Exploring the Spin Structure of Neutron using Deep Inelastic Scattering

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**NUCLEON SPIN STRUCTURE**

1964 Quark Model proposed by Murray Gellman and George Zweig  
1968 Experiment in SLAC; evidence that proton consists of point-like objects called Partons  
1987 EMC experiment at CERN; only a fraction of nucleon spin comes from quark spin

"PROTON SPIN CRISIS"

Current Understanding:  
$S_N = S_2^2 + L_1^2 + L_2^2 = \frac{1}{2}$

How do Quarks and Gluons contribute to overall spin of a nucleon?

**DEEP INELASTIC SCATTERING**

Unpolarized Cross Section:  
$\frac{d^2\sigma}{dE'dE} = \frac{1}{4\pi^2} \left( \frac{Q^2}{M^2} \right) \left( \frac{E'E}{E-E'} \right)^2 \left( 1 + \frac{Q^2}{M^2} \right)^2 \frac{dW}{d\Omega}$

Polarized Cross Section:  
$\frac{d^2\sigma}{dE'dE} = \frac{1}{4\pi^2} \left( \frac{Q^2}{M^2} \right) \left( \frac{E'E}{E-E'} \right)^2 \left( 1 + \frac{Q^2}{M^2} \right)^2 \left( 1 - 2\gamma \cos^2 \theta \right) \frac{dW}{d\Omega}$

• $g_2$: is among the cleanest higher twist observables – contributes in leading order (twist-2) to the transverse spin asymmetry.  
• $g_2(x,Q^2) = g_2^{\text{Born}}(x,Q^2) + g_2^{\perp}(x,Q^2)$

**NEUTRON $g_2$ AND $d_2$**

$g_2^\perp$ (Wandzura & Wilczek)  
$g_2^{\perp}(x,Q^2) = \frac{1}{x} \frac{d^2\sigma}{dE'dE} \bigg|_{\gamma=0}$

Twist-2 (Cortes, Pire & Ralston)

$g_2^{\perp}(x,Q^2) = \frac{1}{x} \frac{d^2\sigma}{dE'dE} \bigg|_{\gamma=0}$

Quark-gluon correlation

$\frac{d^2\sigma}{dE'dE} = \frac{1}{4\pi^2} \left( \frac{Q^2}{M^2} \right) \left( \frac{E'E}{E-E'} \right)^2 \left( 1 + \frac{Q^2}{M^2} \right)^2 \left( 1 - 2\gamma \cos^2 \theta \right) \frac{dW}{d\Omega}$

$\gamma = E'E - E-E' = \text{energy transfer}$

$\theta = \text{scattering angle}$

$\gamma = \text{Fraction of nucleon momentum carried by the struck quark}$

$g_2^\parallel$: is the third moment of the linear combination of the spin structure functions, clean probe of quark-gluon correlations or higher twist effects.

$g_2^\parallel(x,Q^2) = 3 \int_0^1 x^2 [g_2(x,Q^2) + 3g_2(x,Q^2)] dx + \frac{1}{x} \frac{d^2\sigma}{dE'dE}$

It represents average color Lorentz force on the struck quark due to the remnant di-quark system and it is cleanly computable using Lattice QCD

"Color Polarizability"

**THE EXPERIMENT (E12-06-121)**

Objective:  
Measurement of neutron $g_2$ and $d_2$ over a wide range of $x$ and $Q^2$ in Jefferson Lab Hall C.

Existing Results and Projections:

- Projected $d_2^\perp$ at three nearly constant $Q^2 = 3.0, 4.3, 5.6$ (GeV/c)$^2$.
- Benchmark Lattice QCD in high $Q^2$ region.
- Direct overlap with 6 GeV Hall A measurements (dips below elastic).
- Hint of a negative $d_2^\perp$ at moderate $Q^2 \sim3$ (GeV/c)$^2$ was noted in E06-014 at Jefferson Lab.

**DATA ANALYSIS**

Analysis Goal:

- Extract unpolarized cross section ($\sigma_u$) and electron asymmetries ($A_{\lambda}$) to determine $g_2$ and $d_2$.
- $A_{\perp} = \frac{\sigma_{\perp} - \sigma_{\parallel}}{\sigma_{\perp} + \sigma_{\parallel}}$ on the struck quark.
- Access $g_2$ and $d_2$ from the polarized cross section difference.

Polarization Direction Measurements:

- If the target polarization direction deviates slightly from $90^\circ/270^\circ$, the longitudinal asymmetry ($A_{\parallel}$) contributes to the total asymmetry in same order as the transverse asymmetry ($A_{\perp}$).
- Measure absolute direction of the target magnetic field in the Hall C coordinate system precisely within $\pm 1^\circ$.

Online $^3$He Elastic Asymmetries:

1-pass $^3$He elastic data was taken to check $P_P$, $P_\perp$ and other systematics.

$A_{\text{physics}} = \frac{A_{\text{raw}}}{P_P P_\perp_f N_{\text{HMS-A}}}$

Present Status:

- Detector calibration and optics analysis
- Data quality and event selection
- Cross section and asymmetry extraction
- Extract $g_2^{\perp}$, $d_2^{\perp}$

**SUMMARY**

- The experiment was successfully completed on 21st September, 2020.
- Results will provide new insight into spin structure of neutron and quark-gluon correlations, benchmark Lattice QCD predictions.
- Data analysis is in progress, exciting time for the collaboration.

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