Quark helicity distributions from semi-inclusive deep inelastic scattering

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The HERMES collaboration has measured inclusive and semi-inclusive double-spin asymmetries using the longitudinally polarized positron beam of the HERA collider scattered off longitudinally polarized hydrogen and deuterium targets. Five quark helicity distributions including three sea quark flavors were extracted from semi-inclusive deep-inelastic scattering data. The polarization of the up-quark is positive and that of the down-quark is negative. All extracted sea quark polarizations are consistent with zero.

Key words: Polarized lepton beam, polarized gaseous H and D target, inclusive and semi-inclusive DIS, double-spin asymmetry, structure function, purity, quark helicity distributions, isoscalar extraction method

1 Introduction

From studies of deep-inelastic lepton-nucleon scattering (DIS), much has been learned about the quark-gluon structure of the nucleon. The objective of these studies is to determine the fraction of the spin of the nucleon which is carried by the quarks. From the lepton-nucleon double-spin asymmetry \(A_\parallel\) defined as the relative difference of the cross sections with beam and target helicities antiparallel and parallel, the virtual photon asymmetry \(A_1\) can be determined. \(A_1\) in turn can be related to the structure function \(g_1\):

\[
A_1(x, Q^2) \simeq \frac{A_\parallel(x, Q^2)}{D(1 + \eta \gamma)} \simeq \frac{g_1(x, Q^2)}{F_1(x, Q^2)},
\]

where \(D\) is the photon depolarization factor, and \(\eta, \gamma\) are (known to be small) kinematic factors. In LO QCD, \(g_1\) can be interpreted as the charge weighted sum of polarized quark distributions:

\[
g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2(\triangle q(x, Q^2) + \triangle \bar{q}(x, Q^2)),
\]

where the polarized quark densities \(\triangle q\) are defined as the difference \(q^+ - q^-\) between densities of quark with positive and negative helicity with respect to that of the nucleon. The unpolarized quark densities are given by \(q \equiv q^+ + q^-\). In semi-inclusive deep-inelastic scattering (SIDIS) the fractional energy of the detected hadron \(z = E_h/\nu\) and its relative longitudinal momentum with respect to the virtual photon

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direction in the hadronic center of mass frame \( x_F \approx 2p_L/W \) are also measured. The semi-inclusive virtual photon asymmetry for a hadron of type \( h \) in LO QCD is

\[
A_h^1(x, Q^2) \sim \frac{\sum_q e_q^2 \Delta q(x, Q^2) \int dz D_h^q(z, Q^2)}{\sum_q e_q^2 q'(x, Q^2) \int dz D_h^q(z, Q^2)}
\]

with the fragmentation function \( D_h^q \), denoting the probability that a quark of flavor \( q \) fragments into a final state hadron \( h \) carrying the energy fraction \( z \). Introducing the spin-independent purities

\[
P_h^q(x) = \frac{e_q^2 q(x) \int dz D_h^q(z)}{\sum_q e_q^2 q(x) \int dz D_h^q(z)}.
\]

Eq. (4) can be rewritten as:

\[
A_h^1(x) \approx \sum_q P_h^q(x) \frac{\Delta q(x)}{q(x)},
\]

where all quantities have been averaged in each \( x \)-bin over the available range in \( Q^2 \). The purities \( P_h^q \) describe the probability that the hadron \( h \) originates from an event where a quark of flavor \( q \) was struck. They were extracted using Monte Carlo simulations with the limited acceptance of the spectrometer taken into account. For the unpolarized quark distributions the CTEQ5L parametrization [1] was used, for the fragmentation functions the parameters of the LUND string fragmentation model implemented in JETSET [2] were tuned to fit the hadron multiplicities measured by HERMES [3].

2 HERMES experiment

The HERMES experiment at DESY uses the 27.5 GeV polarized positron (or electron) beam at the HERA collider and a pure polarized gaseous target (hydrogen or deuterium). With a large forward acceptance of the HERMES spectrometer and its reliable particle identification [4] it is possible to measure not only inclusive reactions in deep-inelastic scattering, where only the scattered lepton is detected, but also semi-inclusive DIS events, where hadrons are detected in coincidence with the lepton. For the hydrogen data set, pions could be identified using the information from a threshold Cherenkov counter (1996–1997 years). For the deuterium data a Ring-Imaging Cherenkov (RICH, 1998–2000 years) detector provided identification of pions and kaons over the kinematic range of 2–15 GeV/c [5].

3 Results of inclusive analysis

The results shown in Fig. 1 are obtained in the framework of an NLO QCD analysis based on inclusive world data on polarized deep-inelastic lepton-nucleon scattering including the HERMES data set.
Fig. 1. The polarized parton densities at the input scale $Q^2 = 4.0 \text{ GeV}^2$ (solid line) compared to results obtained by BB (long-dashed line) [6], GRSV (dashed-dotted line) [7], and AAC (dashed line) [8]. The shaded areas represent the fully correlated $1 \sigma$ statistical error bands. The dark dotted lines correspond to the positivity bounds taken from unpolarized densities [9].

