Kinematical contributions to the transverse asymmetry in semi-inclusive DIS

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We discuss the contributions of the transverse spin component of the target to the double-spin asymmetries in semi-inclusive deep inelastic scattering of longitudinally polarized electrons off longitudinally polarized protons.

In the studies of semi-inclusive charged and neutral pion production off a longitudinally polarized protons, the HERMES collaboration has observed a single target-spin asymmetry (SSA) \cite{1}. This asymmetry could either result from twist-3 chiral-odd effects \cite{2,3} and/or could be a reflection of the Collins effect \cite{4}. Which of the two is relevant is an open issue. For a further understanding of “transverse asymmetry contribution” we discuss here the double-spin and double-spin azimuthal asymmetries, where those contributions are well defined.

A target with an anti-parallel (parallel) polarization with respect to the beam has a transverse spin component in the virtual photon frame which can only have azimuthal angle $\pi$ (0) (Fig.1). The value of this transverse spin component is

\begin{equation}
|S_T| = |S| \sin \theta_{\gamma},
\end{equation}

where $S$ is target polarization. The quantity $\sin \theta_{\gamma}$ is of order $1/Q$ and is given by

\begin{equation}
\sin \theta_{\gamma} = \sqrt{\frac{4M^2x^2}{Q^2 + 4M^2x^2(1 - y - \frac{M^2x^2y^2}{Q^2})}},
\end{equation}

where $M$ is the nucleon mass.
Fig. 1. (a) – The kinematics of semi-inclusive DIS: \( k_1 (k_2) \) is the 4-momentum of the incoming (outgoing) charged lepton, \( Q^2 = -q^2 \), where \( q = k_1 - k_2 \), is the 4-momentum of the virtual photon. The momentum \( P (P_h) \) is the momentum of the target (observed) hadron. The scaling variables are \( x = Q^2 / 2 (P \cdot q) \), \( y = (P \cdot q) / (P \cdot k_1) \), and \( z = (P \cdot P_h) / (P \cdot q) \). The momentum \( k_{1T} (P_{h\perp}) \) is the incoming lepton (observed hadron) momentum component perpendicular to the virtual photon momentum direction, and \( \phi \) is the azimuthal angle between \( P_{h\perp} \) and \( k_{1T} \). (b) – The definition of the azimuthal angle \( \phi_S \) and the target polarization components in virtual photon frame.

First, we give an estimate of the \( \cos \phi \) moment of the semi-inclusive DIS cross section, which is the following weighted integral of a cross section asymmetry \(^5\).

\[
A_{LL}^{\cos \phi} = \frac{1}{\langle P_{h\perp} \rangle} \int d^2 P_{h\perp} |P_{h\perp}| \cos \phi (\sigma^{++} + \sigma^{-+} - \sigma^{+-} - \sigma^{-+}) \int d^2 P_{h\perp} (\sigma^{++} + \sigma^{-+} - \sigma^{+-} - \sigma^{-+}).
\]

(3)

Here the subscript \( LL \) denotes the longitudinal polarization of the beam and target respectively, \( \sigma \) is a shorthand notation for \( d\sigma^{eN \rightarrow ehX}/dx dy dz d^2 P_{h\perp} \), the superscripts \( ++, -,+-,-- \) denote the helicity states of the beam and target respectively, corresponding to antiparallel (parallel) polarization\(^4\). Assuming 100% beam and target polarization and using the Wandzura-Wilczek (WW) approximation \(^6\), where only the twist-2 distribution and fragmentation functions are used, i.e. the interaction-dependent twist-3 parts are set to zero, one obtains (for more details see Ref. \( \cite{5} \))

\[
A_{LL}^{\cos \phi} = \frac{4}{\langle P_{h\perp} \rangle} \frac{\Delta \sigma_{LL} - d\sigma_{LT}}{\sigma_{UU}},
\]

(4)

