THE FIFTH STRUCTURE FUNCTION

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Overview

- Scientific Background
  - History of Modern Atomic Physics
  - Standard Model
  - The Hadronic Model Versus Quantum Chromodynamics
  - The Significance of the Fifth Structure Function
  - Objective

- Experimental Background
  - CEBAF
  - CEBAF Large Acceptance Spectrometer – CLAS
  - Experimental Setup

- Extracting the Longitudinal-Transverse Asymmetry (Summer 2012)
  - Kinematics
  - Mathematical Approach
  - Computational Approach

- Simulation of CLAS: Testing the Accuracy of Measurements (Summer 2013)
  - Fitting the Asymmetry
  - Simulating a Reaction in CLAS

- Results
- Conclusions
- References
- Acknowledgements
Scientific Background
History

- Democritus (400 BC)
  - “atomos”

- End of the 19th Century → 1930s
  - Electrons, nuclei, ions, photons

- Modern Era
  - 1964 – “Quark” or “Ace”
The Standard Model

- Sheldon Glashow
- 12 Elementary Particles: Spin 1/2
- 4 Force Mediating Particles: Spin 1
- Quark: Non-whole number electron charge
- Lepton: Whole number electron charge
The Hadronic Model

- Interactions between hadrons
- Nuclei approximated as collections of protons and neutrons
- Low Energy Success
Quantum Chromodynamics (QCD)

- Color force
  - Interactions of quarks and gluons making up hadrons
- Asymptotic Freedom
- Confinement
  - ≈ 3 tons of force between
- High Energy Success
- Difficulty Testing
The Hadronic Model Vs. QCD

- Goal: Better understand the behavior of quarks at intermediate energies
Significance of the Fifth Structure Function

- Explore the quark-gluon structure of atomic nuclei
  - First, we need to understand atomic nuclei as collections of protons and neutrons.

- The Structure of the Deuteron
  - Important place to start our understanding of atomic nuclei

- Helicity Asymmetry $A'_{LT} \rightarrow$ Fifth Structure Function
  - Seldom-measured part of Deuteron W.F. where Proton-Neutron force is expected to dominate
Objective

- Measure the largely unknown component of the deuteron wave function (the fifth structure)
  - $^2\text{H}(e,e'p)n$ Reaction
  - Never completed in this energy range
- Test the accuracy of our analysis
  - Monte Carlo Simulation
Experimental Background
CEBAF

- Continuous Electron Beam Accelerator Facility
- Newport News, Virginia
- ≈ 1 mile long
- Max: 5.7 GeV Beam Energy
CEBAF

- Injector
- North/South Linear Accelerators
  - SRF technology
- Recirculating Arcs
- Experimental Halls

Figure 1: Layout of CEBAF.
Hall B: CLAS

- **CEBAF Large Acceptance Spectrometer**
  - 1995-2012
- 45-ton, three-story, spectrometer
- Six identical Sectors
- Nearly $4\pi$ Solid Angle
Hall B: CLAS

- Superconducting Toroidal Magnet
- Drift Chambers
- Cherenkov Counters
- Time-of-Flight Scintillators
- Electromagnetic Calorimeters
Hall B: CLAS

- Toroidal Magnet
  - Provides a magnetic field
  - Two magnetic polarity settings (Normal/Reversed)
Drift Chambers

Detector for particles with ionizing radiation

Detects both presence and location of radiation

Quasi-Geiger counter (I. Lab)

Three Regions
Hall B: CLAS

- Cherenkov Detectors
  - Allow us to differentiate between pions and electrons
  - Detects electromagnetic radiation emissions
Hall B: CLAS

- Time-of-Flight Scintillators
  - Lighter and heavier particle differentiation
  - Scintillators: Variety of materials
  - Detection possible by photo multiplier tubes
Hall B: CLAS

