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Unveiling the nucleon tensor charge at Jefferson Lab: A study of the SoLID case

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ABSTRACT

Future experiments at the Jefferson Lab 12 GeV upgrade, in particular, the Solenoidal Large Intensity Device (SoLID), aim at a very precise data set in the region where the partonic structure of the nucleon is dominated by the valence quarks. One of the main goals is to constrain the quark transversity distributions. We apply recent theoretical advances of the global QCD extraction of the transversity distributions to study the impact of future experimental data from the SoLID experiments. Especially, we develop a simple strategy based on the Hessian matrix analysis that allows one to estimate the uncertainties of the transversity quark distributions and their tensor charges extracted from SoLID data simulation. We find that the SoLID measurements with the proton and the effective neutron targets can improve the precision of the u- and d-quark transversity distributions up to one order of magnitude in the range $0.05 < x < 0.6$.

1. Introduction

The nucleon tensor charge is a fundamental property of the nucleon and its determination is among the main goals of existing and future experimental facilities [1–7]. It also plays an important role in constraining new physics beyond the standard model [8–10] and has been an active subject of lattice QCD [9,11–19] and Dyson–Schwinger Equation (DSE) [20,21] calculations. In terms of the partonic structure of the nucleon, the tensor charge, δq for a particular quark type q, is constructed from the quark transversity distribution, $h_1(x, Q^2)$, which is one of the three leading-twist quark distributions that describe completely spin-1/2 nucleon [1–5]:

$$\delta q\left(Q^2\right) \equiv \int_0^1 dx\, \left(h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)\right) . \quad (1)$$

It is extremely important to extend the experimental study of the quark transversity distribution to both large and small Bjorken x to constrain the total tensor charge contributions. The Jefferson Lab 12 GeV program [6] is going to explore the region of relatively large-x dominated by valence quarks while the planned Electron Ion Collider [5,7,22] is going to extend the range to unexplored lower values of x, providing a possibility to study the anti-quark transversity distributions.

In this paper we analyze the impact of future proposed SoLID experiment at Jefferson Lab 12 GeV on the determination of tensor charge and transversity distributions for u- and d-quarks. Our

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studies are based on the QCD global fit of the available Semi-Inclusive Deep Inelastic Scattering (SIDIS) data and e^+e^- annihilation into hadron pairs performed in Ref. [23] which we will refer as KPSY15. The current available experimental data suggests that anti-quark transversities are very small compared to u- and d-quark transversities. In this study we assumed that anti-quark transversities are negligible. Using the best fit of transversity distributions of Ref. [23] we simulated pseudodata for SoLID experiment and estimate the improvement of u- and d-quark transversity distributions with respect to our present knowledge. In order to perform a reliable estimate of improvement we develop a simple method based on Hessian error analysis described in Section 4.

This study also provides information on contribution of tensor charge from kinematical region of Jefferson Lab 12 GeV and will serve as a guide in planning future experiments.

2. Present status of extraction of transversity from experimental data

Transversity is a chiral odd quantity and thus in order to be measured in a physics process it should couple to another chiral odd distribution. There are several ways of accessing transversity. It can be studied in SIDIS process where it couples, for instance, to the Collins TMD fragmentation functions [24], and produces the so-called Collins asymmetries. Transversity can also couple to the dihadron interference fragmentation functions in SIDIS [25] and thus collinear transversity can be studied directly. Transversity can be studied in the Drell–Yan process in polarized hadron–hadron scattering [26,27] where it couples either to anti-quark transversity or to the so-called the Boer–Mulders functions.

SIDIS experimental measurements have been made at HERMES [28,29], COMPASS [30–32], and JLab HALL A [33] experiments. The BELLE, BABAR and the BESIII collaborations have studied the asymmetries in e^+e^- annihilation into hadron pairs at the center of mass energy around $\sqrt{s} \simeq 10.6$ GeV [34–36], and $\sqrt{s} \simeq 3.6$ GeV [37], respectively.

The effort to extract transversity distributions and Collins fragmentation functions has been carried out extensively in the last few years [38–41,23]. QCD analysis of the data where transversity couples to the so-called dihadron interference fragmentation functions was performed in Ref. [42]. These results have demonstrated the powerful capability of the asymmetry measurements in constraining quark transversity distributions and hence the nucleon tensor charge in high energy scattering experiments. The first extraction of the transversity distributions and Collins fragmentation functions with TMD evolution was performed in Refs. [43,23].

Collins asymmetries in SIDIS are generated by the convolution of the transversity function h_1 and Collins function $H_1^\perp$. The relevant contributions to the SIDIS cross-sections are

$$\frac{d^6\sigma}{dx_B dy dz d\psi d^2 P_T} = \sigma_0 \Big[F_{UU} + \sin(\phi_h + \phi_s) \frac{2(1-y)}{1+(1-y)^2} F_{UT}^{\sin(\phi_h+\phi_s)} + \ldots \Big], \quad (2)$$

