Measurement of Single Target-Spin Asymmetry in Semi-Inclusive $n^\uparrow(e,e'\pi^-)$ Reaction on a Transversely Polarized $^3$He Target

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Hall A Collaboration Experiment

The Institutions


Collaboration members (103 members)

Physics Motivation: Transversity

- Remaining frontier of $k_T$– independent structure functions
- Connections to many other $k_T$– dependent distribution and fragmentation functions
- Major experimental efforts to measure transversity using lepton and hadron beams
Transversity

• Some characteristics of transversity:
  – $\delta q(x) = \Delta q(x)$ for non-relativistic quarks
  – $\delta q$ and gluons do not mix $\rightarrow$ $Q^2$-evolution for $\delta q$ and $\Delta q$ are different
  – Chiral-odd $\rightarrow$ not accessible in inclusive DIS

Chiral-quark soliton model

Quark – diquark model (solid) and pQCD-based model (dashed)

Similar to helicity distributions

hep-ph/0101300

B. Q. Ma, I. Schmidt and J. J. Yang,
PRD 65, 034010 (2002)
How to measure transversity?

- Chiral-odd → not accessible in DIS
- Require another chiral-odd object

- Transversely Polarized Drell-Yan
- Semi-Inclusive DIS
  - Single-hadron (Collins fragmentation function, $H_1^\perp(z)$)
  - Two hadrons (Interference fragmentation function)
  - Vector meson polarization
  - $\Lambda$ - polarization
Semi-inclusive DIS can access all leading-twist quark distributions

Leading-Twist Quark Distributions
(A total of eight distributions)

Three have no $k_T$ dependence

The other five are transverse momentum ($k_T$) dependent (TMD)

Transversity

Sivers function
Observation of Single-Spin Azimuthal Asymmetry

\[ ep \rightarrow e'\pi x \]

Longitudinally polarized target

\[ <S_T> \sim 0.15 \]

Origins of the azimuthal asymmetry?

Collins effect: Correlation between the quark’s transverse spin with pion’s \( p_T \) in the fragmentation process \( \rightarrow \delta q(x) \cdot H_1^\parallel(z) \).

Sivers effect: Correlation between the transverse spin of the proton with the quark’s transverse momentum \( \rightarrow f_{1T}^\perp(x) \cdot D(z) \).

Other higher twist effects could also contribute.
\( A_{UT} \sin(\phi) \) from transv. pol. H target

Simultaneous fit to \( \sin(\phi + \phi_s) \) and \( \sin(\phi - \phi_s) \)

„Collins“ moments

hep-ex/0507013

- Product of \( \delta q(x)H_1^\perp(z) \) is non-zero
- A surprising flavor dependence: \( H_1^\perp, \text{unfavored} / H_1^\perp, \text{favored} \approx -1 \)
- Extraction of \( \delta q(x) \) requires an independent measurement of Collins function \( H_1^\perp(z) \)
Collins functions from Belle

\[ e^+ e^- \rightarrow \pi\pi x \] (cos 2\(\phi\) correlation between pions)

Asymmetry \( \approx (H_1^+(z_1)/D_1(z_1)) (H_1^+(z_2)/D_1(z_2)) \)

- Significant non-zero asymmetries
- Rising behaviour vs. \(z\)
- First direct measurement of the Collins function

[Image of graph showing Collins functions]

hep-ex/0507063
Extraction of Collins functions from the Collins asymmetry measurements

Fits to the Hermes data $p^+(e, e'\pi)$

Assuming $H_{1,\text{fav}}^\perp(z) = C_{\text{fav}} z (1 - z) D_{1}^{\text{fav}}(z); \quad H_{1,\text{unfav}}^\perp(z) = C_{\text{unfav}} z (1 - z) D_{1}^{\text{fav}}(z)$

$C_{\text{fav}} = -0.29 \pm 0.04, \quad C_{\text{unfav}} = 0.33 \pm 0.04$

( Vogelsang and Yuan, hep-ph/0507266 )

$H_{1,\text{unfavored}}^\perp / H_{1,\text{favored}}^\perp \approx -1$
Sivers moments from transversity experiments

