Precision Measurement of the Neutron d_2: The Color Field Response to the Polarized Nucleon

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TEMPLE UNIVERSITY

Outline

1. The Spin Structure of the Nucleon
   - Current Status of the Spin Structure
2. d_2^n: Higher Twist Effects
   - Quark-Gluon Correlations
   - Expressions of d_2^n
3. The Experiment
   - The Measurement of d_2^n
   - The Experimental Setup
4. Preliminary Analysis
   - Left High-Resolution Spectrometer
   - BigBite Spectrometer
   - Compton Polarimeter
5. Projected Results
6. Summary

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Current Status of the Spin Structure

- For the nucleon, the total spin is broken down (in the light-cone gauge) into its constituents:
  - $\frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + L_q + L_G$
    $\Delta q =$ valence and sea quark spin
    $\Delta G =$ gluon spin
    $L_{q,G} =$ orbital angular momenta of quarks and gluons
  - Measurements show that quark contribution to the nucleon spin is $\sim 30\%$ (CERN,DESY,SLAC)
  - Measurements of the gluon contribution are negligible (BNL)
- All of this work corresponds to the investigation of g_1 under the interpretation of the Feynman Parton Model and pQCD
- The g_2 structure function is not as well known. It contains quark-gluon correlations inside the initial nucleon
  - Subsequently, g_2 does not have a simple interpretation in the Parton Model

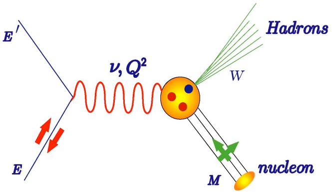
Polarized DIS

- Allows access to the spin structure functions:

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

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

- We can write g_1 and g_2 in terms of these measurable asymmetries and unpolarized cross sections



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Quark-Gluon Correlations (1)

- The g_2 structure function provides a direct probe into quark-gluon interactions, and is given by a spin-flip Compton amplitude
  - Seen in the imaginary part of virtual Compton scattering:

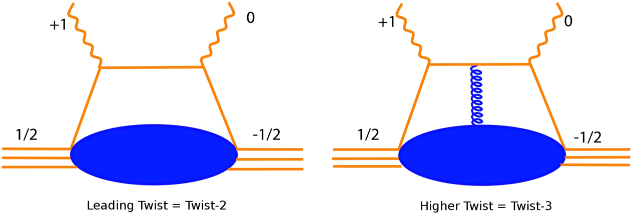

Figure: Higher twist contributions to virtual Compton scattering

Quark-Gluon Correlations (2)

The g_2 Structure Function

- g_2 can be broken into two parts:

$$g_2\left(x,Q^2\right) = g_2^{WW}\left(x,Q^2\right) + \overline{g_2}\left(x,Q^2\right)$$

where:

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

$$\overline{g_2}\left(x,Q^2\right) = -\int_x^1 \frac{1}{y}\frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T\left(y,Q^2\right) + \xi\left(y,Q^2\right)\right] dy$$

- The transverse polarization density (h_T) is suppressed by the ratio of the quark and target masses
- ξ is a twist-3 term arising from quark-gluon correlations

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Expressions of d_2^n (1)

d_2^n From the Structure Functions

- d_2^n is expressed as the second moment of a linear combination of g_1 and g_2:

$$d_2^n\left(Q^2\right) = \int_0^1 x^2\left[2g_1\left(x,Q^2\right)+3g_2\left(x,Q^2\right)\right]dx$$
$$= 6\int_0^1 x^2\overline{g_2}\left(x,Q^2\right)dx$$

- d_2^n is a direct measure of twist-3 effects in the neutron

Expressions of d_2^n (2)

d_2^n as a Lorentz Color Force

- The expression for the transverse (color) force on the active quark right after it is struck by the virtual photon in the interaction reads:

$$\begin{aligned} F^y(0) &\equiv -\frac{\sqrt{2}}{2P^+}\langle P,S \mid \bar{\psi}_q(0)\, G^{+y}(0)\, \gamma^+ \psi_q(0) \mid P,S\rangle \\ &= -\frac{1}{2}M^2 d_2^n \end{aligned}$$

- d_2^n is a measure of this transverse Lorentz color force (M. Burkardt)

Expressions of d_2^n (3)

