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Measurement of pretzelosity asymmetry of charged pion production in Semi-Inclusive Deep Inelastic Scattering on a polarized $^3$He target

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An experiment to measure single-spin asymmetries of semi-inclusive production of charged pions in deep-inelastic scattering on a transversely polarized $^3$He target was performed at Jefferson Lab
Studies of nucleon structure have been and still are at the frontier of understanding how quantum chromodynamics (QCD) works in the non-perturbative region. It has been known for decades that the nucleon is composed of quarks and gluons. However, how quarks and gluons contribute to the elementary properties of the nucleon is still an open question. Among these properties, the nucleon spin has been at the center of interests for more than two decades since the European Muon Collaboration’s discovery that quark spins were found to contribute only a small portion to the nucleon spin [1]. In last two decades, polarized deep-inelastic scattering (DIS) experiments [2] have confirmed that the quark spin only contributes to about 25% of the nucleon spin with significantly improved precision. In more recent years, efforts have also been devoted to the determination of the gluon’s intrinsic contribution to the nucleon spin both from fixet-target polarized DIS and from polarized proton-proton collision measurements [3]. New results [4–6] from the RHIC-spin program suggest that the gluon spin may only contribute to the proton spin at a level comparable to those of quark spins. These findings suggest that the orbital angular momentum (OAM) of quarks and gluons, the most elusive piece, may actually be the largest contributor.

In recent years, major theoretical and experimental efforts have focused on accessing OAM of quarks. The development of the general parton distribution functions (GPDs) [7] and the transverse-momentum-dependent parton distribution functions (TMDs) [8] provides not only the three-dimensional imaging of the nucleon, but also promising ways to access OAM. By investigating correlations between the quark position and the momentum, GPDs supply a new way to characterize the contribution of the quarks’ orbital motion to the spin of the nucleon. On the other hand, TMDs investigate the parton distributions in three-dimensional momentum space and provide information about the relationship between the quark momenta and the spin of either the nucleon or the quark. Most TMDs are expected to vanish in the absence of quark orbital motion. Thus they supply important and complementary (to GPDs) ways to access the OAM’s contribution to the nucleon spin.

Among the 8 leading-twist TMDs, there are only three that remain non-zero after integrating over the parton transverse momentum [8]. They are the unpolarized parton distribution function (PDF) $f_1$, the longitudinally polarized PDF $g_1$ (helicity), and the transversely polarized PDF $h_1$ (transversity). The distribution $f_1$ has been extensively studied for several decades. The distribution $g_1$ is also relatively well understood by continuous efforts since 1970s [2]. For the $h_1$, although less known than the former two, pioneering studies were made in recent years, both theoretically and experimentally [9]. One of the least known TMDs, $h_{1T}$, referred to as pretzelosity, has drawn significant attention recently [10–14] due to its intuitive relation to the quark OAM. As one of the eight leading-twist TMDs, it has a probabilistic interpretation as in a transversely polarized nucleon the parton number density of which is transversely polarized in a direction perpendicular to the nucleon polarization direction, subtracted by the parton number density with the opposite parton-polarization direction. Same as transversity, pretzelosity also has an odd chirality, which leads to an important consequence that there are only quark pretzelosity distributions, with no gluonic counterparts.

In a class of relativistic quark models [13, 14], pretzelosity can be expressed as the difference between the helicity and the transversity. In the light cone the difference of quark polarization between the longitudinal and transverse direction is due to the fact that boost and rotation operators do not commute. A non-zero value of the pretzelosity is thus a direct consequence of this relativistic nature of quark motion. Another interesting feature is that pretzelosity emerges from the interference of quark wave-function components differing by two units of orbital angular momentum [15]. Pretzelosity is the only leading-twist TMD carrying this unique feature. In certain models, the quark OAM can be directly accessed via pretzelosity [13, 14]. This finding was first obtained in a quark-diquark model [16] and a bag model [12], and then confirmed in a large class of quark models respecting spherical symmetry [14].

In experiments, pretzelosity is suppressed in the inclusive DIS processes due to its chiral-odd nature. However, combined with another chiral-odd object such as the Collins fragmentation function [17], it leads to a measurable effect in the semi-inclusive DIS (SIDIS) [18] in which a leading hadron is detected in addition to the scattered lepton. Specifically, with an unpolarized lepton beam scattered from a transversely polarized nucleon target, a non-zero $h_{1T}$ would produce an azimuthal angular dependent single-spin asymmetry (SSA).

