Spin Physics and Applications with Polarized 3He Target

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Overview

- Electron Scattering-Kinematics, Spin Structure Function $p(\vec{e}, e'\pi^+)n$

- Single Spin Asymmetries Measurement with Transversely Polarized $^3$He

- Production of Polarized $^3$He Target at KNU

- MRI Applications of Polarized $^3$He
Energy Transfer Dependence of Cross-Section: \((e,e')\)
Cross sections and Beam Asymmetries

\[ p(\vec{e}, e\pi^+)n \]

\[ Q^2 = 1.7 - 4.5 \text{ GeV}^2 \]
\[ W = 1.15 - 1.7 \text{ GeV} \]

PRC 77, 0152081 (2008)
K. Park, W. Kim et al.

• Over 31,000 Cross-Sections Measured
• Over 4,000 Asymmetries Measured

\[
\frac{\partial^5 \sigma}{\partial E_f \partial \Omega_e \partial \Omega^*_\pi} = \Gamma_v \times \frac{d^2 \sigma}{d \Omega^*_\pi},
\]

where

\[
\Gamma_v = \frac{\alpha}{2\pi^2 Q^2} \frac{(W^2 - M_p^2) E_f}{2M_p E_e} \frac{1}{1 - \epsilon}
\]

\[
\epsilon = \left[ 1 + 2 \left( 1 + \frac{v^2}{Q^2} \right) \tan^2 \frac{\theta_e}{2} \right]^{-1}
\]

\[
\frac{d^2 \sigma}{d \Omega^*_\pi} = \sigma_T + \epsilon \sigma_L + \epsilon \sigma_{TT} \cos 2\phi^*_\pi + \sqrt{2\epsilon(1 + \epsilon)}\sigma_{LT} \cos \phi^*_\pi
\]

\[ + h\sqrt{2\epsilon(1 - \epsilon)}\sigma_{LT'} \sin \phi^*_\pi. \]
Electroexcitation of the Roper resonance for $1.7 < Q^2 < 4.5$ GeV$^2$

G. Aznauiy, K. Park, W.Kim
PRC 78 (2008),
PRC 80 (2009).

Dispersion Relation
Unitary Isobar Model.

Helicity Amplitude for:
$\gamma^* p \rightarrow N(1440)P_{11}$
Transition:
A first Radial Excitation of the 3g Ground State
$\vec{p}(e, e' p) \pi^0$

$A = \frac{\cos \theta^* v_{T'} R_{T'} + 2 \sin \theta^* \cos \phi^* v_{TL'} R_{TL'}}{v_L R_L + v_T R_T}$

$\frac{d^2 \sigma}{d\Omega d\omega} = \sum \pm \Delta h(\theta^*, \phi^*)$
Simultaneous Measurements of $T'$ and $TL'$ asymmetries
Measurement of Spin Observables Using a Storage Ring with Polarized Beam and Polarized Internal Gas Target

$^{3}\text{He} (\vec{p}, \vec{p}')$

IUCF K. Lee et al., PRL 70, 738 (1993)
Polarization Correlation Coefficient

T. Uesaka et al.,
PL B 467 (1999),
RIKEN

\[ ^3\text{He}(d, p) ^4\text{He} \]

\[ \begin{align*}
1 & \quad 1/2 \quad 0 & \quad 1/2 \\
\uparrow d & \quad \downarrow ^3\text{He} & \quad \uparrow ^4\text{He} & \quad \downarrow p \\
\uparrow S & \quad \downarrow S \quad \rightarrow \quad \uparrow S & \quad \downarrow S & \quad \rightarrow \quad \uparrow S & \quad \downarrow S \\
\downarrow D & \quad \uparrow S \quad \rightarrow \quad \uparrow D & \quad \downarrow S & \quad \rightarrow \quad \uparrow D & \quad \downarrow S
\end{align*} \]

\[ \text{NOT Allowed} \quad \text{Allowed} \]

\[ T_{20} \]

\[ \kappa_0 \]

\[ k_{pn} \ [\text{fm}^{-1}] \]
Xiaodong Jiang, W. Kim et. al.

• Introduction
  Collins effect: transversely polarized quarks generate left-right bias in fragmentation.
  Sivers effect: quarks’ transverse motion generate left-right bias in “effective” density.

• HERMES and COMAPSS results of SIDIS target single-spin asymmetry.
  • HERMES proton published results.
  • COMPASS deuteron published results.

• JLab Hall A “Neutron Transversity” Experiment (E06-010 SIDIS).
  • Preliminary results of $^3$He single-spin asymmetries $A_{UT}$. 
Left-Right Asymmetries
Left-Right Asymmetries
Collins and Sivers Effects can be Separated in Semi-Inclusive Deep-Inelastic Scattering Experiments

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

\[ \sigma_{UT} \propto S_T (1 - y) \frac{P_{h\perp}}{z M_h} \sin(\phi_h^l + \phi_S^l) \cdot \sum e_q^2 h^q_1(x) \otimes H^\perp_{1q} (z, P_{h\perp}^2) \]

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

Collins effect (linked with transversity \( h_1 \)) and Sivers effect (linked with T-Odd distribution \( f_{1T}^{\perp} \)) can be separate through the angular dependence of the asymmetries.
The first measurement of target single spin asymmetries in the semi-inclusive $3\text{He}(e, e'\pi^\pm)X$ reaction on a transversely polarized target.