The Color Field Polarizabilities

- Considering OPE in the rest frame of the nucleon and introducing color singlet operators $O_{B,E}$,

$$O_B = \psi^\dagger g \vec{B} \psi \quad O_E = \psi^\dagger \vec{\alpha} \times g \vec{E} \psi$$

  a relation containing the gluon color field polarizabilities χ is obtained:

$$\langle P, S \mid O_{B,E} \mid P, S \rangle = 2\chi_{B,E} M^2 \vec{S}$$

  d_2^n can be written as a linear combination of $\chi_{B,E}$

$$d_2^n = \frac{1}{8}\left(\chi_E + 2\chi_B\right)$$

- d_2^n can be seen as a measure of the response of the gulon color fields to the polarization of the nucleon (X. Ji)

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The Measurement of d_2^n

- Writing g_1, g_2 in terms of $\sigma_0, A_\parallel, A_\perp$ we obtain the explicit form of d_2^n to be evaluated:

$$
\begin{aligned}
g_1 &= \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[A_\parallel + \tan(\theta/2)\,A_\perp\right] \\
g_2 &= \frac{MQ^2}{4\alpha^2}\frac{y^2}{(1-y)(2-y)}\sigma_0\left[-A_\parallel + \frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}A_\perp\right] \\
d_2^n &= \int_0^1 \frac{MQ^2}{4\alpha^2}\frac{x^2y^2}{(1-y)(2-y)}\sigma_0 \\
&\times \left[\left(3\frac{1+(1-y)\cos\theta}{(1-y)\sin\theta} + \frac{4}{y}\tan(\theta/2)\right)A_\perp + \left(\frac{4}{y}-3\right)A_\parallel\right]dx
\end{aligned}
$$

$$
A_\parallel = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{2\sigma_0} \qquad A_\perp = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{2\sigma_0}
$$

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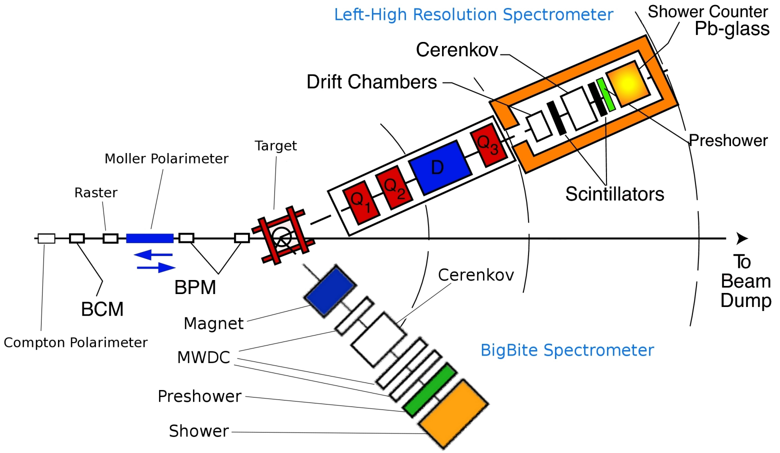
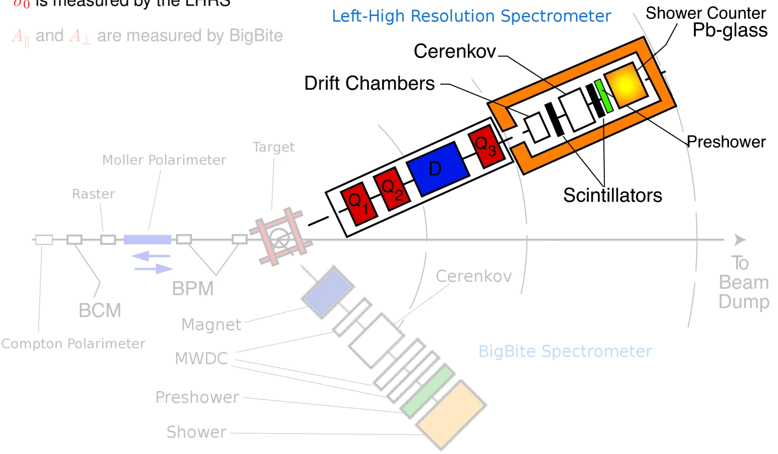
The Experimental Setup (1)



The Experimental Setup (1)

