Future (transverse) spin physics at Jefferson Lab

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Abstract. The studies of GPDs and TMDs with polarizations at 6 GeV at Jefferson Lab have already shown great promises. The 12-GeV spin program will significantly advance our knowledge about the three-dimensional structure of the nucleon in the valence quark region, and the QCD dynamics responsible for the structure. With the possibility of a future electron ion collider with polarized beams, the next frontier of QCD will be reached. This proceeding paper will focus on future studies of TMDs using polarizations.

Introduction
Spin degrees of freedom have opened new opportunities in the study of the structure of the nucleon, a subject of fundamental importance to the ultimate understanding of how quantum chromodynamics works in the nonperturbative region. The high-intensity, high-polarization electron beam with a maximum beam energy of 6 GeV at the CEBAF facility at Jefferson Laboratory, together with a number of novel polarized targets and recoil polarimeters, have significantly advanced our knowledge about the structure of the nucleon. The 6-GeV spin physics program has enjoyed great success ranging from the famous results on the proton electric-to-magnetic form factor ratio [1], measurements of the strange quark form factors from parity-violation electron scattering [2, 3], measurements of nucleon longitudinal spin structure function [4, 5, 6], to the initial investigations of the transverse momentum dependent parton distribution functions (TMDs) [7, 8, 9] and the generalized parton distributions (GPDs) [10, 11]. In the next few years, the CEBAF facility will complete the energy upgrade to 12 GeV. The upcoming 12-GeV spin program will extend the success of the 6-GeV program to the next level, particularly in the study of the three-dimensional structure of the nucleon. Looking beyond the 12-GeV era, a new initiative on an Electron-Ion Collider is being actively pursued in the United States. Such a facility will allow for a detailed three-dimensional mapping of the nucleon structure (GPDs and TMDs) of the sea and gluons as well as the valence quarks, and a study of the QCD dynamics responsible for the structure.

Transverse Momentum Dependent Parton Distribution Functions (TMDs)
At leading twist three quark distribution functions survive upon integration over the transverse momenta of quarks: the unpolarized parton distribution $f_1$, the longitudinal polarized parton
distribution $g_1$, and the quark transversity distribution $h_1$. Among the three leading twist parton distribution functions (PDFs), the transversity function is the least known one. It is a chiral-odd transversely polarized quark distribution function [12] and describes the net quark parton distribution functions (PDFs), the transversity function is the least known one. It is a transversity distribution function $h_1(x, Q^2)$. Like the axial charge $\Delta q^a = \int_0^1 dx (g_1^q(x) + g_1^\bar{q}(x))$, the tensor charge $\delta q^a = \int_0^1 dx (h_1^q(x) - h_1^{\bar{q}}(x))$ is a basic property of the nucleon.

Besides $f_1$, $g_1$ and $h_1$, there are five more transverse momentum dependent distribution functions [14, 15]. These five functions are the Sivers function ($f_{1T}^q$), the Boer-Mulders function ($h_{1T}^q$), the pretzelosity function ($h_{1T}^{\bar{q}}$), and the so-called worm-gear 1 ($h_{1L}^q$) and worm-gear 2 ($g_{1T}^q$) functions. Since these TMDs provide the description of the parton distributions beyond the collinear approximation, they depend not only on the longitudinal momentum fraction $x$, but also on the transverse momentum, $k_T$. An intuitive interpretation of the $k_T$ dependent transversity distribution, $h_1$, is the probability of finding a transversely polarized parton inside a transversely polarized nucleon with certain longitudinal momentum fraction $x$ and transverse momentum $k_T$.

