First Measurement of the Transverse Spin Asymmetries of the Deuteron in Semi-inclusive Deep Inelastic Scattering


(_COMPASS Collaboration)

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The importance of transverse spin effects at high energy in hadronic physics was first suggested by the discovery in 1976 that Λ hyperons produced in pN interactions exhibited an anomalously large large transverse polarization [1]. This effect could not be easily explained. For a long time it was believed to be forbidden at the leading twist in QCD [2], and very little theoretical work was devoted to this field for more than a decade.

This situation changed in the 1990s. After the first hints of large single transverse spin asymmetries in inclusive π⁰ production in polarized pp scattering at CERN [3], remarkably large asymmetries were found at Fermilab both for neutral and charged pions [4]. In parallel, intense theoretical activity was taking place: the significance of the quark transversity distribution, already introduced in 1979 [5] to describe a quark in a transversely polarized parent nucleon (no intrinsic quark transverse momentum kₜ), or after integration over kₜ, these three distributions exhaust the information on the internal dynamics of the nucleon. More distributions are allowed admitting a finite kₜ, or at higher twist [12–15].

The distributions Δₜq are difficult to measure, since they are chirally odd and therefore absent in inclusive DIS. They may instead be extracted from measurements of the single-spin asymmetries in cross sections for semi-inclusive DIS (SIDIS) of leptons on transversely polarized nucleons, in which a hadron is also detected in the final state. In these processes the measurable asymmetry, the “Collins asymmetry” A_Coll, is due to the combined effect of Δₜq and another chirally odd function, Δ₀qD₀q, which describes the spin-dependent part of the hadronization of a transversely polarized quark q into a hadron h. At leading order in the collinear case A_Coll can be written as

\[ A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q \Delta_0^q D_0^q}{\sum_q e_q^2 q D_0^h}, \]

where \( e_q \) is the quark charge. According to Collins [8], the quantity \( \Delta_0^q D_0^h \) can be obtained by investigating the fragmentation of a polarized quark q into a hadron h, and is related to the \( \vec{p}_T^h \) dependent fragmentation function

\[ D_0^h(z, \vec{p}_T^h) = D_0^q(z, |\vec{p}_T^q|^2) + \Delta_0^q D_0^q(z, |\vec{p}_T^q|^2) \sin \Phi_C. \]

Here \( \vec{p}_T^h \) is the hadron transverse momentum with respect to the struck quark direction, i.e., the virtual photon direction, and \( z = E_h/(E_t - E_f) \) is the fraction of available energy carried by the hadron. \( E_h, E_t, \) and \( E_f \) are the energies of the hadron, the incoming lepton, and the scattered lepton, respectively. The “Collins angle” \( \Phi_C \) is conveniently defined in a coordinate system in which the z axis is the virtual photon direction and the x-z plane is the lepton scattering plane, as illustrated in Fig. 1. In this reference system \( \Phi_C = \phi_h - \phi_s' \), where \( \phi_h \) is the azimuthal angle of the hadron in the scattering plane.
thal angle of the hadron, and $\phi_s$ is the azimuthal angle of the transverse spin of the struck quark. Since $\phi_s' = \pi - \phi_s$, with $\phi_s$ the azimuthal angle of the transverse spin of the initial quark (nucleon), one obtains $\sin\Phi_c = -\sin(\phi_b + \phi_s)$.

An entirely different mechanism was suggested by Sivers [16] as a possible cause of the transverse spin effects observed in $pp$ scattering. This mechanism could also be responsible for a spin asymmetry in the cross section of SIDIS of leptons on transversely polarized nucleons. Allowing for an intrinsic $k_T$ dependence of the quark distribution in a nucleon, a left-right asymmetry could be induced in such a distribution by a transverse nucleon polarization, $q_T(x, \vec{k}_T) = q(x, |\vec{k}_T|^2) + \Delta q(x, |\vec{k}_T|^2)\sin\Phi_S$, where $\Phi_S = \phi_b - \phi_s \neq \Phi_C$ is the “Sivers angle.” Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the “Sivers asymmetry”

$$A_{Siv} = \frac{\sum_q e_q^2 \Delta q \cos\Phi_h}{\sum_q e_q^2 q D_q h}$$

in the distribution of the hadrons resulting from the quark fragmentation with respect to the nucleon polarization, which could be revealed as a $\sin\Phi_S$ modulation in the number of produced hadrons. Measuring SIDIS on a transversely polarized target allows the Collins and the Sivers effects to be disentangled [17].

