Jefferson Lab Neutron ($^3$He) Transversity Experiments

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- Leading twist Transverse Momentum Dependent parton distributions (TMDs) and experimental approach.
- Experiment E06-010 at JLab Hall A: Neutron Transversity
  - Semi-Inclusive deep-inelastic reaction: $n\uparrow(e,e' h)X$.
  - Experimental setup.
  - Polarized $^3$He target performance.
  - e-arm detector: BigBite spectrometer.
  - h-arm detector: High Resolution Spectrometer.
- Data quality and analysis status (no preliminary asymmetries).
Parton distributions in collinear configuration: 3 PDFs survive the integration of $k_T$

• Un-polarized Nucleon Structure Function
  – Longitudinal Momentum Distribution
• Longitudinal Polarized Nucleon Structure Function.
• Transversity:
  – Quark transverse spin distribution in a transversely polarized nucleon.
  – Chiral-odd.
  – Can be accessed through Semi-Inclusive DIS

\[
\Phi(x, S) = \frac{1}{2} \left[ f_1(x) \not{n}_+ + S_L g_{1L}(x) \gamma^5 \not{n}_+ + h_{1T} i\sigma_{\mu\nu} \gamma^5 n^\mu_+ S^\nu_T \right]
\]
when involving quark intrinsic $kT$, 8 leading twist TMDs...

$$\Phi(x, k_\perp) = \frac{1}{2} \left[ f_1 \gamma_+ + f_{1T} \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_\perp^\nu k_\perp^\rho S_T^\sigma}{M} + \left( S_L g_{1L} + \frac{k_\perp \cdot S_T}{M} g_{1T} \right) \gamma^5 \gamma_+ \right. $$

$$\left. + \left( h_{1T} i\sigma_{\mu\nu} \gamma^5 n_\perp^\mu S_T^\nu + \left( S_L h_{1L}^\perp + \frac{k_\perp \cdot S_T}{M} h_{1T}^\perp \right) i\sigma_{\mu\nu} \gamma^5 n_\perp^\mu k_\perp^\nu \right) \right]$$

Can be accessed in SIDIS through angular dependence, with polarized beam/target. In E06-010, with a transversely polarized target we can access...

\[
\begin{align*}
F_{UU} & \sim \sum_a e_a^2 f_{1a}^a \otimes D_1^a \\
F_{LL} & \sim \sum_a e_a^2 g_{1L}^a \otimes D_1^a \\
F_{UU}^{\cos(2\phi)} & \sim \sum_a e_a^2 h_{1}^a \otimes H_{1}^a \\
F_{UL}^{\sin(2\phi)} & \sim \sum_a e_a^2 h_{1L}^a \otimes H_{1}^a
\end{align*}
\]

\[
\begin{align*}
F_{\cos(\phi-\phi_S)}^{LT} & \sim \sum_a e_a^2 g_{1T}^a \otimes D_1^a \\
F_{\sin(\phi-\phi_S)}^{LT} & \sim \sum_a e_a^2 f_{1T}^a \otimes D_1^a \\
F_{\sin(\phi+\phi_S)}^{LT} & \sim \sum_a e_a^2 h_{1T}^a \otimes H_{1}^a \\
F_{\sin(3\phi-\phi_S)}^{LT} & \sim \sum_a e_a^2 h_{1T}^a \otimes H_{1}^a
\end{align*}
\]

\{ chiral-even TMDs \}

\{ chiral-odd TMDs \}
Neutron Transversity Experiment at JLab (E06-010)

• CEBAF accelerator provides continuous polarized electron beam
  – $E_{\text{beam}} = 5.892 \text{ GeV}$
  – $P_{\text{beam}} = 85\%$
Jefferson Lab E06-010 Collaboration

Institutions

Collaboration members

• Ph.D. thesis:
  C. Dutta (Kentucky), J. Huang (MIT), A. Kalyan (Kentucky), J. Katich (W&M), X. Qian (Duke), Y. Wang (UIUC), Y. Zhang (Lanzhou U)
E06-010 Setup: \( n^\uparrow (e,e'h)X \)

- Beam: \( E_0 = 5.892 \text{ GeV} \)
- \( \text{HRS}_L \)@ 16° as h-arm: \( P = 2.35 \text{ GeV/c} \)
- BigBite@30° as e-arm:
  - \( \Delta \Omega = 64 \text{ msr}, \ P = 0.8 \sim 2.0 \text{ GeV/c} \)
- A high density polarized neutron target (\(^3\text{He})
- Measure target single-spin asymmetries (Collins, Sivers) in valence quark region: \( x = 0.1 \sim 0.4 \)
BigBite Spectrometer as the electron-Arm of the Coincidence

A 1.2 Tesla dipole magnet, 3 drift chambers (18 wire planes) for tracking. a pre-shower+scintillator+shower package.