- Electromagnetic Calorimeters
  - Differentiate electrons and neutral particles
  - Comprised of alternating layers of lead/scintillator
  - Particles interact in the lead creating a shower of photons in the scintillator
Hall B: CLAS

- Trajectory
- Charge
- Momentum
- Energy
- Scattering Angle
- Velocity
Experimental Setup

- 2.56 GeV beam
- Both normal and reversed magnetic torus polarities
- Dual, co-linear liquid hydrogen-deuterium cell target
Extracting the Asymmetry (Summer 2012)
Extracting the Asymmetry

- Kinematics of the $^2\text{H}(e,e'p)n$ reaction
  - Quasi-elastic collisions
Extracting the Asymmetry

- **Mathematical Approach**
  - **Differential Cross Section**
    \[
    \frac{d^5 \sigma}{dQ^2 dp_m d\phi_{pq} d\Omega_e d\Omega_p} = \sigma^\pm = \sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2\phi_{PQ} + h\sigma_{LT} \sin \phi_{pq}
    \]

- **Helicity Asymmetry**
  \[
  A_h(Q^2,p_m,\phi_{pq}) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
  \]
Extracting the Asymmetry

- **Mathematical Approach**
  - **Differential Cross Section**
    \[
    \frac{d^5\sigma}{dQ^2 dp_m d\phi_{pq} d\Omega_e d\Omega_p} = \sigma^\pm = \sigma_L + \sigma_T + \sigma_{LT} \cos\phi_{pq} + \sigma_{TT} \cos 2\phi_{pq} + h\sigma_{LT} \sin\phi_{pq}
    \]

- **Helicity Asymmetry**
  \[
  A_h(Q^2, p_m, \phi_{pq}) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
  \]

\[\approx |\psi|^2\]
Extracting the Asymmetry

- **Mathematical Approach**
  - **Differential Cross Section**

\[
\frac{d^5 \sigma}{dQ^2 dp_m d\phi_{pq} d\Omega_e d\Omega_p} = \sigma^\pm = \sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2\phi_{pq} + h\sigma_{LT'} \sin \phi_{pq}
\]

- **Helicity Asymmetry**

\[
A_h(Q^2, p_m, \phi_{pq}) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
\]

\(p_m = p_p - q\)

**NOT ZERO FOR OUT-OF-PLANE MEASUREMENTS!**
Extracting the Asymmetry

\[ A_h(Q^2, p_m, \Phi_{pq}) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \]

\[ A_h(Q^2, p_m, \Phi_{pq}) = \frac{(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2 \phi_{pq} + \sigma_{LT} \sin \phi_{pq}) - (\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2 \phi_{pq} - \sigma_{LT} \sin \phi_{pq})}{(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2 \phi_{pq} + \sigma_{LT} \sin \phi_{pq}) + (\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2 \phi_{pq} - \sigma_{LT} \sin \phi_{pq})} \]

\[ A_h(Q^2, p_m, \Phi_{pq}) = \frac{2(\sigma_{LT} \sin \phi_{pq})}{2(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2 \phi_{pq})} \]

\[ A_h(Q^2, p_m, \Phi_{pq}) = \frac{\sigma_{LT} \sin \phi_{pq}}{\sigma_L + \sigma_T} = A'_{LT} \sin \phi_{pq} \]
Extracting the Asymmetry

\[ A_h(Q^2, p_m, \phi_{pq}) = \frac{(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{PT} \cos 2\phi_{pq} + \sigma_{LT'} \sin \phi_{pq}) - (\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{PT} \cos 2\phi_{pq} - \sigma_{LT'} \sin \phi_{pq})}{(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{PT} \cos 2\phi_{pq} + \sigma_{LT'} \sin \phi_{pq}) + (\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{PT} \cos 2\phi_{pq} - \sigma_{LT'} \sin \phi_{pq})} \]

\[ A_h(Q^2, p_m, \Phi_{pq}) = \frac{2(\sigma_{LT'} \sin \phi_{pq})}{2(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{PT} \cos 2\phi_{pq})} \]