In this Letter first results are given of the charged hadron single-spin asymmetries in SIDIS of high energy muons on a transversely polarized $^6\text{LiD}$ target measured in 2002 by the COMPASS Collaboration.

The COMPASS spectrometer has been set up at the CERN SPS muon beam. The experiment has taken data from 2002 to 2004 at a muon momentum of 160 GeV/$c$ with beam rates of $4 \times 10^7$ muons/s. The beam is naturally polarized by the $\pi$-decay mechanism, with a polarization of about $-76\%$. The polarized target system [18] consists of two cells (upstream $u$, downstream $d$), each 60 cm long, located along the beam one after the other in two separate rf cavities and oppositely polarized. The target magnet can provide both a solenoid field (2.5 T) and a dipole field (0.4 T) used for adiabatic spin rotation and for the transversity measurements. Correspondingly, the target polarization can be oriented either longitudinally or transversely to the beam direction. Polarizations of 50% have been reached routinely with the $^6\text{LiD}$ target, which has a favorable dilution factor $f \approx 0.4$, since $^6\text{Li}$ basically consists of a deuteron plus an $^4\text{He}$ core. The target polarization is measured with a relative precision of 5%. Particle tracking is performed using several stations of scintillating fibers, micromesh gaseous chambers, and gas electron multiplier chambers. Large-area tracking devices comprise gaseous detectors (drift chambers, straw tubes, and multiwire proportional chambers) placed around the two spectrometer magnets. Muons are identified in large-area farocci tubes and drift tubes downstream of hadron absorbers. The trigger [19] is formed by several hodoscope systems supplemented by two hadron calorimeters. Veto counters are installed in front of the target to reject the beam halo. More information on the COMPASS spectrometer can be found in Ref. [20].

In 2002 about $6 \times 10^8$ events, corresponding to 260 Tbytes of data, were collected. About 20% of the sample was taken in the transverse spin mode, in two separate periods. Each period started with the $u$ cell of the target downwardly polarized and the $d$ cell upwardly polarized. After 4–5 days a polarization reversal was performed by changing the rf frequencies in the two cells.

Because the asymmetries are obtained by comparing data taken several days apart, the stability of the apparatus is crucial. To check the stability of reconstruction, the data were sampled in time. The hit distributions on all trackers were scrutinized, as well as the number of reconstructed events, the number of vertices per event, and the number of tracks per event in the whole spectrometer and in its various subregions. In addition, the distributions of a few relevant quantities were monitored for their stability throughout the data, like the Bjorken variable $x$, the relative energy transfer in the muon scattering process $y = (E_f - E_i)/E_i$, and the photon virtuality $Q^2$. These investigations led to the exclusion of about 4% of the data from the final sample.

In the analysis, events were selected in which a vertex with incident and scattered muon and at least one outgoing charged hadron was found in one of the two target cells. A clean identification of muons and hadrons was achieved on the basis of the amount of material traversed in the spectrometer. In addition, DIS cuts $Q^2 > 1$ (GeV/$c$)$^2$, $W > 5$ GeV/$c^2$, and $0.1 < y < 0.9$ were applied to the data as well as a cut on the transverse momentum of the hadrons ($p_T^h > 0.1$ GeV/$c$).

To enhance the asymmetry signal, we first evaluated the Collins and Sivers asymmetries for the leading hadron of each event, the underlying idea being that in the string fragmentation it is the most sensitive to the properties of the parent quark spin [21]. The leading hadron was defined as the most energetic hadron with $z > 0.25$, as well as originating from the reaction vertex. The total number of events that finally entered the analysis was $1.6 \times 10^6$ comprising $8.7 \times 10^5$ events with positive leading hadrons and $7.0 \times 10^5$ events with negative leading hadrons.