The experimental determination of the transversity function is challenging - it is not accessible in polarized inclusive deep-inelastic scattering (DIS) measurements due to its chiral-odd nature. However, paired with another hadron in the initial state, for example double polarized Drell-Yan processes (two transverse distributions) [16], or in the final state, for example semi-inclusive deep-inelastic [17] scattering (SIDIS) (transversity and Collins fragmentation function), leading twist $h_1$ can be accessed without suppression by a hard scale. The most feasible way to access the transversity distribution function is via an azimuthal single spin asymmetry, in semi-inclusive deep-inelastic lepto-production of mesons on a transversely polarized nucleon target, $l N^1 \rightarrow l' h X$. In this case the other chiral-odd partner is the Collins fragmentation function, $H_{1L}^q$ [17], which has been extracted from $e^+e^-$ collisions by BELLE [18]. The evidence of non-trivial transverse spin effects in SIDIS has been observed in the transverse single spin asymmetries measured by the HERMES [19, 20, 21] and the COMPASS [22] experiments where an unpolarized lepton beam is scattered off a transversely polarized proton target, $l P^1 \rightarrow l' h X$. Besides the non-zero Collins asymmetry, which contains $h_1$ and $H_{1L}^q$ discussed previously, another non-zero asymmetry (Sivers asymmetry), was also observed. The Sivers asymmetry is associated with the Sivers function, a naive T-odd TMD [23].

The first model dependent extraction of the transversity distributions has been carried out [24] by combining SIDIS [21, 20, 25, 26] data with $e^+e^-$ collision data [18]. In addition, the extraction of the Sivers function [27, 28, 29, 30, 31] has been performed by combining SIDIS data from the HERMES [21] on the proton and COMPASS data [32] on the deuteron. Complementing the data from the HERMES [21, 20], COMPASS [26], and BELLE [18] experiments, the recent release from the Jefferson Lab Hall A experiment E06-010 [7] on the neutron (with polarized $^3$He) will facilitate a flavor decomposition of the transversity, and the Sivers functions in the overlapping kinematic regime. However, a model-independent determination of these leading twist functions requires data in a wider kinematic range with a high precision in four dimensions ($Q^2, x, z, P_T$). We will discuss such an experiment [33, 34] next which will take place after the 12-GeV energy upgrade at Jefferson Laboratory.

**Single-Target Spin Asymmetry from Semi-Inclusive Deep-Inelastic Scattering (SIDIS)**

The SIDIS process requires the detection of both the scattered electron and one of the leading hadrons produced in the final state. In general, the process can be expressed as:

$$\ell(P_1^e) + N(P) \rightarrow \ell(P_2) + h(P_h) + X$$

(1)
hadron plane
lepton plane

Figure 1. Definitions of azimuthal angles $\phi_h$ and $\phi_S$, and the hadron transverse momentum for SIDIS [35].

where $\ell$, $N$, $\ell'$ and $h$ denote the initial electron, the initial proton, the scattered electron, and one of the leading hadrons produced in the final state, respectively. All the four-momenta are given in parentheses. The major Lorentz invariant variables are defined as:

$$x = \frac{Q^2}{2P \cdot q}, \quad y = \frac{P \cdot q}{P \cdot q}, \quad z = \frac{P \cdot P_{h}}{P \cdot q}, \quad s = (P_{e}^{2} + P)^{2}. \quad (2)$$

The $s$ is the center-of-mass energy squared of the initial electron-nucleon system. In addition, there are a few frame-dependent kinematic variables, $\phi_S$, $\phi_H$, and $P_T$, which are also essential to SIDIS process. They are defined according to the Trento convention as illustrated in figure 1 in the nucleon-at-rest frame.

The differential cross section in a SIDIS $(e,e' h)$ reaction, in which the beam is not polarized and the target is transversely polarized, can be expressed as the sum of target spin-independent and target spin-dependent terms at leading twist:

$$\frac{d\sigma^h}{dx_B dy d\phi_S d\phi_h dP_{h\perp}^2} = d\sigma^{UU} + d\sigma^{UT}, \quad (3)$$

$$= d\sigma^{UU} + d\sigma^{Collins}_U + d\sigma^{Sivers}_U + d\sigma^{pretzelosity}_U.$$

$P_{h\perp}$ are defined according to the Trento convention [35] as illustrated in figure 1. Each term in equation 3 can be expressed as a convolution of a TMD and a fragmentation functions (FF) [35].