Measure a particle’s trajectory for momentum reconstruction.
BigBite Optics Calibration, momentum

1\textsuperscript{st} pass beam, E': 1-1.2 GeV
p<1 GeV, calibrated with \Delta
2\textsuperscript{nd} pass beam, E': 1.7-1.9 GeV
1.7>p>1.2 Checked with resonance states

Elastic H, Elastic He3
BigBite Optics Calibration

- Optics for both negative and positive charged particles have been done
- Wire Chamber Spatial Resolution: 180 µm
- Vertex Resolution: 1 cm
- Angular Resolution: ~ 10 mrad
- Momentum Resolution: 1%

BigBite Sieve Slit
Electron PID in BigBite spectrometer

- Pre-shower+Shower for trigger. Energy resolution: ~8%.
- $e^-/\pi^-$ well separated
Analysis Progress, HRS\textsubscript{L} Spectrometer

- Hadron Arm @16 degrees with $p_0 = 2.35$ GeV/c
- Detector and Spectrometer Optics Calibration are done
  - Clean e/\pii separation with Gas Cherenkov and lead glass.
  - Kaon PID by:
    - A1: Pion rejection $> 90\%$
    - RICH: K/p separation $\sim 4$ s
    - TOF: K/p separation $\sim 4$ s
  - 3D Momentum and Vertex Reconstruction

Spectrometer Angular Reconstruction:

Sieve Slit Data on carbon multi-foil targets.

Carbon multi-foil. Vertex reconstruction.
Coincidence time-of-flight

- Scintillator plane in Both Spectrometers provides timing information
- Coincidence timing resolution ~ 430ps
- $K-\pi$ separation on Hadron Arm (as additional approach to hadron arm PID)
Separation of Collins, Sivers and Pretzelosity through angular dependence, with finite acceptance spectrometers

\[ A_{UT}(\phi_h^l, \phi_S^l) = \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \]

- Rotate target spin in four direction to increase \( \phi_s \) coverage

\[
\sigma_{UT} \propto S_T (1 - y) \frac{P_{h \perp}}{z M_h} \sin(\phi_h^l + \phi_S^l) \cdot \sum e_q^2 h_1^q(x) \otimes H_{1q}^{1h}(z, P_{h \perp}^2)
\]

\[
+ S_T (1 - y + \frac{y^2}{2}) \frac{P_{h \perp}}{z M_N} \sin(\phi_h^l - \phi_S^l) \cdot \sum e_q^2 f_{1T}^{1q}(x) \otimes D_{1q}^{h}(z_h, P_{h \perp}^2)
\]

\[
+ S_T (1 - y) \frac{P_{h \perp}^3}{6z^2 M_N^2 M_h} \sin(3\phi_h^l - \phi_S^l) \cdot \sum e_q^2 h_{1T}^{1q}(x) \otimes H_{1q}^{1h}(z_h, P_{h \perp}^2)
\]
Polarized $^3$He Target

- Effective polarized neutron target
- High luminosity: $L(n) = 10^{36}$ cm$^{-2}$ s$^{-1}$
- Fast spin exchange with K/Rb hybrid cells
Polarized $^3$He Target Setup for E06-010

- New **vertical coil** together with existing horizontal coils and **new oven** allow $^3$He to be polarized in **ALL** three directions!

- New narrow band **COMET lasers** make optical pumping more efficient.