Fig. 2. The structure function $xg_1^p$ as function of $x$. The experimental data are evolved to a common value of $Q^2 = 5.0 \text{ GeV}^2$ (data points measured at $Q^2 > 1.0 \text{ GeV}^2$ are taken only). The error bars shown are the statistical and systematical ones added in quadrature. The experimental distribution is well described by the NLO QCD fit (solid line) within the statistical and systematic error bands (shaded and hatched areas). Shown for comparison are the curves obtained by BB (long-dashed) [6], GRSV (dashed-dotted) [7], and AAC (dashed) [8].

The polarized densities $\triangle u_\nu$ and $\triangle d_\nu$ are constrained best by the current world data while $\triangle G$ and $\triangle q$ are still only poorly determined. The spin structure functions $g_1^p$, $g_1^n$ and $g_2^n$ are well described. As an example, the world data on $xg_1^p(x)$ which contain the new HERMES data set are shown in Fig. 2. The experimental data are evolved to $Q^2 = 5.0\text{ GeV}^2$ representing a reasonable common world average value.

4 Results of semi-inclusive analysis

Figure 3 shows the semi-inclusive asymmetries for pions and kaons on the deuteron target, within a momentum range of $4 < p_h < 13.8 \text{ GeV}$. The SIDIS asymmetries are measured at $Q^2 > 1\text{ GeV}^2$, $W^2 > 10\text{ GeV}^2$ and $y < 0.85$, with the hadron required to have $0.2 < z < 0.8$ and $x_F > 0.1$. The lower $z$ cut and the cut on $x_F$ effectively suppress hadrons from the target fragmentation region, while
the upper $z$ cut reduces contribution from exclusive events to the semi-inclusive sample.

Except for negative kaons, whose asymmetries are consistent with zero, all asymmetries are positive and rising with $x$. Since a negative kaon constitutes a sea-only object ($\bar{u}s$) its asymmetry is more sensitive to sea quarks than that for other hadrons which all contain valence quarks of the nucleon.

![Graph showing semi-inclusive asymmetries](image)

Fig. 3. The HERMES results on semi-inclusive asymmetries on deuterium target for identified charged pions (compared to all charged hadrons from SMC in the $x$-range of HERMES), and for identified charged kaons. The error bands represent the systematic uncertainties.

In order to get access to helicity distributions in SIDIS the purity formalism has been used. Equation (5) can be generalized for a set of measured asymmetries combined into a vector $\vec{A}$:

$$\vec{A} \approx P \vec{Q},$$

where $P$ is now a matrix of purities and $\vec{Q}$ is the vector of quark polarizations to be determined. For the recent analysis, $\vec{Q} = (\triangle u/u, \triangle \bar{u}/\bar{u}, \triangle d/d, \triangle \bar{d}/\bar{d}, \triangle s/s, \triangle \bar{s}/\bar{s} \equiv 0)$ is used. The vector $\vec{A}$ contains the semi-inclusive asymmetries of both proton and deuteron targets as well as the inclusive asymmetries within the same kinematic range. From the solution of Eq. (6) vector $\vec{Q}$ obtained by minimization methods, the quark helicity distributions $\Delta q(x)$ can be derived by multiplying each of the quark polarizations with the corresponding unpolarized PDF at fixed $Q^2 = 2.5 \text{ GeV}^2$.

Figure 4 shows the results of this procedure for the $x$-weighted distributions $x\Delta q(x)$. Note that in contrast to the LO QCD fits to inclusive data overlaid in Fig. 4, in the HERMES analysis no assumptions were made on the symmetry of the sea flavors, except that $\Delta \bar{s}/\bar{s}$ is assumed to be zero. The systematic error bands include uncertainties in addition to the experimental error of the asymmetries (used pdf’s, tune for extracting purities). For $x > 0.3$, the polarization of the sea flavors was fixed at zero, the small uncertainties for the non-sea flavors arising from this as well as from setting $\Delta \bar{s}/\bar{s} \equiv 0$ were also included in their systematic error. As expected the helicity density of the $u$ quark is found to be positive and large at $x > 0.1$, and that of the $d$ quark is negative and rather flat in $x$. The helicity densities of the light sea quarks are found to be compatible with zero. Contrary
to the small negative strange sea polarization resulting from QCD fits to inclusive data, the strange quark helicity appears slightly positive. For sea quarks within the experimental uncertainties there is no disagreement with the QCD fits.

Fig. 4. The quark helicity distributions $x\Delta q(x, Q_0^2)$ evaluated at a common value of $Q_0^2 = 2.5 \text{ GeV}^2$ as a function of $x$. The dashed line is the GRSV2000 parametrization (LO, valence scenario)\cite{7} scaled with $1/(1+R)$ and the dashed-dotted line is the Bl"umlein-B"ottcher (BB) parametrization (LO, scenario 1) \cite{6}.

An alternative analysis was also performed to extract $\Delta s(x) + \Delta \bar{s}(x)$. Because the strange quark helicity $\Delta s(x) + \Delta \bar{s}(x)$ has no isospin, it can be extracted from
the isoscalar deuteron target alone. A simple purity matrix can be computed using kaon fragmentation functions from $e^+e^-$ collider data describing specifically the likelihood of strange quark fragmentation into kaon. The results from the five flavor fit to the full data set on both the proton and deuteron targets are also shown in Fig. 5. A comparison of the first moments of the helicity densities in the measured $x$ region provides a good agreement between the two methods.

References