The target SSA is defined as:

$$A_{UT} \equiv \frac{1}{|S_T|} \frac{d\sigma^{UT}}{d\sigma^{UU}} \quad (4)$$

The Collins, Sivers and pretzelosity asymmetries have different angular dependence:

$$A_{UT}(\phi_h, \phi_S) \equiv \frac{1}{|S_T|} \frac{d\sigma(\phi_h, \phi_S) - d\sigma(\phi_h, \phi_S + \pi)}{d\sigma(\phi_h, \phi_S) + d\sigma(\phi_h, \phi_S + \pi)}, \quad (5)$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S) + A_{UT}^{pretzelosity} \sin(3\phi_h - \phi_S).$$

where
$$A_{UT}^{\text{Collins}} = D_{nn} \cdot 2\sin(\phi_h + \phi_S)_{UT} = D_{nn} \cdot \left[ \frac{-\hat{h} \cdot k_T}{M_h} \sin \left( \frac{h_1 \times H_1^+}{f_1 \times D_1} \right) \right],$$  \hspace{1cm} (6)

$$A_{UT}^{\text{Sivers}} = 2\sin(\phi_h - \phi_S)_{UT} = \left[ \frac{-\hat{h} \cdot p_T}{M} f_{1UT}^+ \right],$$  \hspace{1cm} (7)

$$A_{UT}^{\text{Pretzelosity}} = D_{nn} \cdot 2\sin(3\phi_h - \phi_S)_{UT}$$

$$= D_{nn} \cdot \left[ \frac{2(\hat{h} \cdot p_T)(\hat{p}_T \cdot k_T) + p_T^2 (\hat{h} \cdot k_T) - 4(\hat{h} \cdot p_T^2)(\hat{h} \cdot k_T^1)}{2M^2 M_h} \right] h_{1UT}^+ \otimes H_1^+, $$

where following the definition used by the COMPASS Collaboration [22], \(D_{nn} = (1 - y)/(1 - y + \frac{M^2}{p_T^2})\), which agrees to a few percent with what was used by the HERMES Collaboration [21].

\(D_1\) is the unpolarized fragmentation function and \(H_1^+\) is the Collins fragmentation function [17]. The unit vector \(\hat{h} = P_{h \perp}/|P_{h \perp}|\) and the convolution in equations 4-6 represent an integration over transverse momentum of initial \((k_T)\) and final quark \((p_T)\) with proper weighting [35].

**The SoLID-SIDIS Experiment**

Recently, a new experiment [33] has been approved at Jefferson Lab to extend the study of SIDIS to a real 4-D manner \((x, Q^2, z\) and \(p_T)\), these new results will significantly advance our understanding of transverse spin physics. The Sivers distribution and the Pretzelosity distribution functions, crucial to understand relativistic effects and the role of quark orbital angular momentum inside the nucleon, will also be mapped precisely in four dimensions in this new experiment. The large \(p_T\) region covered in this new experiment is important in testing various theoretical approaches. This new experiment also allows for a study of higher-twist contributions.

This new experiment consists of a superconducting solenoid magnet, a large-acceptance detector system, and a high-pressure polarized \(^3\)He target positioned upstream of the magnet. The polarized \(^3\)He target is based on the technique of spin-exchange optical pumping of hybrid Rb-K alkali atoms. Such a target was used successfully in the recently completed SSA experiment [7] with a 6-GeV electron beam at JLab and an in-beam polarization of 60-65% was achieved [36]. Six layers of GEM detectors will be placed inside the coils as tracking detectors. A combination of an electromagnetic calorimeter, gas Čerenkov counters, a layer of Multi-gap Resistive Plate Chamber (MRPC) and a thin layer of scintillator will be used for particle identification in the forward-angle region. As only electrons will be identified in the large-angle region, a shashlyk-type [37, 38] electromagnetic calorimeter will be sufficient to provide the pion rejection. Details about the experiment can be found in [33, 34].

