Extraction of $g_1^p$, $g_1^d$ and $\Delta g/g$ from HERMES data

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Abstract. HERMES collected deep-inelastic scattering (DIS) events of 27.6 GeV longitudinally polarised positrons off longitudinally polarised hydrogen and deuterium gas targets internal to the HERA storage ring. Double-spin asymmetries $A_{p,d}^\parallel$ of cross sections in inclusive DIS allow the precise extraction of spin structure functions of the proton $g_1^p(x, Q^2)$ and the deuteron $g_1^d(x, Q^2)$ in the kinematic range $0.0041 \leq x \leq 0.9$ and $0.18 \text{GeV}^2 \leq Q^2 \leq 20 \text{GeV}^2$. Furthermore, double-spin asymmetries of inclusive production of charged hadrons as a function of transverse momentum $p_T$ have been measured. For $p_T > 1 \text{ GeV}$ the asymmetries are sensitive to the spin dependent gluon distribution function $\Delta g$. Using a Leading Order Monte Carlo model to obtain information on the background asymmetry and background process kinematics, $\Delta g/g$ has been extracted.

1. The spin structure functions $g_1^p$ and $g_1^d$

Double-spin asymmetries $A_{p,d}^\parallel$ of cross sections in inclusive DIS $l + N \rightarrow l + X$ of longitudinally polarised charged leptons off longitudinally polarised protons and deuterons have been measured by the HERMES experiment. Based on these asymmetries, the structure functions $g_1^{p,d}$ can be extracted:

$$g_1^{p,d}(x, Q^2) = \frac{1}{1 - \frac{Q^4}{24\pi \alpha^2 y}} \left[ \frac{Q^4}{8\pi \alpha^2 y} \frac{\partial^2 \sigma_{UU}(x, Q^2)}{\partial x \partial Q^2} A_{p,d}^\parallel(x, Q^2) + \frac{y}{2} g_2(x, Q^2) \right]. \quad (1)$$

Here, $-Q^2$ is the squared four-momentum transferred by the virtual photon, $x$ is the fraction of the nucleon’s light-cone momentum carried by the struck quark, and $y$ and $\gamma$ are kinematic factors. In addition, Eq. 1 contains the unpolarised cross section $\frac{\partial^2 \sigma_{UU}(x, Q^2)}{\partial x \partial Q^2}$ and the structure function $g_2$, both of which can be obtained from parametrisations.

The analysis presented here is based on proton data collected in 1996 and 1997 as well as deuteron data collected in the year 2000. The scattered lepton (electron or positron) was identified by combining the responses of the transition radiation detector, the pre-shower detector and the calorimeter. In addition the information from the Čerenkov detector (proton target) or the RICH detector (deuteron target) was used. This results in a lepton efficiency larger than 96%, with a hadron contamination below 0.2%. Charge symmetric background from meson Dalitz decays and photon conversion into $e^+e^-$ pairs was corrected for by subtracting the number of leptons with charge opposite to the beam charge in each kinematic bin. Kinematic and geometric cuts were applied to ensure that tracks were fully contained within the spectrometer acceptance and to restrict the scattering kinematics to the DIS regime. After these data selection cuts, the
proton (deuteron) data sample consisted of 3.5M (10.2M) events. The HERMES spectrometer is described in detail in [1].

Following the cuts, the resulting \((x, Q^2)\) plane with the limits \(0.0041 \leq x \leq 0.9\) and \(0.18 \text{GeV}^2 \leq Q^2 \leq 20 \text{GeV}^2\) was divided in 19 \(x\) bins, most of which were further subdivided into 3 \(Q^2\) bins. In this binning, the measured asymmetry \(A_{\parallel}^m\) was extracted:

\[
A_{\parallel}^m(x, Q^2) = \frac{1}{P_T P_B} \frac{N^{-\bar{\sigma}}(x, Q^2) \mathcal{L}^{-\bar{\sigma}} - N^{-\bar{\sigma}}(x, Q^2) \mathcal{L}^{-\bar{\sigma}}}{N^\bar{\sigma}(x, Q^2) \mathcal{L}^\bar{\sigma} + N^\bar{\sigma}(x, Q^2) \mathcal{L}^\bar{\sigma}}. \tag{2}
\]

\(\mathcal{L}\) denotes the dead-time-weighted luminosity, \(N(x, Q^2)\) the count rate in the respective bin. The symbols \('^{-\bar{\sigma}}'\) and \('^{-\bar{\sigma}}'\) specify parallel and anti-parallel states of the beam and target spins, respectively. The polarisation of the beam \((P_B)\) and the target \((P_T)\) were \(P_B = 0.53 \pm 0.018\) and \(P_T = 0.85 \pm 0.032\) for the proton data and \(P_B = 0.53 \pm 0.010\) and \(P_T = 0.84 \pm 0.03\) for the deuteron data.

The asymmetry was evaluated separately for the top and bottom half of the detector in order to allow polarisation independent systematic effects in the respective detector halves to cancel independently. The final asymmetry is the weighted average. An unfolding algorithm was applied to correct for radiative and detector smearing as well as elastic and quasi-elastic background. This procedure removes systematic correlations due to kinematic smearing, instead the data points are statistically correlated. For the deuteron case a correction was applied to take into account the contribution of the tensor structure function \(b_4^T\) to the cross section[2].

Based on this Born asymmetries, \(g_1^f\) and \(g_2^f\) were extracted with Eq. 1 using parametrisations [3], [4] and [5] to model the unpolarised cross section. \(g_2\) was calculated from a parametrisation of all available proton and deuteron data ([6], [7], [8], [9], [10]).