We searched separately for Collins and Sivers asymmetries in the data. The $\Phi$ distribution of the number of events for each cell and for each polarization state can be written as

$$N_j(\Phi_j) = F n \sigma a_j(\Phi_j)(1 + e_j \sin\Phi_j),$$

where $j = C, S$, and $F$ is the muon flux, $n$ the number of target particles, $\sigma$ the spin averaged cross section, and $a_j$
the product of angular acceptance and efficiency of the spectrometer. The asymmetries $\epsilon_j$ are $\epsilon_C = f|P_T|D_{NN}|A_{Coll}$ and $\epsilon_S = f|P_T|A_{Siv}$. The factor $f$ is the polarized target dilution factor, $P_T$ the deuteron polarization, and $D_{NN} = (1 - y)/(1 - y + y^2)/2$ the transverse spin transfer coefficient from the initial to the struck quark [12]. To highlight the physics process we are after, in Eq. (4) we have omitted terms that either average out in the evaluation of the asymmetry or lead only to negligible corrections due to a nonuniform angular acceptance. The beam polarization contributes to the asymmetry only by higher-twist effects, which are not considered in this leading-order analysis.

The asymmetries $\epsilon_C$ and $\epsilon_S$ were evaluated from the number of events with the two target spin orientations ($\uparrow$ spin up, and $\downarrow$ spin down) by fitting the quantities

$$A_n^\pi(\Phi_j) = \frac{N^\pi_j(\Phi_j) - rN^\pi_j(\Phi_j + \pi)}{N^\pi_j(\Phi_j) + rN^\pi_j(\Phi_j + \pi)}$$

with the functions $\epsilon_C \sin \Phi_C$ and $\epsilon_S \sin \Phi_S$. The normalization factor $r$ has been taken equal to the ratio of the total number of detected events in the two orientations of the target polarization. Note that two events having the same topology in the laboratory before and after the target spin rotation have angles $\Phi_j$ and $\Phi_j + \pi$, respectively; thus the acceptance cancels in Eq. (5) as long as the ratio $d^\pi_j/(\Phi_j)/d^\pi_j/(\Phi_j + \pi)$ is constant in $\Phi_j$.

The evaluation of the asymmetries was performed separately for the two data-taking periods and for the two target cells. These four sets of measured asymmetries turned out to be statistically compatible, and were then combined by taking weighted averages. Plots of the measured values of $A_{Coll}$ and $A_{Siv}$ against the three kinematic variables $x$, $z$, and $p_T^2$ are given in Fig. 2. The errors shown in the figure are only statistical.

The mean values of $z$ and $p_T^2$ are roughly constant (~0.44 and 0.51 GeV/c, respectively) over the whole $x$ range while $\langle Q^2 \rangle$ increases from ~1.1 (GeV/c)$^2$ in the first $x$ bin to ~20 (GeV/c)$^2$ in the last one.

Systematic errors due to the uncertainties in $P_T$, $D_{NN}$, and $f$ are negligibly small. Several tests were made to check that there are no effects distorting the measured asymmetries, splitting the data sample (i) in time, (ii) in two halves of the target cells, and (iii) according to the hadron momentum. The asymmetries measured for the different samples were found to be compatible. Also, the results were stable with respect to different choices of the normalization factor $r$.

The method of extracting the asymmetries is expected to minimize systematic effects due to acceptance, and this is confirmed by the compatibility of the asymmetries measured in the two cells $u$ and $d$. Under the reasonable assumption that the ratio $a^1_{j,u}(\Phi_j + \pi)/a^1_{j,d}(\Phi_j)$ before the polarization reversal be equal to the corresponding ratio $a^1_{j,u}(\Phi_j)/a^1_{j,d}(\Phi_j + \pi)$ after the reversal, the requirement that the ratios $a^1_{j,u}(\Phi_j + \pi)/a^1_{j,u}(\Phi_j)$ and $a^1_{j,d}(\Phi_j)/a^1_{j,d}(\Phi_j + \pi)$ be constant in $\Phi_j$ within each data-taking period has been verified by constructing the ratio

$$R_j(\Phi) = \frac{N^1_{j,u}(\Phi_j)N^1_{j,d}(\Phi_j + \pi)}{N^1_{j,u}(\Phi_j + \pi)N^1_{j,d}(\Phi_j)} \propto \frac{[a^1_{j,u}(\Phi_j)]^2}{[a^1_{j,u}(\Phi_j + \pi)]^2}$$

FIG. 2. Collins asymmetry (top) and Sivers asymmetry (bottom) against $x$, $z$, and $p_T$ for positive (full points) and negative hadrons (open points). Error bars are statistical only. The first column gives the asymmetries for all hadrons, the other three columns for the leading hadrons. In all the plots the points are slightly shifted horizontally with respect to the measured value.