Due to the nature of the large acceptance solenoid detector, we will have a complete \(2\pi\) coverage for \(\phi_S\). The full \(2\pi\) azimuthal angular coverage and a large \(\phi_h\) azimuthal angular coverage are very important in disentangling different asymmetries (Collins, Sivers and Pretzelosity) to high precisions so that potential contributions from other azimuthal angular dependent terms due to higher-twist contributions \((\sin(\phi_S)\) and \(\sin(2\phi_h - \phi_S)\)) can be separated out. As an example, the projected results for \(\pi^+ (\pi^-)\) Collins and Pretzelosity asymmetries at one typical kinematic bin, is shown in figure 2 together with theoretical predictions of Collins asymmetries from Anselmino et al. [39], Vogelsang and Yuan [40] and predictions of Collins/Pretzelosity asymmetries from Ma and collaborators [41, 42], and Pasquini [43, 44]. The projected E06-010 results [7] are shown as black points. The \(x\)-axis is \(x_{bj}\), and the \(y\)-axis on
the left side is $P_T$, the transverse momentum of the hadron. The $y$-position of the projections shows the average $P_T$ value for the corresponding kinematic bin. The $y$-axis on the right side shows the scale of the asymmetry. The statistical uncertainties follow the scale on the right side of the $y$-axis as do the theoretical calculations. The corresponding Sivers asymmetries for $\pi^+$ are shown in figure 3. The complete projection of the experiment can be found in [33].

The SoLID experiment discussed in this section will provide SSA data with excellent statistical and systematic precisions in 4-D ($x, z, P_T, \text{and } Q^2$) over a large kinematic range. These data will significantly advance our understanding of TMDs and QCD. Measurements with SoLID, combined with the CLAS12 measurements [45, 46] using polarized proton and deuteron targets will provide an unprecedented opportunity to obtain a three-dimensional map of the Collins and Sivers asymmetries in the kinematic region $0.1 < x < 0.5, 0.3 < z < 0.7$ with $P_T < 1.5$ GeV, necessary to precisely determine the nucleon’s partonic substructure. The combined results on Collins asymmetry together with the Collins fragmentation function extracted from the $e^+e^-$ collision data, will allow for a flavor separation of the quark tensor charge, and achieve a determination of the d quark tensor charge to an accuracy of 10%. This new experiment will have a major impact on other related programs and particularly on the design of future facilities with the study of TMDs as one of their important physics goals, for example the electron-ion collider (EIC), and the FAIR project at GSI.

**Figure 2.** 11 GeV Projections with SoLID. $\pi^+$ Collins/Pretzelosity asymmetries.

**Figure 3.** 11 GeV Projections with SoLID. $\pi^+$ Sivers asymmetries.

### TMDs at Electron-Ion-Collider (EIC)

In the 2007 Nuclear Science Advisory Committee (NSAC) Long Range Plan, “An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier.” An EIC will allow a complete study of the three-dimensional structure of the nucleon, particularly will allow for the study of the role of gluons in nucleon and nuclei, and the study of the evolutions of GPDs and TMDs. Below we present a case study for the study of TMDs at a medium-energy EIC [47].

In an EIC, a beam of electrons collides with a beam of ions. Following the definitions given in section 2.1, one can immediately obtain the important relation

$$s = (P^i_e + P)^2 \approx 2P^i_e \cdot P ~ \text{ and } ~ Q^2 = x \cdot y \cdot s,$$

(9)
which clearly illustrates the relationship between $x$ and $Q^2$ at a fixed value of $s$.

