and $d$ quark asymmetries and world data
- Approved for 25 days with A- rating
Spin Physics beyond 6 GeV

- **CEBAF energy upgrade**: extended $x$, $Q^2$ ranges, better count rates
  - Precision tests of local polarized and unpolarized duality possible
  - Semi-Inclusive spin asymmetries with horizontal and vertical polarized targets (single spin LOI-04-003)
  - Inclusive tests of Collins (time odd) asymmetry= time reversal invariance (LOI-01-002)
  - Effects of nuclear binding on spin structure in $^6,^7$Li and other nuclear targets
CREDITS

• Hypephysics
  – http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html#hph

• Oxford

• DESY (Feynman diag.)
  – http://www.desy.de/~gbrandt/feyn/

• Patterns in Nature
  – http://accept.la.asu.edu/PiN/rdg/polarize/polarize.shtml

• The Physics Classroom
  – http://www.glenbrook.k12.il.us/gbssci/phys/Class/light/u12l1e.html

• Molecular Expressions
  – http://www.microscopy.fsu.edu/primer/index.html
Proton Unpolarized SF's

- Used E. Christy's fit to JLab Hall C $e-p$ inelastic data to get
  - unpolarized H cross section in MonteCarlo for dilution factor
  - unpolarized proton $F_1$, $F_2$ and $R$. 

![Graph showing $F_1$, $F_2$, and $R$ versus W (MeV)]
MC-data Comparison

Carbon data used to fit QFS model.

\[ P_0 = 4.7 \text{ GeV/c} \quad \text{and} \quad P_0 = 4.1 \text{ GeV/c} \]
Compare data spectra to MonteCarlo simulation for two (or more) values of packing fraction.

- Interpolate to match data.
Polarized Duality for $g_1$?

- **SLAC E143**
  - converted $A_\parallel$ to $g_1$
  - assumed $A_2 = 0 = g_2$.
- **Resolution $\Delta W$ too coarse for local duality test**
- **Global duality ratio of integrals**
  - 9.7 GeV 7° data: $0.65$
Hall A $g_1$ duality: low $Q^2$

- $Q^2$ low ($< 1$ GeV$^2$)
  - Inclusive scattering on $^3$He
  - Model independent $g_1$
    (measured both $A_\parallel$ and $A_\perp$)
  - $g_1$ for neutron vs $^3$He
- Quantitative test needed
- (Plot from S. Choi, for E94-010)
Hall A $g_1$ duality: intermediate $Q^2$

- Dedicated experiment on $^3$He target
- Model independent $g_1$
  (measured both $A_\parallel$ and $A_\perp$)
- $g_1$ for neutron from $^3$He
- Took data in early 2003
  - Analysis in progress
- (Plot from P. Solvignon, for E01-012)
Hall B $g_1$ duality: proton

- $Q^2$ low - intermediate
  - $g_1$ from $A_\parallel$ only - $A_2$ from model (small)
  - E155 DIS global fit at $Q^2 = 10\text{ GeV}^2$

- Quantitative test pending
- (Preliminary eg1b results)
Partons inside the nucleon

- Partonic structure of the nucleon established from DIS
- Partons:
  - colored quarks, anti-\(q\), gluons
  - colorless hadrons
  - six quark flavors
- Quantum ChromoDynamics: 2004 Physics Nobel prize for asymptotic freedom - strong force is weak at short distances (= high energy)
Polarized photons

- Real and virtual photons can be polarized
  - real photons are transverse waves only; \( \mathbf{E} \) and \( \mathbf{B} \) fields perpendicular to motion
  - linear and circular polarization
  - virtual photons can have longitudinal polarization: photon spin \( \mathbf{J} = 1\hbar, J_z = \pm 1, 0 \)
  - virtual photon mass squared \(-Q^2 \neq 0\) allows \( J_z = 0 \)
JLab Polarized Electron Beam

- CEBAF recirculating linear accelerators: final energy $\propto$ number of passes
  - $E_{\text{maximum}} = 5.78$ GeV
  - $I_{\text{maximum}} = 140$ $\mu$A

- Electrons emitted by photoelectric effect with polarized laser light
  - Maximum source polarization $\sim 75$-85%
HMS

- Quadrupole magnets focus particles
- Dipole disperses particles by momentum
  \[ F_{\text{cent.}} = \frac{mv^2}{R} = qvB = F_{\text{Lorentz}} \]
- Detectors
  - Drift chambers track particles
  - Cherenkov and shower calorimeter identify particles
  - Scintillators give time of flight
Methods and Sample of Expected Results

- $A_{1N}^{\pi^+ - \pi^-}$: valence quark helicities
  - combine with inclusive data to probe polarized light sea flavor asymmetry
  - Fixed $z$ semi-inclusive asymmetries in terms of ratios $D_h^+/D_h^-$, $D_s^+/D_h^-$
    - identical phase space for $h^+$ and $h^-$
    - Fit all $z$ data at fixed $x$ to determine five quark flavor helicities using known PDF's
  - Compare $A_{1N}^{\pi^+ + \pi^-}$ with inclusive result to test factorization
Sample of Expected Results (II)

- Expected results for the $u$ and $d$ quark asymmetries and world data.

- Other tests/results:
  - Combined proton and deuteron data for both $h^+$, $h^-$ is independent of $D$'s.
  - Data on $K^{+,-}$ asymmetries
  - Additional low $x$ inclusive data
Methods and Sample of Expected Results

- Leader-Christova (LO and NLO): $A_{1N}^{π^++π^-}$ to get valence quark helicities
- combine with inclusive data to probe polarized light sea flavor asymmetry
- Fixed $z$ semi-inclusive asymmetries in terms of ratios $D_h^+/D_h^-$, $D_s^+/D_h^-$
- identical phase space for $h^+$ and $h^-$
- Fit to all $z$ data points at fixed $x$ determines five quark flavor helicity distributions using known PDF's
- Compare combined $A_{1N}^{π^++π^-}$ asymmetries with inclusive result to test factorization
- Additional methods: Purity (HERMES); global LO and NLO fits
Scaling and DIS

- Parton, QCD predictions:
  - DIS scattering same at all energy scales
    - Scattering depends on one dimensionless parameter $x = Q^2/(2M\nu)$
    - $Q^2 =$ four-momentum squared of virtual photon
    - $\nu =$ energy of virtual photon
  - Deviations of $F_2(x)$ from scaling: gluon radiation

Figure 23: A comparison of the PDF at NLO from the statistical model (solid) with MRST2002 (dashed) [45] and CTEQ6 (dotted) [46], for quarks $u, d, s$ and gluon at $Q^2 = 20\text{GeV}^2$. 