$A_{UT}^{\sin(\phi-\phi_S)}$ from Hermes transv. pol. H target

“Sivers” moments

First measurement of Sivers asymmetry

Sivers function nonzero $\rightarrow$ orbital angular momentum of quarks

hep-ex/0507013
Extraction of Sivers functions from the Sivers moment measurements

Fits to the Hermes data

“Prediction” of the Compass data

Assuming $f_{1T}^{u}(x) = S_u x(1-x)u(x)$; $f_{1T}^{d}(x) = S_d x(1-x)d(x)$

$S_u = -0.81 \pm 0.07$,  $S_d = 1.86 \pm 0.28$

(Vogelsang and Yuan, hep-ph/0507266)

Striking flavor dependence of the Sivers function
Opportunities at JLab for transversity experiments

• High-intensity CW electron beam
• High-density polarized $^3$He target which could be polarized transversely
• Probe valence-quark region similar to HERMES kinematics, providing complimentary information on transversely polarized neutron
• An independent test of the striking flavor structures of Collins and Sivers functions observed at HERMES/COMPASS
$^3\text{He}^{(e,e'\pi^-)}x$ at Hall-A

- **Beam**
  - 6 GeV, 15 µA e$^-$ beam

- **Target**
  - Optically pumped Rb-K spin-exchange $^3\text{He}$ target, 50 mg/cm$^2$, ~42% polarization, transversely polarized with tunable direction

- **Electron detection**
  - BigBite spectrometer, Solid angle = 60 msr, $\theta_{\text{Lab}} = 30^\circ$

- **Charged pion detection**
  - HRS spectrometer, $\theta_{\text{Lab}} = -16^\circ$
Kinematic coverage of the electron arm

- BigBite spectrometer set at $\theta=30^\circ$ at beam-right detecting electrons with $0.5 < E' < 2.2$ GeV.

- The coverage in Bjorken-x is $0.135 < x < 0.405$, corresponding to valence-quark region.

- For the four x bins, the range of mean-$Q^2$ is $1.3 < \langle Q^2 \rangle < 3.1$ (GeV/c)$^2$.

- The coverage in W, the invariant mass of the hadronic system, is $2.33 < W < 3.05$ GeV, well above the resonances region.
Kinematic coverage of the hadron arm

- HRS\textsubscript{L} situated at $\theta = -16^\circ$ will measure charged hadrons with mean momentum $p = 2.4$ GeV/c.
- The fraction of the virtual photon energy carried by the hadron, $z = \frac{E_h}{\nu}$, is $z \approx 0.5$ to detect leading pion in the current fragmentation region.
- A cut of $W' > 1.5$ GeV is required to stay away from the delta resonance production region.
Hall-A polarized $^3$He target

- 40-cm long Rb-K spin-exchange hybrid cell at 10 atm with beam current of 15 µA
- 42% target polarization with spin-flip frequency of 20 minutes
- A third set of Helmholtz coils will be added, together with the laser optics, to allow for vertical polarization of the $^3$He target
Coverage of the Collins angle

$$\phi_{\text{Collins}} = \phi^l_h + \phi^l_S$$

$$\phi^l_S = 0^\circ \text{ (black), } \phi^l_S = 90^\circ \text{ (red), } \phi^l_S = 180^\circ \text{ (blue), } \phi^l_S = 270^\circ \text{ (purple)}$$
Coverage of the Sivers angle

\[ \phi_{\text{Sivers}} = \phi_{h}^l - \phi_{S}^l \]

\[ \phi_{S}^l = 0^\circ \text{ (black), } \phi_{S}^l = 90^\circ \text{ (red), } \phi_{S}^l = 180^\circ \text{ (blue), } \phi_{S}^l = 270^\circ \text{ (purple)} \]
### Beam time request and count rate estimate

#### Beam time request

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production on $^3\text{He}$</td>
<td>528</td>
</tr>
<tr>
<td>Reference cell runs</td>
<td>16</td>
</tr>
<tr>
<td>Target spin rotation and polarization measurement</td>
<td>32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>576 (24 days)</strong></td>
</tr>
</tbody>
</table>