The upcoming JLab 12 GeV upgrade would access the SIDIS phase space at low $Q^2$ and high $x$ region due to the smaller values of $s$. The black band in figure 4 shows the phase space of the approved 11-GeV SoLID SIDIS experiment [33]. In order to bridge between the phase spaces of $11+60$ GeV ($11$ GeV: electron momentum, $60$ GeV: proton (ion) momentum) configuration and the JLab 12 GeV upgrade, a low-energy configuration of EIC, e.g. $3+20$ GeV configuration is strongly desired. Such a configuration would overlap with both phase spaces of the $11+60$ GeV configuration and the JLab 11-GeV fixed-target experiment. In addition, a higher-energy configuration, $11+100$ GeV (green band in figure 4), would extend the study of SIDIS process to even lower $x$ and, higher $Q^2$ regions.

In order to achieve a quark flavor separation from the SIDIS data, measurements with both proton and neutron are essential. Light-ion beams of polarized deuteron and polarized $^3$He ions are effective polarized neutron beams. However, the phase space of the light ion is not the same as that of the proton. Given a fixed accelerator configuration, momentum per nucleon in an ion is proportional to $Z/A$, in which $Z$ is the atomic number, and $A$ is the mass number. Figure 5 illustrates different mappings of these three ion beams (accelerator: $11+60$ GeV configuration $^1$).

Figure 4. Mapping of SIDIS phase space of different energy configurations for EIC with a proton beam. The 12 GeV phase space is shown as the black band.

Figure 5. Mapping of SIDIS phase space of different ion beams (proton, deuteron and $^3$He), given a fixed accelerator configuration ($11+60$ GeV).

Figure 6 shows the expected projection of $\pi^+$ Sivers asymmetry with a proton beam $^2$ at a high-luminosity EIC (36 days at $3\times10^{34}$ nucleons/(cm$^2$ s)) in the kinematic bin of $0.4 < z < 0.45$ and $0.4 \text{ GeV} < P_T < 0.6 \text{ GeV}$. The $x$-axis is the $x$, and the left $y$-axis is the $Q^2$. The position of each point in the plot represents the position of the kinematic bin in the $x$-$Q^2$ phase space. The right $y$-axis is the asymmetry. The error bar of each point follows the right axis. Together with the projection, several asymmetry calculations are also presented. The codes to calculate the Collins and Pretzelosity asymmetries are from from Ma et al. [41, 42], and the Sivers asymmetry calculations are from Prokudin et al. [31] (black and dashed lines), and [48] (red dashed line). In the calculation, the PDF is from MRST2004 parametrization [49], and the FF is from Ref. [50]. Ref. [42] provides the Collins and Pretzelosity distributions, in which the $P_T$ dependence is from Ref. [51]. The Sivers TMD is according to Ref. [52] and the recent result of Prokudin et al.,

$^1$ 60 GeV represents the beam momentum for proton.

$^2$ As discussed previously, the projected results of Collins/pretzlocity asymmetry are slightly different from those of Sivers.


**Figure 6.** Projection with proton on $\pi^+$ in a particular $P_T$ and $z$ bin along with the calculated asymmetries. The position of the dots are according to the $Q^2$ axis on the left and the $x$ axis, while the error bar of each dot is according to the scale of the asymmetry axis on the right. The calculated asymmetries are also according to the asymmetry axis. The black, green, and red dots represent the 11+60 GeV, 11+100 GeV, and 3+20 GeV EIC configuration.

and the Collins FF is according to Ref. [51]. The calculated asymmetry also follows the right $y$-axis of the plot. Full four-dimensional projections for the entire phase space and projections for electron-light ions (D and $^3$He) can be found in [53].

With a high-luminosity EIC, target SSA (TSSA) can be precisely mapped in the full $x$, $Q^2$, $z$ and $P_T$ four-dimensional phase space. In particular, the EIC would facilitate the exploration of high $Q^2$-high $x$, and low $Q^2$-low $x$ phase spaces. Furthermore, the large coverage of $P_T$ would explore the TSSA in the high $P_T$ region for the first time with SIDIS. The high luminosity is essential to realize the multi-dimensional mapping and extend the TSSA measurements to the extreme conditions (high $P_T$, high $Q^2$ etc.), and low $x$ region in order to study gluon TMDs.

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