where $\sigma_0 = \frac{2\pi\alpha_{\text{em}}^2}{Q^2} \frac{1+(1-y)^2}{y}$, and ϕ_s and ϕ_h are the azimuthal angles for the nucleon spin and the transverse momentum of the outgoing hadron with respect to the lepton plane, respectively, $d\psi \simeq d\phi_s$. F_{UU} and $F_{UT}^{\sin(\phi_h+\phi_s)}$ are the unpolarized and transverse spin-dependent polarized structure functions respectively, and the ellipsis represents other polarized structure functions not relevant for this analysis. The polarized structure function $F_{UT}^{\sin(\phi_h+\phi_s)}$ contains the convolution of transversity distributions with the Collins fragmentation functions, $h_1 \otimes H_1^\perp$, and unpolarized structure function F_{UU} is the convolution of the unpolarized TMD distributions and the unpolarized fragmentation functions, $f_1 \otimes D_1$. The Collins asymmetry is defined as

$$A_{UT}^{\sin(\phi_h+\phi_s)}(x, y, z, P_T) = \frac{2(1-y)}{1+(1-y)^2} \frac{F_{UT}^{\sin(\phi_h+\phi_s)}}{F_{UU}} . \quad (3)$$

Neglecting sea quark contributions, the structure function $F_{UT}^{\sin(\phi_h+\phi_s)}$ for the proton (P) and the neutron (N) targets can be written as:

$$F_{UT}^{\sin(\phi_h+\phi_s)}(P, \pi^+) = e_u^2 h_1^u \otimes H_1^{\perp, fav} + e_d^2 h_1^d \otimes H_1^{\perp, unf} , \quad (4)$$

$$F_{UT}^{\sin(\phi_h+\phi_s)}(P, \pi^-) = e_u^2 h_1^u \otimes H_1^{\perp, unf} + e_d^2 h_1^d \otimes H_1^{\perp, fav} , \quad (5)$$

$$F_{UT}^{\sin(\phi_h+\phi_s)}(N, \pi^+) = e_u^2 h_1^d \otimes H_1^{\perp, fav} + e_d^2 h_1^u \otimes H_1^{\perp, unf} , \quad (6)$$

$$F_{UT}^{\sin(\phi_h+\phi_s)}(N, \pi^-) = e_u^2 h_1^d \otimes H_1^{\perp, unf} + e_d^2 h_1^u \otimes H_1^{\perp, fav} . \quad (7)$$

Here $H_1^{\perp, fav}$ and $H_1^{\perp, unf}$, are the *favored* and the *unfavored* Collins fragmentation functions, respectively. In this context, *favored* refers to fragmentation of struck quarks of the same type as the constituent valence quarks of the produced pion while the *unfavored* being the opposite case. Previous global analysis [23,40] have found that both the *favored* and *unfavored* Collins functions have approximately similar magnitude (with opposite signs). Therefore, since $e_u^2 = 4e_d^2$, the u-quark transversity is more constrained in the proton sample than d-quark transversity and the situation is reversed in the neutron case. One expects from these considerations that only the neutron target can help to reach the same relative impact on determination of d-quark transversity compared to improvement of u-quark transversity from the proton target data.

In the KPSY15 analysis the transversity distributions was parametrized as at the input scale $Q_0 = \sqrt{2.4}$ GeV as

$$h_1^q(x, Q_0) = N_q^h x^{a_q} (1-x)^{b_q} \frac{(a_q + b_q)^{a_q+b_q}}{a_q^{a_q} b_q^{b_q}} \cdot \frac{1}{2} \left(f_1^q(x, Q_0) + g_1^q(x, Q_0) \right) , \quad (8)$$

where f_1^q and g_1^q are the collinear unpolarized [44] and polarized [45] quark distributions for $q = u$- and d-quark, respectively.

On the other hand, the twist-3 Collins fragmentation functions were parametrized in terms of the unpolarized fragmentation functions,

$$\hat{H}_{fav}^{(3)}(z, Q_0) = N_u^c z^{\alpha_u} (1-z)^{\beta_u} D_{\pi^+/u}(z, Q_0) , \quad (9)$$

$$\hat{H}_{unf}^{(3)}(z, Q_0) = N_d^c z^{\alpha_d} (1-z)^{\beta_d} D_{\pi^+/d}(z, Q_0) , \quad (10)$$

which correspond to the favored and unfavored Collins fragmentation functions, respectively. For $D_{\pi^+/q}$ we use the recent extraction from Ref. [46].

In summary, the analysis of KPSY15 used a total of 13 parameters in their global fit: N_u^h, N_d^h, a_u, a_d, b_u, b_d, N_u^c, N_d^c, α_u, α_d, β_d, β_u, g_c (GeV^2), where g_c is a parameter to model the width of the Collins fragmentation function. The parameters are shown in Table 1.

Table 1
Fitted parameters of the transversity distributions for u- and d-quark, and Collins fragmentation functions. The table is from Ref. [23].

$N_u^h = 0.85 \pm 0.09$	$a_u = 0.69 \pm 0.04$	$b_u = 0.05 \pm 0.04$
$N_d^h = -1.0 \pm 0.13$	$a_d = 1.79 \pm 0.32$	$b_d = 7.00 \pm 2.65$
$N_u^c = -0.262 \pm 0.025$	$\alpha_u = 1.69 \pm 0.01$	$\beta_u = 0.00 \pm 0.54$
$N_d^c = 0.195 \pm 0.007$	$\alpha_d = 0.32 \pm 0.04$	$\beta_d = 0.00 \pm 0.79$
$g_c = 0.0236 \pm 0.0007$	(GeV^2)	