Exploring the Spin Structure of Neutron using Deep Inelastic Scattering

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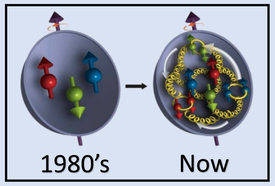
NUCLEON SPIN STRUCTURE



1964 Quark Model proposed by Murray Gellman and George Zwei

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:

$$S_z^N = S_z^q + L_z^q + J_z^g = \frac{\hbar}{2}$$

S_z^q = Quark spin
L_z^q = Quark orbital angular momenta
J_z^g = total angular momentum of the gluons

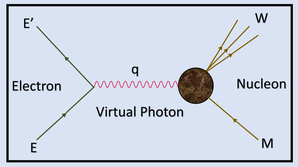
How do Quarks and Gluons contribute to overall spin of a nucleon?

DEEP INELASTIC SCATTERING

Unpolarized Cross Section:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{2}{M}F_1(x,Q^2)\sin^2\frac{\theta}{2} + \frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$

F_1, F_2: Unpolarized structure functions



Polarized Cross Section:

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow-\uparrow\Uparrow) = \frac{4\alpha^2E'}{MQ^2\nu E}\left[(E+E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right] = \Delta\sigma_{\parallel}$$

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow-\uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta\, E'^2}{MQ^2\nu^2E}\left[\nu g_1(x,Q2) - 2Eg_2(x,Q^2)\right] = \Delta\sigma_{\perp}$$

g_1, g_2: Spin structure functions

Q^2 = $-q^2$
ν = E-E' = energy transfer
θ = scattering angle
x = Fraction of nucleon momentum carried by the struck quark

NEUTRON g_2 AND d_2

- g_2 is among the cleanest higher twist observables – contributes in leading order (twist-2) to the transverse spin asymmetry.

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

Twist-2 *(Wandzura & Wilczek)*

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(x,Q^2)}{y}dy$$

Twist-3 *(Cortes, Pire & Ralston)*

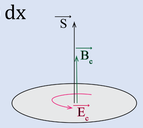
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) - \xi(y,Q^2)\right)\frac{dy}{y}$$

Quark-gluon correlation

- d_2 is the third moment of the linear combination of the spin structure function, clean probe of quark-gluon correlations or higher twist effects.

$$d_2(Q^2) = 3\int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = 3\int_0^1 x^2\bar{g}_2(x,Q^2)\,dx$$

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.

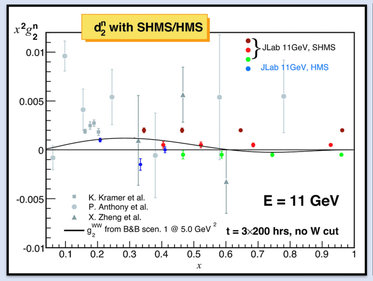


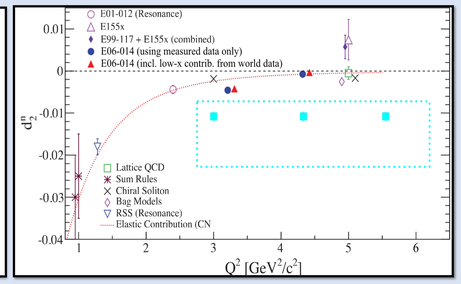
"Color Polarizability"

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.**

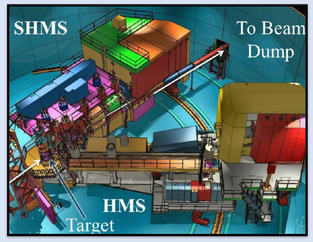
Existing Results and Projections:





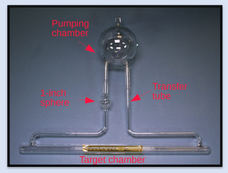
- Projected d_2^n at three nearly constant **Q^2 = 3.0, 4.3, 5.6 (GeV/c)^2**.
- Benchmark Lattice QCD in high Q^2 region.
- Direct overlap with 6 GeV Hall A measurements (dips below elastic).
- Hint of a negative d_2^n, **negative twist-3 at moderate Q^2 ~ 3 (GeV/c)^2** was noted in E06-014 at Jefferson Lab.