At the leading twist and following the Trento convention [19], the azimuthal angular dependence of the target
SSA can be written as:

\[
A_{UT}(\phi_h, \phi_s) = \frac{1}{P_{\text{He}}} \frac{Y(\phi_h, \phi_s) - Y(\phi_h, \phi_s + \pi)}{Y(\phi_h, \phi_s) + Y(\phi_h, \phi_s + \pi)} 
\approx A^C \cdot \sin(\phi_h + \phi_s) + A^S \cdot \sin(\phi_h - \phi_s) 
+ A^P \cdot \sin(3\phi_h - \phi_s),
\]

where the subscript \(U\) and \(T\) stand for the unpolarized beam and the transversely polarized target, respectively. \(P_{\text{He}}\) is the polarization of the target, \(Y\) is the normalized yield, \(\phi_h\) is the angle between the lepton plane and the hadron plane, which is defined by the hadron momentum direction and the virtual photon momentum direction, and \(\phi_s\) is the angle between the target spin direction and the lepton plane. The three leading-twist asymmetries [20] correspond to the Collins asymmetry \((A^C)\), the Sivers asymmetry \((A^S)\) and the pretzelosity asymmetry \((A^P)\). The Collins asymmetry is the transversity distribution function convoluted with the Collins fragmentation function, while the Sivers asymmetry is the Sivers distribution function convoluted with the unpolarized fragmentation function. The last term, referred to as the pretzelosity asymmetry, is the pretzelosity distribution function convoluted with the Collins fragmentation function. As shown in Eq. (1), these three terms have different azimuthal angular dependences, therefore it is possible to simultaneously determine all three terms by studying the angular dependence.

The HERMES collaboration carried out the first measurement of Collins and Sivers asymmetries [21] with electron and positron beams on a transversely polarized proton target. The COMPASS collaboration performed measurements with a muon beam on transversely polarized proton [22] and deuteron targets [23]. In Hall A at Jefferson Lab (JLab), an exploratory experiment E06-010 [24, 25] was carried out, for the first time using a gas target. The extracted Collins and Sivers asymmetries were published [24]. In extracting these asymmetries, the pretzelosity term was not included. Its uncertainty was estimated and included in the systematic uncertainties.

In this paper, we present the results of the pretzelosity asymmetry extracted from the JLab E06-010 data. As shown in Fig. 1, a 5.9-GeV electron beam was incident on a transversely polarized gaseous \(^3\)He target with an average current of 12 \(\mu\)A. The target [26] was polarized by spin-exchange optical pumping [27] of a Rb/K mixture, with which an average polarization is 55.4 \(\pm\) 2.8\%.

The scattered electrons were detected using the BigBite spectrometer [26] at beam right with a solid-angle acceptance of \(\sim 64\) msr. Three sets of drift chambers with eighteen wire planes in total were used for tracking. Lead-glass pre-shower and shower detectors were used to identify electrons. The hadron contamination of the electron sample in the SIDIS process was suppressed to below 2\% in the momentum range of 0.6-2.5 GeV. The produced hadrons were detected in the left arm of the high resolution spectrometers [26] (LHRS). A gas Cherenkov detector and two layers of lead-glass detectors provided a clean separation of pions from electrons. An aerogel Cherenkov detector and the coincident time-of-flight technique (about 25 meters from the target to the LHRS focal plane) were employed to distinguish pions from kaons and protons.

To extract moments of the SSA, it is important to have the azimuthal angular coverage as complete as possible. In the case of pretzelosity asymmetry, the azimuthal angle is \((3\phi_h - \phi_s)\) and the range is \([0, 2\pi]\). In the experiment, the BigBite and the LHRS spectrometer covered only part of the \(2\pi\) angular range. To increase the angular coverage, four different target spin orientations orthogonal to the beam direction, transverse left, transverse right, vertical up, and vertical down, were used. For each target spin orientation the spectrometers covered only a section of the phase space as shown in the left panel of Fig. 2 (target spin vertical up). However, data from all four orientations, when combined, covered the full angular range as shown in the right panel of Fig. 2, where magenta, green, red, and blue are for horizontal beam left, horizontal beam right, vertical up, and vertical down, respectively. In order to achieve target polarizations in these four orientations, three pairs of mutually orthogonal Helmholtz coils were employed. During the experiment, the target spin direction was flipped every twenty minutes using the adiabatic fast passage technique, in which the magnetic holding field direction and strength remained unchanged.

Several kinematic cuts were used to select SIDIS events: the negative square of the four-momentum transfer \(Q^2 > 1\) GeV\(^2\), the invariant mass of the virtual photon-nucleon system \(W > 2.3\) GeV, and the invariant mass of the undetected final state particles \(W' > 1.6\) GeV. Data were divided into 4 Bjorken-\(x\) bins with roughly equal statistics. The central kinematics are pre-
In Eq. (2) the scaling variable $x$ is defined as $P_{t\perp} \cos(3\phi_h - \phi_s)$ in a polar coordinate. In each panel the $x$-axis is defined as $P_{t\perp} \cos(3\phi_h - \phi_s)$ and the $y$-axis is defined as $P_{t\perp} \sin(3\phi_h - \phi_s)$. The left panel shows the data in only one target spin orientation (horizontal beam left), while the right panel shows the data in all four orientations.

In Eq. (2) the cross section ratio $\sigma_{3He}/\sigma_{N_2}$ was measured through dedicated data taking with a reference target cell filled with known amount of $^3$He and $N_2$ gases. The number densities of $^3$He and $N_2$ in the polarized target were verified by taking the data of electron elastic scattering on both the reference target and the production $^3$He target [28]. Another important correction was made due to the pair-produced background electrons (and positions) in the SIDIS electron samples. This is especially significant in the lowest $x$ bin corresponding to the lowest momentum. Dedicated data were taken with the BigBite spectrometer in reversed polarity to measure the yield of the coincident $(e,e'\pi^\pm)$ events, which is identical to the yield of $(e,e'\pi^\pm)$ events in the charge-symmetric pair production. This effect was corrected as a dilution since the measured asymmetries of the coincident $(e,e'\pi^\pm)$ events were consistent with zero.

