SANE:
Spin Asymmetries on the Nucleon Experiment
Accessing the Nucleon Spin Structure

Jonathan Mulholland, UVA

JLAB: Hall C, E07-003

Sane Collaborators:

Spokerspersons: S. Choi (Seoul), Z-E. Meziani (Temple), O. A. Rondon (UVA)

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Lepton Scattering
How Scattering Provides Insight into Systems

\[ \frac{d\sigma}{d\Omega} \text{ Differential Cross-section—essentially probability of} \]
\[ \text{interaction for different energies, angles, etc. of scattering} \]

**Example**: Rutherford Scattering: scattering point-like (non-Dirac)
from an infinitely massive charged point like particle

\[ \frac{d\sigma}{d\Omega}^{\text{Rutherford}} = \frac{Z^2 e^4}{4E_0^2 \sin^4(\theta/2)} \]

**Example**: Mott scattering is as above, but for Dirac particle—
good approximation for an electron scattering off a nucleus.

\[ \frac{d\sigma}{d\Omega}^{\text{Mott}} = \frac{Z^2 e^4}{4E_0^2 \sin^4(\theta/2)} \cos^2(\theta/2) \]
Scattering of an Electron From a Hadron

\[
\frac{d^2 \sigma}{d \Omega d E'} = \frac{\alpha^2}{2 M Q^4} \frac{E'}{E} L_{\mu \nu} W_{\mu \nu}
\]

Some variables

- \( k \), the incoming electron 4-momentum
- \( k' \), the outgoing electron 4-momentum
- \( q \), the virtual photon momentum transferred to the nucleus
- \( P \), the hadron's initial 4-momentum

Also...

\[ Q^2 = -q^2 \quad \text{and} \quad \gamma = E_e - E_e' \]
no mystery here...just kinematic variables (we'll detect the scattered electron)
Hadronic Tensor...all the mystery's here

\[ W^{\mu \nu} = W^{(S)\mu \nu} + i W^{(A)\mu \nu} \]

\[
\frac{1}{2M} W^{(S)\mu \nu} = (-g_{\mu \nu} + \frac{q_{\mu} q_{\nu}}{q^2}) W_1(\nu, Q^2)
+ (P_\mu - \frac{P \cdot q}{q^2} q_\mu)(P_\nu - \frac{P \cdot q}{q^2} q_\nu) \frac{W_2(\nu, Q^2)}{M^2}
\]

\[
\frac{1}{2M} W^{(A)\mu \nu} = \epsilon_{\mu \nu \alpha \beta} q^\alpha \{ M S^\beta G_1(\nu, Q^2) + [P \cdot q S^\beta - S \cdot q P^\beta] \} \frac{G_2(\nu, Q^2)}{M}
\]

Although complicated, all we are saying is that we are stuffing all the unknown interactions into the W's and G's.
The Symmetric Terms

If one averages over the initial spins and sum over the final spin states, one obtains a cross section that depends only on the symmetric terms...

\[
\frac{d^2 \sigma}{d \Omega d E'} = \frac{\alpha^2}{2 M Q^4} \frac{E'}{E} L^{(S)}_{\mu \nu} W^{\mu \nu(S)}
\]

\[
= \sigma_{Mott} \left[ 2 W_1(\nu, Q^2) \tan^2(\theta/2) + W_2(\nu, Q^2) \right]
\]

\(W_1\) and \(W_2\) show us how the scattering process differs from Mott scattering.
The Anti-Symmetric Terms

or

Enter the Spin Structure Functions

The cross sections for scattering with the target hadron's spin parallel to the electron and with the target hadron's spin in the scattering plane and perpendicular to the electron spin involve only the anti-symmetric terms.

\[
\frac{d^2 \sigma_{\parallel}}{d \Omega d E'} = 4 \sigma_{Mott} \tan^2 \left( \frac{\theta}{2} \right) \left[ (E + E' \cos(\theta)) M G_1 - Q^2 G_2 \right]
\]

\[
\frac{d^2 \sigma_{\perp}}{d \Omega d E'} = 4 \sigma_{Mott} \tan^2 \left( \frac{\theta}{2} \right) E' \sin(\theta) (M G_1 + 2E G_2)
\]
Bjorken Scaling and The Structure Functions' Limit

Higher $Q^2$ means a smaller wavelength, which means better resolution. At a high enough energy loss in DIS, one is scattering elastically off of free quarks.

**Bjorken Limit**

$$Q^2 \rightarrow \infty \quad \nu^2 \rightarrow \infty$$

\[ MW_1(\nu, Q^2) \rightarrow F_1(x) \quad \nu M^2 G_1(\nu, Q^2) \rightarrow g_1(x) \]

\[ \nu W_2(\nu, Q^2) \rightarrow F_2(x) \quad \nu^2 M G_2(\nu, Q^2) \rightarrow g_2(x) \]

where $\chi = \frac{Q^2}{2M \nu}$ is the fraction of the nucleon's momentum carried by the struck quark in the Breit Frame.
Finding Meaning in the Bjorken Limit

$F_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) + q_i^\downarrow(x)] = \frac{1}{2} \sum_i e_i^2 q_i(x)$

$g_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) - q_i^\downarrow(x)] = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$

Where's the Spin?