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and verifying its constancy in $\Phi_j$. This constancy holds even using the entire data sample after releasing the $z$ cut. It has to be stressed also that, under the same assumption, possible false asymmetries due to variations in $\Phi_j$ of the acceptance ratios to first order have opposite signs in the two cells and cancel in the average.

To estimate the size of possible systematic effects, the asymmetries have also been evaluated using two other estimators that are independent of relative luminosities and rely on different assumptions of the acceptance variations, e.g., the ratio product

$$\frac{N^j_{j,u}(\Phi_j)}{N^j_{j,u}(\Phi_j + \pi)} \times \frac{N^j_{j,d}(\Phi_j)}{N^j_{j,d}(\Phi_j + \pi)}\quad (7)$$

and the geometric mean

$$\frac{\sqrt{N^j_{j,t}(\Phi_j)N^j_{j,t}(\Phi_j) - N^j_{j,t}(\Phi_j + \pi)N^j_{j,t}(\Phi_j + \pi)}}{\sqrt{N^j_{j,t}(\Phi_j)N^j_{j,t}(\Phi_j) + N^j_{j,t}(\Phi_j + \pi)N^j_{j,t}(\Phi_j + \pi)}}\quad (8)$$

Differences from the results displayed in Fig. 2 were observed only within the statistical errors of the measured asymmetries.

The conclusion from all these studies is that systematic errors are smaller than the quoted statistical errors.

Within the statistical accuracy of the data, both $A_{\text{Coll}}$ and $A_{\text{Siv}}$ turn out to be small and compatible with zero, with a marginal indication of a Collins effect at large $z$ in both the positive and the negative hadron data. By means of Monte Carlo simulations, we estimated that the following factors could together dilute a possible leading pion asymmetry by a factor of 0.6 at most: (i) the acceptance of the spectrometer for leading hadrons (by cutting at $z > 0.25$ the reconstructed charged leading particle is the generated most energetic hadron in about 80% of the cases); (ii) nonidentification of the charged hadron (about 80% of the charged leading hadrons are pions); (iii) smearing of the kinematical quantities due to the experimental resolution of the spectrometer (negligible effect). For the simulation, which reproduces well the experimental distributions, we used LEPTO 6.5.1 and GEANT 3. Simulations were also performed to check the possible correlation between the measured values of $\varepsilon_C$ and $\varepsilon_S$. Asymmetries up to 20% were generated, and no appreciable mixing was observed.

This analysis has been repeated for all hadrons, i.e., both the Collins and the Sivers asymmetries have been evaluated for all the reconstructed hadrons with $z > 0.2$. The total number of hadrons entering the analysis is in increased by a factor of 1.5 with respect to the leading hadron analysis, but the results are very similar, i.e., small values for the asymmetries. For reasons of space, the asymmetries are displayed in Fig. 2 as a function of $x$ only. All the measured asymmetries are available on HEPDATA [22].

The COMPASS measurements on the transversely polarized deuteron target have a statistical accuracy of the same order as the recent measurement on protons performed by the HERMES Collaboration [11]. The small measured values of the deuteron asymmetries can be understood because $\Delta_T u$ and $\Delta_T d$ are likely to have the opposite sign as for the helicity distributions, and some cancellation is expected between the proton and the neutron asymmetries. In particular, the measured values of $A_{\text{Coll}}$ for positive hadrons do not show at large $x$ the negative trend suggested both by the naive expectation $A_{\text{Coll}}^u = -\Delta_T u / u$ and the model prediction of Ref. [23]. Attention is drawn to the fact that the conventions used in Refs. [11,23] give an opposite sign for the Collins asymmetry as compared to this Letter. Alternatively, it could be that the Collins effect is too small to allow for quark polarimetry with this set of data. Different quark polarimeters are also being tried, e.g., hadron pairs and $\Lambda$ production. The analysis of the full sample of deuteron data, including the 2003 and 2004 runs, will reduce the errors by at least a factor of 2, and the COMPASS Collaboration also intends to take data with a polarized proton target. Precise transversely polarized proton and deuteron data will allow a flavor separation of transversity in the near future.

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