In the analysis, the systematic uncertainties due to omission of the other $\phi_H$- and $\phi_S$-dependent terms in the binned least-$\chi^2$ fit, including the Cahn ($\langle \cos(\phi_S) \rangle$) and Boer-Mulders ($\langle \cos(2\phi_H) \rangle$) effects, higher-twist terms ($\langle \sin(\phi_S) \rangle$ and $\langle \sin(2\phi_H - \phi_s) \rangle$), and the $A_{UL}$ terms ($\langle \sin(\phi_h) \rangle$ and $\langle \sin(2\phi_h) \rangle$) [20, 29], were estimated. The $A_{UL}$ terms were induced by a small longitudinal component of the target polarization in the virtual photon-nucleon center-of-mass frame of the SIDIS process. Of all these effects, the uncertainty of the $\langle \sin(2\phi_h - \phi_s) \rangle$ term was largest (~16% of the statistical uncertainty), followed by the $\langle \sin(\phi_h) \rangle$ term (~14% of the statistical uncertainty). To estimate the systematic uncertainty induced by $K^\pm$ contamination in $\pi^\pm$ sample, the coincident $(e,e'K^\pm)$ events were selected and the $\sin(3\phi_h - \phi_s)$ term of the asymmetry was extracted by maximum likelihood method. Then, the systematic uncertainty was evaluated as the difference between the $\sin(3\phi_h - \phi_s)$ terms of the $(e,e'\pi^\pm)$ and the $(e,e'K^\pm)$ samples, weighted by the contamination ratios of the $K^\pm$ in $\pi^\pm$ samples. Other ingredients of the systematic uncertainties included the yield drift, the target polarization, the target-density fluctuation, the detector tracking efficiency, the DAQ live time, the nitrogen dilution, and the photon contamination in the BigBite spectrometer. Since those ingredients have no azimuthal angular dependence and share the same data set of [24], they have the same values as in [24].

The extracted moments of the pretzelosity asymmetry on the $^3$He target are shown in the top two panels of Fig. 3 and in the Table. II. Only statistical uncertainties are included in the error bars. The experimental systematic uncertainties are combined in quadrature and shown as the band labeled as “Sys.”. All the extracted $\pi^+$ and $\pi^-$ pretzelosity terms, which were cross checked with an unbinned maximum-likelihood fit, are small and consistent with zero within the uncertainties. This observation further supports the assumption in previous analysis [24] that the inclusion of pretzelosity term has little effect on the extraction of Collins and Sivers term.

To extract the pretzelosity asymmetries on neutron,
the effective polarization method was used:

\[ A_n^p = \frac{1}{(1 - f_p)P_n} \left( A_{3He}^p - f_p A_n^p P_p \right), \tag{3} \]

where the proton dilution factor \( f_p \equiv 2\sigma_p/\sigma_{3He} \) was obtained by measuring the yields of unpolarized proton and \(^3\)He targets at the same kinematics. The same model uncertainty due to final-state interactions as in [24] was taken into account for \( f_p \). \( P_n = 0.86^{+0.02}_{-0.01} \) and \( P_p = -0.028^{+0.009}_{-0.004} \) are the effective polarizations of the neutron and proton in a \(^3\)He nucleus [30, 31], respectively. Due to the scarcity of available data and the small effective polarization of the proton, no correction was applied to account for the effect due to the proton asymmetry. The uncertainty due to this omission was estimated and included in the systematic uncertainty. For positive pions at the highest \( x \) bin, the asymmetry is magnified by nearly one order of magnitude from \(^3\)He to the neutron, due to the large proton dilution.

The extracted moments of the pretzelosity asymmetry on the neutron are listed in Table III and are also shown in the bottom two panels of Fig. 3, in which they are compared with the quark-diquark model (QDM) [16] and light-cone constituent-quark model (LCQM) [32, 33].

**TABLE III.** Values and uncertainties of the extracted neutron asymmetries.

| \( x \) | \( \pi^+ \) terms | \( \pi^- \) terms |
|-------|-----------------|-----------------|
|       | asym. stat. sys. | asym. stat. sys. | asym. stat. sys. |
| 0.156 | 0.049 0.164 0.038 | -0.035 0.110 0.025 |
| 0.206 | 0.185 0.169 0.050 | 0.097 0.143 0.040 |
| 0.265 | 0.074 0.105 0.030 | -0.057 0.076 0.022 |
| 0.349 | -0.246 0.143 0.044 | -0.057 0.079 0.022 |

**FIG. 3.** (Color online) The extracted pretzelosity asymmetries on \(^3\)He nuclei (top panels) and on the neutron (bottom panels) are shown together with uncertainty bands for both \( \pi^+ \) and \( \pi^- \) electron-production.
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