σ_0 is measured by the LHRS

$A_\parallel$ and $A_\perp$ are measured by BigBite



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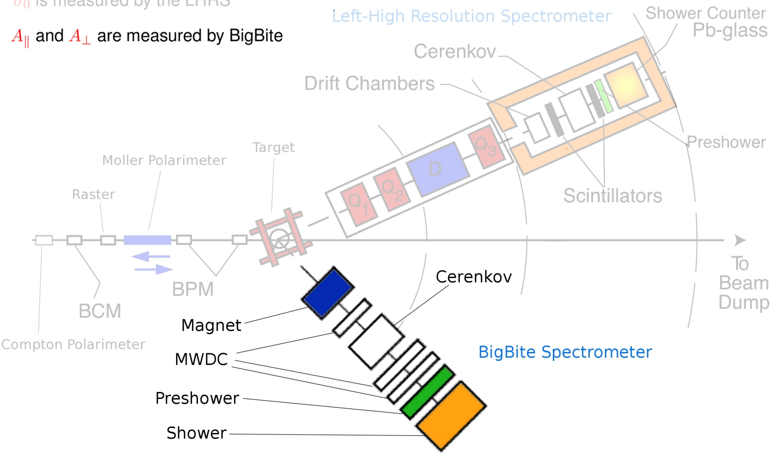


The Experimental Setup (2)
LHRS Detectors

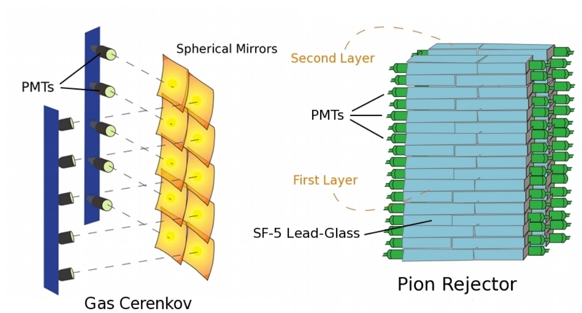


Figure: Drawings of the Gas Cerenkov and Pion Rejector in the Left High-Resolution Spectrometer

The Experimental Setup (3)
BigBite Gas Cerenkov

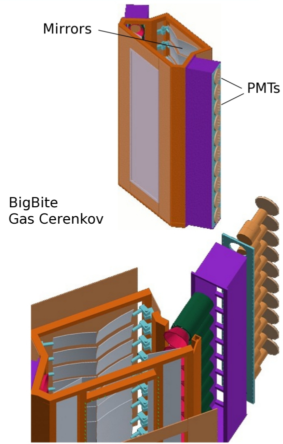
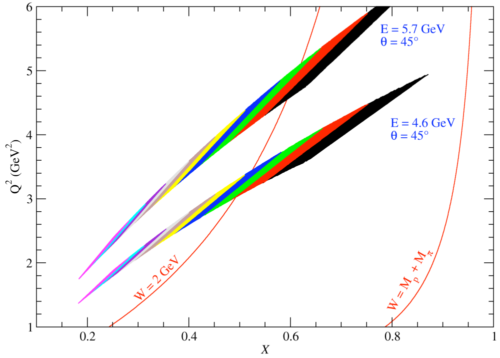


Figure: Drawings of the Gas Cerenkov in the BigBite Spectrometer

Kinematic Range



- The two bands represent the angular acceptance of the BigBite Spectrometer
- The ten colored stripes represent the different momentum settings in the LHRS for each beam energy

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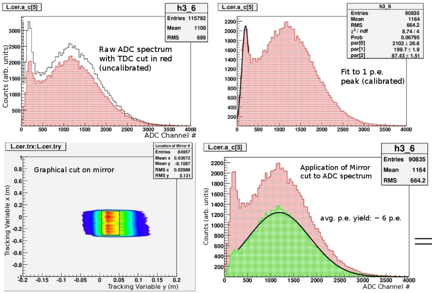
Left High-Resolution Spectrometer (1)

Gas Cerenkov Calibration

- Gain-match 1 photoelectron (p.e.) peaks
- Determine avg. # of p.e. for each PMT

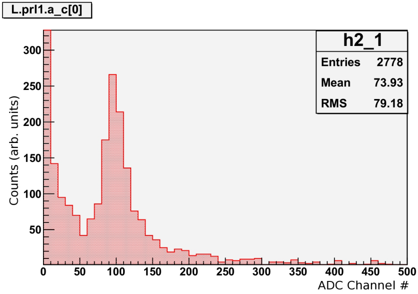


Mirror	1 p.e.	$n_{\text{p.e.}}$	# p.e.
1	196.8	967.3	4.45
2	198.6	715.3	3.48
3	198.4	1335	6.73
4	197.8	1344	6.75
5	198.5	1154	5.83
6	199.7	1184	5.93
7	199.5	1212	6.08
8	198.6	1225	6.17
9	194.9	1072	5.50
10	196.7	1010	5.13