\(^1\)It leads to positive \( g_1(x) \).
where
\[ \Delta \sigma_{LL}^{WW} \approx -4\lambda e S_L \frac{Q}{\sqrt{1-y}} M^2 g_1(x) z D_1(z), \] (5)
\[ d\sigma_{LT}^{WW} \approx \lambda e |S_T| (2-y) M \left[ \int_x^1 du \frac{g_1(u)}{u} \right] z D_1(z), \] (6)
\[ \sigma_{UU} = \frac{[1+(1-y)^2]}{y} f_1(x) D_1(z), \] (7)

being \( f_1 \) and \( g_1 \) \((D_1)\) the well-known leading twist distribution (fragmentation) functions. Notice that the cross section \(d\sigma_{LT}\) is positive but gives a negative contribution to the asymmetry \(|\vec{A}\)| because of the dependence on the azimuthal angle \(\phi_S\): \(\sigma^+ - \sigma^- = -d\sigma_{LT}\) and \(\sigma^- - \sigma^+ = d\sigma_{LT}\) at \(\phi_S = \pi(0)\) (see Fig.1 (b)).

It is important to point out that in the WW approximation the \(\cos \phi\) asymmetry reduces to a kinematical effect conditioned by intrinsic transverse momentum of partons similar to the \(\cos \phi\) asymmetry in unpolarized semi-inclusive DIS [7].

In Fig.2 (a), the asymmetry \(A_{LL}^{\cos \phi}\) of Eq.(3) for \(\pi^+\) production as a function of \(x\). The dashed line corresponds to contribution of the \(\Delta \sigma_{LL}\), dot-dashed one to \(d\sigma_{LT}\) and the solid line is the difference of those two; (b) – Double-spin asymmetry, defined by Eq.(8), as a function of \(x\). The full-curve corresponds to \(\Delta \sigma_{LL}'\) contribution and the dashed one is the total asymmetry.

In Fig.2(a), the asymmetry \(A_{LL}^{\cos \phi}\) for \(\pi^+\) production on a proton is shown as a function of \(x\). The curves are calculated by integrating over the HERMES kinematical ranges [5]. As it can be seen, the WW approximation gives the large negative double-spin \(\cos \phi\) asymmetry; the "kinematic" contribution coming from the transverse component of the target polarization is small (up to 25% at large \(x\)).
Let us now consider the following asymmetry

$$A = \frac{\int d^2P_{h\perp} (\sigma^{++} - \sigma^{-+})}{\int d^2P_{h\perp} (\sigma^{++} + \sigma^{-+})},$$

which can be written as [2,8]

$$A = \frac{\Delta \sigma'_{LL} + d\sigma'_{LT}}{\sigma_{UU}},$$

with

$$\Delta \sigma'_{LL} = \lambda eS_L (2 - y) g_1(x) D_1(z),$$

$$d\sigma'_{LT} \approx \frac{4M}{Q} |S| y \sqrt{1 - y x^2} [\int_x^1 du \frac{g_1(u)}{u}] D_1(z).$$

In Fig.2(b), this asymmetry is given as a function of $x$. As it is shown, the contribution from the target transverse component is negligible. Another possibility for studying the “kinematical” contributions is considering of $\sin(2\phi - \phi_S)$ – weighted asymmetry, $A_{LT}^{\sin(2\phi - \phi_S)}$, and its contribution to the target longitudinally polarized case.

In summary, the double-spin and the double-spin azimuthal asymmetries of semi-inclusive DIS of longitudinally polarized electrons off longitudinally polarized protons at twist-two level was investigated. A sizable negative $\cos \phi$ asymmetry is found for HERMES kinematics; the ‘kinematical’ contribution from target transverse component ($S_T$) to the $\cos \phi$ asymmetry, $A_{LL}^{\cos \phi}$, is small and that to the double-spin asymmetry, $A$, is negligible. Then, the measurements of SSA with transversely polarized target could help to understand the transverse asymmetry effects in the longitudinally polarized target case.

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