- Automatic spin flip every **20** minutes.
Target Performance

- Online EPR/NMR measurements show an average 65% target polarization with 15 μA beam and 20 minute spin flip

\[ L(n) = 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \]
Kinematics Coverage

- $y$: $0.6 \sim 0.9$
- $Q^2$: $0.6 \sim 3 \ (GeV/c)^2$
- $W'$: $1.5 \sim 2.3 \ (GeV/c^2)$
- $z$: $0.4 \sim 0.6$

$x < 0.25$

Pretzelosity Angle: $3\phi_h - \phi_s$

$x > 0.25$
Expected Statistical Uncertainties, Collins and Sivers Moments.
E06-010 Data Analysis Status as of 10/13/2009

**Raw Data**
- Run data base
- Spectrometer optics
- Detector calibration
- Scalers
- Target polarization
- Random target spin assignment

**Farm Production**
- HRS
- PID cuts
- Reconstruction Cuts
- Beam Cuts
- Luminosity Studies
- cTOF Cuts

**Event Selection**
- BigBite
- BigBite
- BPM
- Raster

**Witness Asymmetry**
- Corrections: luminosity, DAQ deadtime, detector efficiency, ...

**Measured Asymmetry**
- "Open Box Party": allow access to real target spin flag for coincidence events.

**Physics Analysis**
- Dilution correction
- Background Asymmetry
- Radiative corrections
- Separation of Collins vs Sivers

Two independent teams: Blue vs Red.

Open box party set to 11/20/09

Xiaodong Jiang @ DNP 2009
## A Double-Blind Analysis

<table>
<thead>
<tr>
<th>Witness channel target single-spin asymmetries.</th>
<th>(e,p)<em>{HRS} and (e,\pi^+)</em>{HRS}</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>(e,\pi^-)_{HRS}</td>
</tr>
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<td></td>
<td>(e,e')_{HRS}</td>
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<td>(e,e')_{BigBite}</td>
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<th>Accidental (e,e'\pi) off cTOF peak.</th>
<th>(e,e')<em>{BigBite} \otimes (e,\pi)</em>{HRS}</th>
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<th>Polarized (^{3})He target coin. (e,e'\pi).</th>
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<td>real target spin flag</td>
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### Key Points
- Witness channel target single-spin asymmetries.
- Accidental (e,e'\pi) off cTOF peak.
- Unpolarized targets: \(^{12}\)C, N\(_2\), H\(_2\), \(^{3}\)He.
- Polarized \(^{3}\)He target coin. (e,e'\pi).
- Blinded box, no deliberate access.
- Real target spin flag
- Fake target spin flag-1, 2, 3...

- 10/13/2009
- Xiaodong Jiang @ DNP-2009
Sammary of E06-010

• Experiment was carried out at JLab Oct. 2008 to Feb. 2009.
• Statistics achieved the proposal goal (roughly).
• Detector calibrations and target analysis are completed.
• Starting to extract witness channel asymmetries and SIDIS asymmetries…
• Expect preliminary asymmetry results in ~8-10 months. Strong constraints to Sivers functions (especially on d-quark).
\[ \sigma(\phi, \phi_S) = \sigma_{UU} \{ 1 + 2\langle \cos \phi \rangle_{UU} \cos \phi + 2\langle \cos 2\phi \rangle_{UU} \cos 2\phi \\
+ |S_T| \{ 2\langle \sin(\phi - \phi_S) \rangle_{UT} \sin(\phi - \phi_S) + 2\langle \sin(\phi + \phi_S) \rangle_{UT} \sin(\phi + \phi_S) + ... \} \}
\]

\[
2\langle \sin(\phi - \phi_S) \rangle_{UT} = - \frac{\sum_q e_q^2 f_{1T}^{\perp, q}(x, p_T^2) \otimes D_1^q(z, k_T^2)}{\sum_q e_q^2 f_{1T}^{q}(x) \otimes D_1^q(z)}
\]

The difference SSA of \( \pi^+ - \pi^- \):

\[
A_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \equiv \frac{1}{|S_T|} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}
\]

\[
A_{UT}^{\pi^+ - \pi^-}(p) \propto f_{1T}^{\perp, d_v} - 4 f_{1T}^{\perp, u_v}
\]

\[
A_{UT}^{\pi^+ - \pi^-}(n) \propto f_{1T}^{\perp, u_v} - 4 f_{1T}^{\perp, d_v}
\]
Results from full 2002–2005 $H^\uparrow$ target data

Sivers Moments for $\pi^+$ $\pi^-$

Collins Moments for $\pi^+$ $\pi^-$