Left High-Resolution Spectrometer (2)

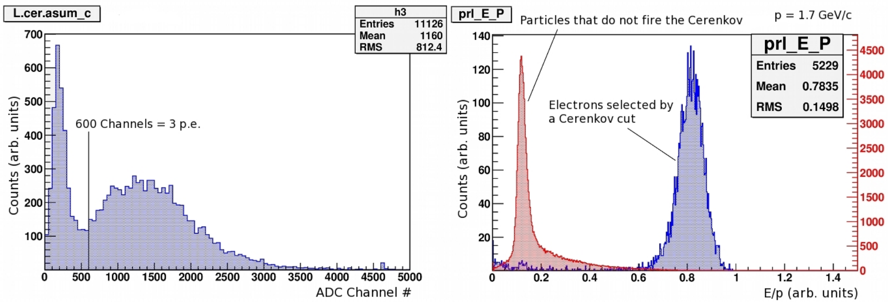
Pion Rejector Calibration

- We want each block in the pion rejector to have the same response for any given p
- Gain-match each PMT
  - Do this for the pions in the ADC spectra, since pions deposit the same amount of energy in the calorimeter for any p for the kinematic range of our experiment



Left High-Resolution Spectrometer (3)

Pion Rejector Calibration



- A cut on the Cerenkov ADC spectrum (sum) is applied to the shower to select good electrons
- Clean separation of e^-, π

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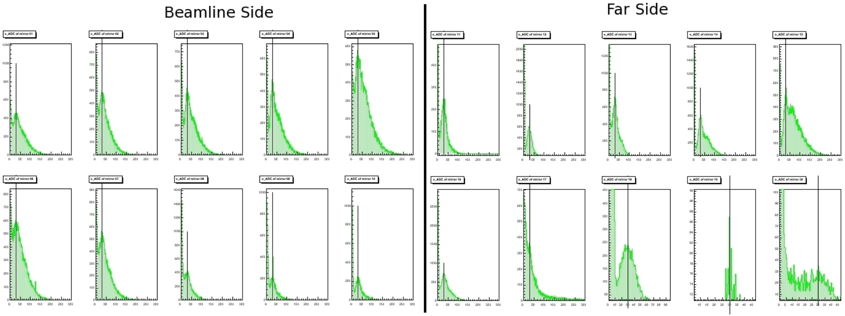
BigBite Spectrometer (1)
Gas Cerenkov Calibration

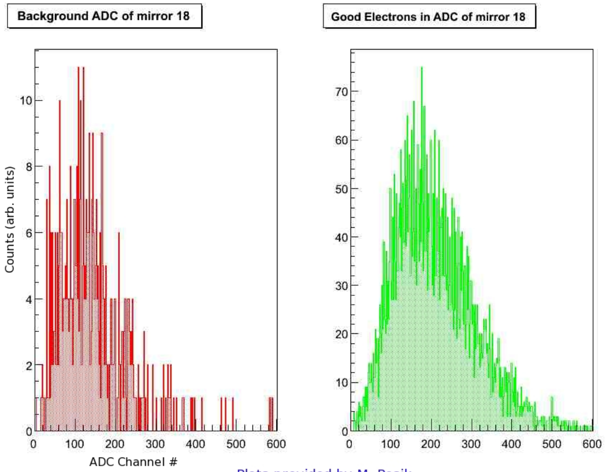
- 1 p.e. gain-matching using LED runs:



Plots provided by M. Posik

BigBite Spectrometer (2)
Gas Cerenkov Calibration

- Applying to production runs:



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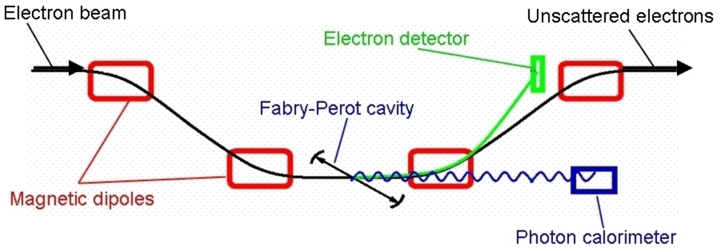
Compton Polarimeter (1)