$S_z^p = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle$
Ellis-Jaffe Sum Rule

Ellis-Jaffe Sum Rule: 
\[ \Gamma_{1}^{p} = \int_{0}^{1} g_{1}^{p}(x) \, dx = \frac{1}{2} \left( \frac{4}{9} \Delta u + \frac{1}{9} [\Delta d + \Delta s] \right) \]

Quark Constituent Model Predicts: 
\[ \Gamma_{1}^{p} = .278 \]

or 
\[ \Delta G = \langle L_z \rangle = 0 \quad \text{and} \quad S_{z}^{\text{proton}} = \frac{1}{2} \Delta \Sigma = \frac{1}{2} \]

EMC measurement result: 
\[ \Gamma_{1}^{p} = .143 \quad \text{ALERT!} \]

Conclusion: The valence quark spins contribute only a fraction of the total proton spin. Studying \( g_{1}(x) \) is quite important!
$g_1$'s more obscure but equally important sibling

g_2$ provides corrections to sum rules and information about QCD interactions

$g_2(x)$ is made up of twist 2 and twist 3 terms

$$g_2(x) = g_1(x) + \int_x^1 g_1(x') \frac{dx'}{x'} - \int_x^1 \frac{\partial}{\partial x'} \left[ \frac{m}{M} h_T(x', Q^2) + \xi(x', Q^2) \right] \frac{dx'}{x'}$$

These terms are contributed by $q$-$q$ and $q$-$g$ interactions and can provide corrections to sum rules.
SANE's Access to $g_1$ and $g_2$

...through the asymmetries $A_1$ and $A_2$, which are themselves linear combinations of the experimental asymmetries $A_\parallel$ and $A_\perp$

$$g_1 = \frac{F_1}{1+y^2} (A_1 + y A_2)$$

$$g_2 = \frac{F_1}{1+y^2} \frac{A_2 - A_1}{y} \text{ with } y = \frac{2xM}{\sqrt{Q^2}}$$

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

$$A_2 = \frac{\sqrt{Q^2}}{2E'D} \left( A_\parallel + \frac{E-E'\cos\theta}{E'\sin\theta \cos\phi} A_\perp \right)$$
The Necessity of Polarization

\[ A_{||, \perp} = \frac{\epsilon}{f P_b P_t C_1} + C_2 \]

- \( N^{-(+)} \): adjusted yields for -(+ beam helicity
- \( P_{b(t)} \): beam (target) polarization
- \( f \): dilution factor
- \( C_1 \) and \( C_2 \): correction factors

\[ \epsilon = \frac{(N^- - N^+)}{(N^- + N^+)} \]

\[ \left( \frac{\delta A}{A} \right)^2 = \frac{1}{(A P_b P_t)^2 N} + \left( \frac{\delta P_b}{P_b} \right)^2 + \left( \frac{\delta P_t}{P_t} \right)^2 + \left( \frac{\delta f}{f} \right)^2 \]

\[ N_{goal} = \frac{1}{(f P_b P_t A \delta \epsilon / \epsilon)^2} \]
SANE'S Setup

B at 80°, 180°
Target
Chicane
He Bag
HMS
The polarized target for SANE is a solid target system developed here at UVA
Dynamic Nuclear Polarization

It is necessary to have free paramagnetic centers in the material one is polarizing. These little magnets are polarized, and then their polarization is transferred to the protons. Several substances naturally have these, such as metals.

SANE will use Frozen 14NH3. Paramagnetic centers are artificially introduced by irradiating the material and knocking out H atoms from the material, creating free radicals.
Zeeman splitting and thermal polarization

The paramagnetic centers (free electrons) split into two populations, $N_1$ and $N_2$.

N$_1$ is # parallel with the field
N$_2$ is # anti-parallel with the field

Polarization

$$P = \frac{N_1 - N_2}{N_1 + N_2} = \tanh \left( \frac{\mu H}{kT} \right)$$

If $H = 2.5$ Tesla and $T = 0.5$ K

$$P_{\text{electron}} = 99.8\%$$

The Protons undergo a similar thermalization, but because their magnetic moment is so small

$$P_{\text{proton}} = 0.5\%$$
Hyperfine Splitting
free radical interacts with nucleon

$\Delta E = g\mu_B H$

Want to collect all the nucleons into the same angular momentum state.
Microwaves drive “forbidden” transitions. What makes everything work out nicely is the relaxation times.

**Proton** $\tau_p \sim 10$s of minutes

**Electron** $\tau_e \sim$ miliseconds
Using our DNP system at UVA we can achieve 95% or better polarization.
Material in the Beam

- Decay due to heat
- Decay due to radiation
- Beam trips
- Fast initial Polarization
Polarization Recovery

While in the beam, lots of different molecular species are being produced. Eventually the DNP mechanism is inhibited by these different species. An anneal can be performed to recover initial polarizability.
We are currently setting up the target system in the test lab, and a cooldown and test run is scheduled for early May.

SANE is scheduled to run at JLAB in October of this year.