Conducted at Jefferson Lab using a 5.9 GeV electron beam, covers a range of $0.14 < x < 0.34$ with $1.3 < Q^2 < 2.7 \text{ GeV}^2$

Collins and Sivers moments were extracted from the angular dependence of the measured SSAs.
Angular Dependence of the Spin-Dependent Asymmetry

In the scattering of an unpolarized lepton beam by a transversely polarized target is described at leading twist in terms of the moments equations:

- Collins:
  $$A_C \equiv 2\langle \sin(\phi_h + \phi_S) \rangle$$
- Sivers:
  $$A_S \equiv 2\langle \sin(\phi_h - \phi_S) \rangle$$

$$A(\phi_h, \phi_S) = \frac{1}{P} \frac{Y_{\phi_h,\phi_S} - Y_{\phi_h,\phi_S+\pi}}{Y_{\phi_h,\phi_S} + Y_{\phi_h,\phi_S+\pi}}$$

$$\approx A_C \sin(\phi_h + \phi_S) + A_S \sin(\phi_h - \phi_S)$$

$$+ A_{pretz} \sin(3\phi_h - \phi_S),$$

$P$: target polarization

$\phi_h$ and $\phi_S$: azimuthal angles of the hadron and the target spin relative to the lepton scattering plane.
3He is uniquely advantageous in the extraction of neutron information because:

- In 3He nucleus, the nuclear spin resides predominantly on the neutron.
- While in deuteron, combined effects of proton and neutron are probed.

Recent calculations by Scopetta of the 3He Collins/Sivers SSAs have shown the approach of Nucleon Effective Polarization:

\[ A_{3\text{He}}^{C/S} = P_n \cdot (1 - f_p) \cdot A_n^{C/S} + P_p f_p \cdot A_p^{C/S} \]

where \( P_n = 0.86^{+0.036}_{-0.02} \) \( (P_p = -0.028^{+0.009}_{-0.004}) \) is the neutron (proton) effective polarization.
Collins and Sivers Moments on 3He for both $\pi^+$ and $\pi^-$ Electro-Production

![Graph showing moments for $\pi^+$ and $\pi^-$ on 3He.](image)
Collins and Sivers Moments on Neutron for both $\pi^+$ and $\pi^-$ Electro-Production
Optical Pumping and Spin Exchange
Polarized $^3$He Setup with Electron Beams

- Diode Laser
- optics
- Oven (160 °C)
- pickup coil
- e⁻ beam
  - $B \sim 30$ Gauss
- rf drive coils
- main coils
- Instrument Control
Experimental Setup

- **Laser**
- **Optics system**
- **Ion pump and gas panel**
- **500°C Oven to bake cell assembly**
- **Oven, coils and heaters**
Results: Polarized $^3$He

$^3$He NMR Signal

Polarization Dependence on time

Exponential Decay of polarization

2007.9.5 Polarized $^3$He achieved in Korea for the first time
Comparison of water and 3He MRI

2 Tesla

21 Gauss

Water

He 3
Healthy and unhealthy lungs

Image of polarized $^3$He injecting into dog’s intestine

Image of human lung

MRI of mouse brain using $^{129}$Xe
Comparison MRI Image of human body
(a) 20,000 Gauss $^1$H MRI (b) 20 Gauss polarized $^3$He MRI

Unhealthy lung’s MRI Image using polarized $^3$He gas
Plan for MRI Research

KNU

$^3\text{He, } ^{129}\text{Xe Production}$

Gacheon Brain Institute
Coil Construction and Pulse Sequence Software

Diagnostic Research and Medical Application
University Hospitals

PNU Radiology Dept
1.5 Tesla MRI for $^3\text{He, } ^{129}\text{Xe}$ and Medical Doctor for Interpretation

Siemens
Modification Access for Hyperpolarized Nuclei Imaging
The first measurement of the target single spin asymmetries in semi-inclusive charged pion electroproduction on a transversely polarized $^3$He target.

The extracted neutron results are consistent with the predictions of global phenomenological fits and quark model calculations.

Demonstrated the power of polarized $^3$He as an effective polarized neutron target.

$^3$He Applications for MRI
Quarks can tell left-right in

\[ p p^\uparrow \rightarrow \pi X \]

One explanation (Sivers effect):
quark’s angular motion generates a left-right density difference.

\[ A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]

- $\pi^+ (u\bar{d})$ favors left
- $\pi^- (d\bar{u})$ favors right

up-quarks favor left ($L_u > 0$), down-quarks favor right ($L_d < 0$).

Transversity distribution is chiral-odd, not accessible through inclusive deep-inelastic scattering. Need to be combined with another chiral-odd object, i.e. Collins fragmentation function.

Through target single spin asymmetry in semi-inclusive DIS.

\[ A_{UT}^{Collins}(x, z) \propto \frac{\sum_q e_q^2 \delta q(x) \otimes H_{1q}^{1\perp}(z, P_{h\perp}^2)}{\sum_q e_q^2 q(x) \otimes D_{1q}^{h\perp}(z, P_{h\perp}^2)} \]

Collins frag. fun. can be accessed in $e^+e^-$ collisions.
Sivers: with transverse motion, quarks on one side of the nucleon are moving towards the probe while on the other side are moving away from the probe.

Left and right are different.