The results are shown in Fig. 1 (left panel) in comparison with other experiments. For protons, the central values of the SMC data are larger than the results from HERMES (and E143) in the low \(x\)-region. It should be noted, however, is that the SMC data was taken at a significantly higher \(\langle Q^2 \rangle\) (right panel). The deuteron results are compatible with zero for \(x < 0.04\), in agreement with COMPASS.

Of special interest is also the first moment of \(g_1\). Experimentally, only a limited range in \(x\) is accessible. However, for \(g_1^f(x)\) the integral shows saturation below \(x = 0.04\). The integrated value allows the extraction of the first moments of the quark helicity distributions, assuming the validity of SU(3) flavour symmetry in hyperon \(\beta\)-decay. In the \(\overline{\text{MS}}\) scheme at \(O(\alpha_s^2)\) and at \(Q^2 = 5 \text{ GeV}^2\), the values are \(\Delta u + \Delta \bar{u} = 0.842 \pm 0.004(\text{theo}) \pm 0.008(\text{exp}) \pm 0.009(\text{evol}), \Delta d + \Delta \bar{d} = -0.427 \pm 0.004(\text{theo}) \pm 0.008(\text{exp}) \pm 0.009(\text{evol})\) and \(\Delta s + \Delta \bar{s} = -0.085 \pm 0.013(\text{theo}) \pm 0.008(\text{exp}) \pm 0.009(\text{evol})\), implying a strange quark helicity which is negative by about 4.7 \(\sigma\). This results in a total quark contribution to the nucleon’s spin of \(\Delta \Sigma = 0.330 \pm 0.011(\text{theo}) \pm 0.025(\text{exp}) \pm 0.028(\text{evol})\).

An extensive description of the analysis procedure is available in [16].

2. The gluon distribution function \(\Delta g/g\)

The \(\Delta g\) measurement presented here is based on the same data set as the \(g_1\) analysis. To extract \(\Delta g/g\), double spin asymmetries of hadron production as a function of \(p_T\) have been extracted:

\[
A_{\parallel}(p_T) = \frac{N_{h}^{-\bar{\sigma}}(p_T) \mathcal{L}^{-\bar{\sigma}} - N_{h}^{-\bar{\sigma}}(p_T) \mathcal{L}^{-\bar{\sigma}}}{N_{h}^{\bar{\sigma}}(p_T) \mathcal{L}^{\bar{\sigma}} + N_{h}^{\bar{\sigma}}(p_T) \mathcal{L}^{\bar{\sigma}}}. \tag{3}
\]

For \(\Delta g\), the high statistics of anti-tagged (=veto on the scattered beam particle) inclusive hadrons was used. Due to the unknown properties of the virtual photon, the transverse
momentum is defined with respect to the beam axis. The resulting asymmetry is shown in Fig. 2 for positive and negative hadrons and both targets. The asymmetries are compared to the results obtained with the Monte Carlo model described below, where the extreme cases $\Delta g/g = \pm 1$ are given together with a $\Delta g/g = 0$ scenario. The influence of the gluon polarisation becomes sizeable for $p_T > 1$ GeV.

The measured asymmetries arise from contributions of different sub-processes involved in the production of inclusive hadrons. To extract the signal from processes initiated by a hard gluon, the Pythia 6.2 Monte Carlo program was used, together with a model of the HERMES detector. The Vector Meson Dominance (VMD) Model in Pythia was adapted to reproduce the observed exclusive $\rho^0$ cross section [17], while the Jetset fragmentation model was tuned to multiplicities of identified hadrons for $Q^2 > 1$ GeV$^2$ measured at HERMES [18]. This model provided the relative contributions of the signal and background processes, as well as their respective asymmetries, using the GRSV2000 PDFs [19] for nucleons and GRS [20] for photons.

The signal asymmetry can then be obtained from the measured asymmetry by subtracting the background asymmetries, weighted with their respective background fractions. The resulting signal asymmetry contains a convolution of $\Delta g(x)/g(x)$ with the polarised hard sub-process cross section integrated over the $x$ range covered by the data. Two methods were applied to extract the average $\langle \Delta g/g \rangle(p_T)$ from this convolution: Method I assumes $\Delta g/g$ to be basically independent of $x$. Method II parametrizes $\Delta g(x)/g(x)$ with a functional form. The parameters of the function were fitted by minimising the $\chi^2$ of the difference between the measured asymmetry and the background.

Fig. 3 shows the average $\langle \Delta g/g \rangle(p_T)$ as obtained from deuteron data for charge combined
Figure 2. Asymmetries of inclusive anti-tagged hadrons. Shown are the asymmetries for a proton (top) and deuteron (bottom) target. The curves are obtained using the Monte Carlo model and spin dependent quark distribution functions, assuming $\Delta g/g(x)=-1, 0$ and $+1$ (top to bottom).

hadrons. The experimental error is estimated to be approx. 14%, arising from uncertainties in the beam and target polarisation measurements. The total systematic error is dominated by the model uncertainties. These were mostly estimated by varying the PDFs and MC parameters influencing the process fractions and the fragmentation model. From the results of Method II, a value of $\Delta g/g = 0.07 \pm 0.03(\text{stat.}) \pm 0.01(\text{sys})^{+0.127}_{-0.105}(\text{sys - Models})$ has been obtained at $\langle x \rangle = 0.22$ and $\langle \mu^2 \rangle = 1.35 \text{ GeV}^2$. An extensive description of the analysis can be found in [17], with an update in [21]. A HERMES publication is in preparation.

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