SETUP AND KINEMATIC COVERAGE



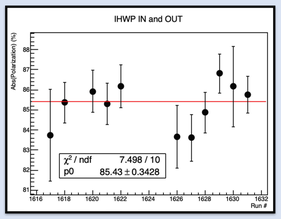
Hall C Layout

- Electron beam polarization ~85% (with ~3% uncertainty).
- Polarized ^{3}He target as an effective neutron target with ~45%-50% polarization in beam.

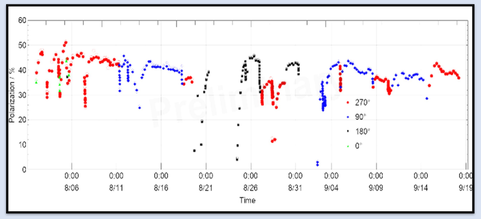


^{3}He Glass Cell

- Polarimetries used: **NMR, EPR, PNMR.**



Moller Polarimetry Results



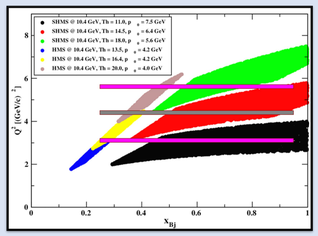
Target polarization during experiment (NMR)

SHMS Production:

Setting	P_0(GeV/c)	Angle(°)	X	Q^2(GeV^2/c^2)	W(GeV)
X	7.5	11.0	0.527	2.866	1.859
Y	6.4	14.5	0.565	4.240	2.036
Z	5.6	18.0	0.633	5.701	2.046

HMS Production:

Setting	P_0(GeV/c)	Angle(°)	X	Q^2(GeV^2/c^2)	W(GeV)
A	4.2	13.5	0.207	2.414	3.178
B	4.2	16.4	0.305	3.554	2.993
C	4.0	20.0	0.418	5.018	2.806



Kinematic Coverage

DATA ANALYSIS

Analysis Goal:

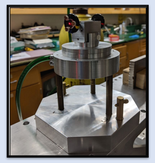
- Extract unpolarized cross section (σ_0) and electron asymmetries ($A_{\parallel}$, $A_{\perp}$) to determine g_1 and g_2.

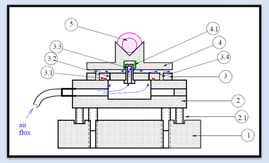
$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[A_{\parallel} + \tan\left(\frac{\theta}{2}\right)A_{\perp}\right] \quad g_2 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[-A_{\parallel} + \frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}A_{\perp}\right]$$

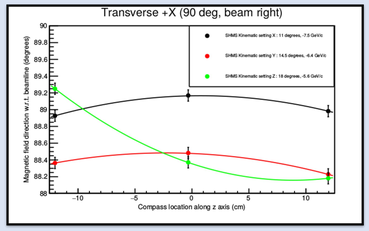
- Access g_1 and g_2 from the polarized cross section difference.

Polarization Direction Measurements:

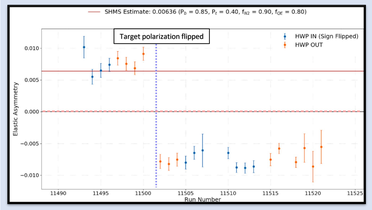
- If the target polarization direction deviates slightly from 90°/270°, the longitudinal asymmetry ($A_{\parallel}$) contributes to the total asymmetry in same order as the transverse asymmetry ($A_{\perp}$).
- Measure **absolute direction** of the target magnetic field in the Hall C coordinate system **precisely within ±0.1°**.





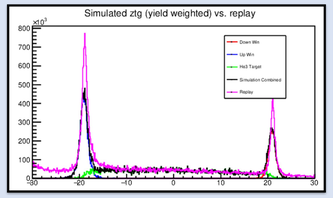


Online ^{3}He Elastic Asymmetries:



1-pass ^{3}He elastic data was taken to check P_bP_t and other systematics.

$$A_{physics} = \frac{A_{raw}}{P_b P_t f_{N2} f_{QE}}$$



Comparison of MC simulation and data HMS-A (charge normalized yield)

Present Status:

- ✓ Detector calibration and optics analysis
- ✓ Data quality and event selection
- Cross section and asymmetry extraction
- Extract g_2^n, d_2^n

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.

ACKNOWLEDGEMENT

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