#### Count rate estimate

<table>
<thead>
<tr>
<th>$&lt;x&gt;$</th>
<th>Rate (Hz)</th>
<th>$N_{\pi}(10^3)$</th>
<th>$\delta A_{UT} (n) %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.135</td>
<td>0.17</td>
<td>317.5</td>
<td>1.47</td>
</tr>
<tr>
<td>0.225</td>
<td>0.12</td>
<td>231.1</td>
<td>1.82</td>
</tr>
<tr>
<td>0.315</td>
<td>0.07</td>
<td>139.7</td>
<td>2.46</td>
</tr>
<tr>
<td>0.405</td>
<td>0.05</td>
<td>95.8</td>
<td>3.03</td>
</tr>
</tbody>
</table>

- Quark distribution function from CTEQ5M
- Pion fragmentation functions from KKP parameterization
- Gaussian pion $P_\perp$ distribution with $<P_\perp^2> = 0.26 \text{ (GeV/c)}^2$
- Effective neutron polarization of 86.5% in $^3\text{He}$ and a dilution factor, $f \approx 0.3$, are used to relate measured $^3\text{He}$ asymmetry to deduced neutron asymmetry
Projected sensitivities of Collins and Sivers asymmetries

\[ A_{\text{Collins}}^{UT} = \frac{(1 - y)}{(1 - y + y^2 / 2)} \frac{\sum_q e_q^2 h_1^q(x) H_{111}(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)} \]

\[ A_{\text{Sivers}}^{UT} = \frac{\sum_q e_q^2 f_{111}^q(x) D_1^q(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)} \]
Predictions of Collins asymmetry on neutron

\[ A_{\text{UT}}^{n\pi^-} \propto 4 \delta d \ H_{1}^{\perp \text{unfav}} + \delta u \ H_{1}^{\perp \text{fav}} \]

\[ H_{1}^{\perp \text{unfav}} / H_{1}^{\perp \text{fav}} \approx D_{1}^{\text{unfav}} / D_{1}^{\text{fav}} \]

\[ H_{1}^{\perp \text{unfav}} / H_{1}^{\perp \text{fav}} \approx -1 \]
Predictions of Sivers asymmetry on neutron

\[ A_{UT}^{n\pi^-} \propto 4 f_{1T}^{\perp(1)d} D_1^{\text{unfav}} + f_{1T}^{\perp(1)u} D_1^{\text{fav}} \]

\[ D_1^{\text{unfav}} / D_1^{\text{fav}} \approx 1/3 \implies A_{UT}^{n\pi^-} \propto \frac{4}{3} f_{1T}^{\perp(1)d} + f_{1T}^{\perp(1)u} \]
Progress since the approval of E-03-004

- Improvement on the polarized $^3$He target (K-Rb hybrid, new laser optical fiber system, etc.)
- Commissioning of the BigBite spectrometer for the SRC and $G^n_E$ experiments. Background rate test run in April 2005
- Operation of the Lumi detectors as luminosity monitor
- Optimization of the experimental configuration and detailed simulation of the background
- First SSA SIDIS data on transversely polarized targets from HERMES and COMPASS
- Many theoretical progress including the proof of factorization in SIDIS
- First SIDIS data from Hall-C and CLAS
Is SIDIS applicable at 6 GeV?

Preliminary results from Hall-C E00-108

$p(e,e'\pi^-)$ and $p(e,e'\pi^+)$ at $x = 0.3$

Data are well described by SIDIS calculations for $0.4 < z < 0.7$
Summary

• The physics of transversity and $k_T$-dependent quark distribution and fragmentation functions is an exciting frontier in nucleon structure.

• High-luminosity JLab beam together with the transversely polarized $^3$He target and the spectrometers at Hall-A provide a unique opportunity to test the intriguing flavor dependence observed in recent SSA experiments.

• Various recent progress both at JLab and around the world has further strengthened the physics case and shown the urgency of the proposed measurements.
Backup Slides
Is SIDIS applicable at 6 GeV?