\[ A_h(Q^2, p_m, \Phi_{pq}) \approx \frac{\sigma_{LT'} \sin \phi_{pq}}{\sigma_L + \sigma_T} = A'_{LT \sin \phi_{pq}} \]
Extracting the Asymmetry

\[
A_h(Q^2, p_m, \phi_{pq}) = \frac{(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi + \sigma_{TT} \cos 2\phi_{PQ} + \sigma_{LT'} \sin \phi_{pq}) - (\sigma_L + \sigma_T + \sigma_{LT} \cos \phi + \sigma_{TT} \cos 2\phi_{PQ} - \sigma_{LT'} \sin \phi_{pq})}{(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2\phi_{PQ} + \sigma_{LT'} \sin \phi_{pq}) + (\sigma_L + \sigma_T + \sigma_{LT} \cos \phi_{pq} + \sigma_{TT} \cos 2\phi_{PQ} - \sigma_{LT'} \sin \phi_{pq})}
\]

\[
A_h(Q^2, p_m, \Phi_{pq}) \approx \frac{2(\sigma_{LT'} \sin \phi_{pq})}{2(\sigma_L + \sigma_T + \sigma_{LT} \cos \phi + \sigma_{TT} \cos 2\phi_{PQ})}
\]

\[
A_h(Q^2, p_m, \Phi_{pq}) = \frac{\sigma_{LT'} \sin \phi_{pq}}{\sigma_L + \sigma_T} = A'_{LT} \sin \phi_{pq}
\]
Extracting the Asymmetry

- Computational Approach
  - C++ code
  - CERN ROOT package

\[ A_h, \text{ Normal Polarity, } p_m=0.30 \text{ GeV/c} \]
\[ A'_h, \text{ Reversed Polarity, } p_m=0.30 \text{ GeV/c} \]
The asymmetry $A'_{LT}$

- Red: $\sin \Phi_{pq}$-weighted average
- Blue: fits to $A_h$ from above
Simulation of CLAS

Simulating a reaction in CLAS

- QUEEG
- txt2part
- QSIM
- gppjlab
- RECSIS
- n10tmaker
- h2root
- eod5root
Simulation of CLAS

- QUEEG
  - Generates quasi-elastic electron events
Simulation of CLAS

- txt2part
  - Converts the output files into BOS data files
  - BOS: CLAS data format
Simulation of CLAS

- GSIM
  - Simulates CLAS
  - Based on GEANT3
Simulation of CLAS

- Fitting the Asymmetry (C.A. Copos)
  - Incorporated into Monte Carlo simulation to model the Fifth Structure Function

\[ A'_{LT}(p_m) = \frac{\delta_1 p_m^2 + \delta_2 p_m^4}{1 + \delta_3 p_m + \delta_4 p_m^2 + \delta_5 p_m^4 + \delta_6 p_m^6} \]
Simulation of CLAS

- gppjlab
  - Makes the GSIM output look real
    - Knocks out dead scintillators and wires
Simulation of CLAS

- RECSIS
  - Standard program for reconstruction of CLAS data
Simulation of CLAS

- n10tmaker
  - Converts the output into hbook ntuples
Simulation of CLAS

- h2root
  - Converts the ntuples into ROOT ntuples
Simulation of CLAS

- eod5root
  - The analysis code in ROOT to extract $A'_{LT}$
  - Code used in Summer 2012
Results (Summer 2013)

- Testing the analysis
  - Red: simulated data
  - Blue: bin-averaged fit
  - Black: Fit to data
Conclusion

- Extracted the asymmetry $A'_{LT}$ from fits to the helicity asymmetry
  - Normal and reversed polarities
  - Comparison to $\sin \phi_{pq}$-weighted method
- Validated our analysis
  - Generated Monte Carlo events modeled after data
  - Events passed through simulation and then our analysis code
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