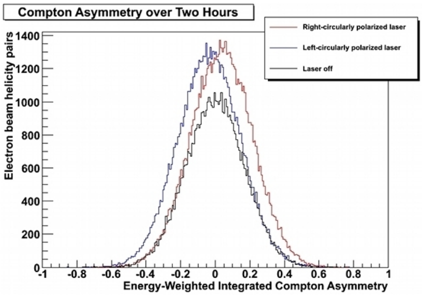
Schematic Diagram

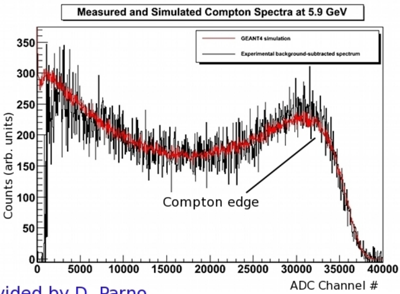


Drawing provided by D. Parno

- Polarization of the beam is measured using the Compton Polarimeter
- Relies on the asymmetry of the Compton cross section, due to the relative orientations of the e^-, γ polarizations

Compton Polarimeter (2)
Asymmetries and Cross Sections

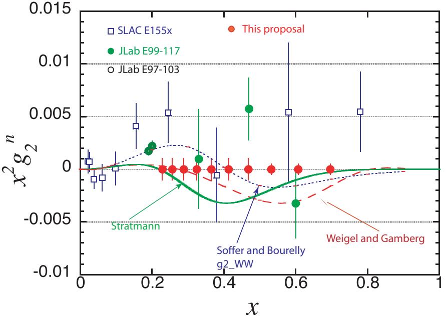




Plots provided by D. Parno

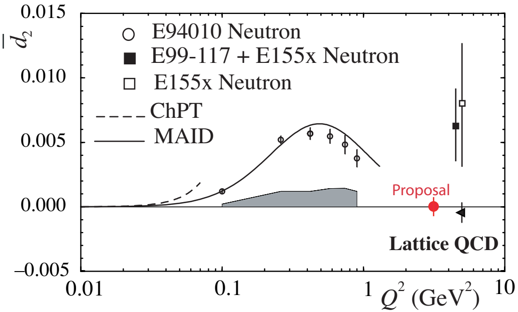
- The final Compton asymmetry is the weighted average of the mean asymmetries for the two polarization states (L,R)
- Compton spectrum shows a measurement of the scattered photon energy, proportional to the Compton cross section. The plot shows the Compton edge – the maximum amount of energy a photon can acquire

Projected Error on $x^2 g_2(x, Q^2)$



- The experiment is designed to minimize the moment of g_2, so as to improve the accuracy of d_2^n

Projected Measurement of d_2^n



- This experiment is expected to have a statistical uncertainty of $\Delta d_2^n = 5 \times 10^{-4}$
  - Four times better than the current world average
  - Provides a benchmark test for Lattice QCD

Summary

- Interested in quark-gluon correlations
- Investigate this by exploting transverse spin interactions through the g_2 structure function leading to higher twist effects seen in the matrix element d_2^n
- Sheds light upon the Lorentz color force inside the nucleon
- This measurement provides a benchmark test on Lattice QCD

Future Work

- Short term goals:
  - Continue work on calibrations in LHRS, BB, and Compton
  - Work towards extracting preliminary $\sigma_0, A_{\parallel}, A_{\perp}$

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- This work is supported by:
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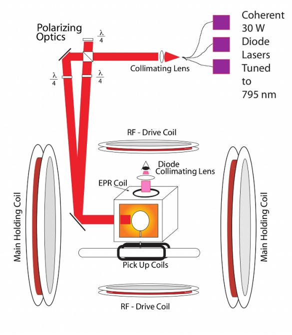
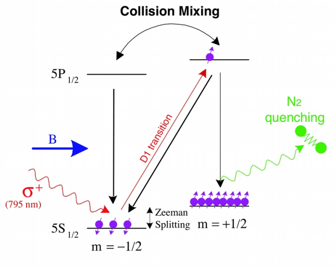
^{3}He Target





- Vaporized Rb is optically pumped using circularly polarized light to polarize its electrons
- Through collision mixing the Rb electrons transfer their spin to the ^{3}He nuclei