Preliminary results from Hall-C E00-108

\[ p(e, e' \pi^\pm) \text{ and } d(e, e' \pi^\pm) \text{ at } x = 0.3 \]

Data are well described by SIDIS calculations for 0.4 < z < 0.7
Disentangling Collins from Sivers asymmetries

simulation taking into account of the finite acceptance of the spectrometer
Disentangling Collins from Sivers asymmetries

simulation taking into account of the finite acceptance of the spectrometer, and the $3\Phi_h - \Phi_s$ term
Systematic errors

• Nuclear effects in $^3$He
  – Proton carries $\sim 2.8\%$ of the polarization and can be well corrected for, using the asymmetry data from HERMES

• Target polarization drift
  – Only contributes to the relative uncertainty of the measured $A_{UT}$ at a level of 4 %

• Decays from exclusive $\rho$-meson production
  – Negligible at $z=0.5$, based on the simulation of Hall-C E00-108

• Other terms in SSA
  – Monte-Carlo simulations indicate very small effect
Why not wait for 12 GeV?

- The measurements can already be done at 6 GeV, and the impact of this first measurement on our current knowledge on SSA should be huge.
- It will provide extremely valuable inputs for optimizing a future program of transversity (and semi-inclusive DIS, in general) at 12 GeV.
- JLab will continue to play an important role in the global effort to understand the spin structure of the nucleons.
$\pi^-$ versus $\pi^+$, which do we prefer?

- If both $\pi^-$ and $\pi^+$ data are obtained, one can make an independent extraction of the Sivers functions based on Jlab data alone (and compare them with Hermes data).
- $\pi^-$ and $\pi^+$ data will provide two independent tests of the current results on Sivers and Collins function obtained at Hermes and Compass.
- If only one charged pion data will be measured, then one can make a single test of the results on Sivers and Collins function. In this case, there is no difference which charged state one selects.
- Under severe beam-time constraints, a measurement for both pions with somewhat reduced statistics might be considered.
All Eight Quark Distributions Are Probed in Semi-Inclusive DIS

\[ d^3 \sigma = \frac{4 \pi \alpha^2 s x}{Q^4} \times \]

\[ \{ [1 + (1 - y)^2] \sum_{q, \bar{q}} e_q^2 f_1^q (x) D_1^q (z, P_{h\perp}^2) \]

\[ + (1 - y) \frac{P_{h\perp}^{q, \bar{q}}}{4z^2 M_N M_h} \cos(2\phi_1') \sum_{q, \bar{q}} e_q^2 h_{1L}^{q, \bar{q}} (x) H_{1L}^{q, \bar{q}} (z, P_{h\perp}^2) \}

\[ - | S_L | (1 - y) \frac{P_{h\perp}^{2}}{4z^2 M_N M_h} \sin(2\phi_1') \sum_{q, \bar{q}} e_q^2 h_{1L}^{q, \bar{q}} (x) H_{1L}^{q, \bar{q}} (z, P_{h\perp}^2) \]

\[ + | S_T | (1 - y + \frac{1}{2} y^2) \frac{P_{h\perp}^{2}}{z M_N} \sin(\phi_1' + \phi_S') \sum_{q, \bar{q}} e_q^2 f_{1T}^{q, \bar{q}} (x) D_1^{q, \bar{q}} (z, P_{h\perp}^2) \]

\[ + | S_T | (1 - y + \frac{1}{2} y^2) \frac{P_{h\perp}^{3}}{6z^2 M_N^2 M_h} \sin(3\phi_1' - 2\phi_S') \sum_{q, \bar{q}} e_q^2 h_{1T}^{q, \bar{q}} (x) H_{1T}^{q, \bar{q}} (z, P_{h\perp}^2) \]

\[ + \lambda_e | S_L | y \left( 1 - \frac{1}{2} y \right) \sum_{q, \bar{q}} e_q^2 g_{1L}^{q, \bar{q}} (x) D_1^{q, \bar{q}} (z, P_{h\perp}^2) \]

\[ + \lambda_e | S_T | y \left( 1 - \frac{1}{2} y \right) \frac{P_{h\perp}^{2}}{z M_N} \cos(\phi_1' - \phi_S') \sum_{q, \bar{q}} e_q^2 g_{1T}^{q, \bar{q}} (x) D_1^{q, \bar{q}} (z, P_{h\perp}^2) \} \]

\[ S_L \text{ and } S_T: \text{ Target Polarizations; } \lambda_e: \text{ Beam Polarization} \]