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# Spin asymmetry in muon–proton deep inelastic scattering on a transversely-polarized target

Spin Muon Collaboration (SMC)

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## Abstract

We measured the spin asymmetry in the scattering of 100 GeV longitudinally-polarized muons on transversely polarized protons. The asymmetry was found to be compatible with zero in the kinematic range  $0.006 < x < 0.6$ ,  $1 < Q^2 < 30 \text{ GeV}^2$ . From this result we derive the upper limits for the virtual photon–proton asymmetry  $A_2$ , and for the spin structure function  $g_2$ . For  $x < 0.15$ ,  $A_2$  is significantly smaller than its positivity limit  $\sqrt{R}$ .

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The nucleon spin-dependent structure functions,  $g_1$  and  $g_2$ , can be determined in deep inelastic scattering of polarized charged leptons on polarized nucleons. Both are important for the understanding of nucleon spin structure. The structure function  $g_1$  is used to test QCD sum rules, and in the quark–parton model it determines the contribution of the quark spins to the

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nucleon spin. The spin structure function  $g_2$  differs from zero because of the masses and the transverse momenta of the quarks. It has a unique leading-order sensitivity to twist-3 operators, i.e., quark–gluon correlation effects in QCD. The measurement of  $g_2$  would provide the first information on these twist-3 operator matrix elements [1].

In general,  $g_2$  can be written as the sum of a contribution,  $g_2^{\text{ww}}$ , directly calculable from  $g_1$  [2] and a pure twist-3 term  $\bar{g}_2$  [1]

$$g_2(x, Q^2) = g_2^{\text{ww}}(x, Q^2) + \bar{g}_2(x, Q^2), \quad (1)$$

with

$$g_2^{\text{ww}}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 g_1(t, Q^2) \frac{dt}{t}, \quad (2)$$

where  $-Q^2$  is the four-momentum transfer squared, and  $x$  is the Bjorken scaling variable. In several recent papers, values for  $\bar{g}_2$  and their approximate  $Q^2$  dependence have been calculated using different assumptions [3–6]. A sum rule for  $g_2$ ,

$$\int_0^1 g_2(x, Q^2) dx = 0, \quad (3)$$

was derived by Burkhardt and Cottingham using Regge theory [7]. It has been regarded as a consequence of conservation of angular momentum [8]. At present the validity of the derivation of this sum rule is in question [9,1], and it is clearly important to test it experimentally.

Two kinds of spin-dependent cross-section asymmetries can be measured in inclusive lepton–nucleon scattering. When the target polarization is parallel to the direction of the longitudinally-polarized beam, the asymmetry is given by  $A_{\parallel}$ , whilst for a target polarized in a direction transverse to the beam, the asymmetry is given by  $A_T$

$$A_{\parallel}(x, Q^2) = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}},$$

$$A_T(x, Q^2, \phi) = \frac{d\sigma^{\downarrow\rightarrow} - d\sigma^{\uparrow\rightarrow}}{d\sigma^{\downarrow\rightarrow} + d\sigma^{\uparrow\rightarrow}}. \quad (4)$$

Here,  $d\sigma^{\uparrow\uparrow}(d\sigma^{\uparrow\downarrow})$  corresponds to  $d^2\sigma/dx dQ^2$  for parallel (antiparallel) beam and target polarization.

For perpendicular target polarisation,  $d\sigma^{\uparrow\rightarrow}$  ( $d\sigma^{\downarrow\rightarrow}$ ) stands for  $d^3\sigma/dx dQ^2 d\phi$ , when the target spin points in the upwards (downwards) direction. The azimuthal angle  $\phi$  is defined about the beam axis,  $\phi = 0$  corresponding to a muon scattered upwards. It can be shown that  $A_T$  is proportional to  $\cos \phi$ , and thus it is convenient to define  $A_{\perp}(x, Q^2) \equiv A_T(x, Q^2, \phi) / \cos \phi$ , which is independent of  $\phi$  [1].

The virtual photon absorption asymmetries

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}, \quad A_2 = \frac{2\sigma_{TL}}{\sigma_{1/2} + \sigma_{3/2}}, \quad (5)$$

are related to the measured asymmetries  $A_{\parallel}$  and  $A_{\perp}$ ,

$$A_{\parallel} = D \left( A_1 + \gamma \frac{(1-y)}{1-y/2} A_2 \right), \quad (6)$$

$$A_{\perp} = d \left( A_2 - \gamma \left(1 - \frac{y}{2}\right) A_1 \right). \quad (7)$$

Here  $\sigma_{1/2}$  and  $\sigma_{3/2}$  are the virtual photon–nucleon absorption cross sections for total helicity 1/2 and 3/2, respectively, and  $\sigma_{TL}$  arises from the helicity spin-flip amplitude in forward photon–nucleon Compton scattering [10,11]. The kinematic factor  $\gamma$  is defined by  $\gamma = \sqrt{Q^2}/\nu = 2Mx/\sqrt{Q^2}$ , where  $\nu$  is the energy transfer in the laboratory frame, and  $y = \nu/E_{\mu}$ . The coefficient  $d$  is related to the virtual photon depolarization factor  $D$  by

$$d = D \frac{\sqrt{1-y}}{1-y/2},$$

$$D = \frac{y(2-y)}{y^2 + 2(1-y)(1+R)}, \quad (8)$$

where  $R$  is the ratio of the longitudinal to transverse photoabsorption cross sections,  $\sigma_L/\sigma_T$ . In the case of  $A_{\parallel}$ , the contribution of the  $A_2$  term relative to  $A_1$  is suppressed by a factor  $\gamma$ . The opposite is true for the case of  $A_{\perp}$ .

Positivity conditions [12] limit the magnitudes of  $A_1$  and  $A_2$

$$|A_1| < 1, \quad |A_2| \leq \sqrt{R}. \quad (9)$$

The asymmetries  $A_1$  and  $A_2$  can be expressed in terms of the structure functions  $g_1$  and  $g_2$

$$A_1 = \frac{1}{F_1}(g_1 - \gamma^2 g_2), \quad A_2 = \frac{\gamma}{F_1}(g_1 + g_2), \quad (10)$$

where  $F_1 = F_2(1 + \gamma^2)/2x(1 + R)$  is the spin-independent structure function. The ratio  $R$ , determined at SLAC [13], is about 0.3 in the range  $0.1 < x < 0.4$  for  $Q^2 \cong 1.5 \text{ GeV}^2$ , and similar values are usually assumed at smaller  $x$ . Using these values of  $R$ , the positivity condition on  $A_2$  (Eq. (9)) combined with Eq. (10) leads to an upper limit for  $|g_2|$  which is approximately of the form  $|x^2 g_2| < K$ , where  $K$  varies from 0.07 to 0.10. Thus, large values of  $g_2$  are allowed in the low  $x$  region.

In the past, only  $A_{\parallel}$  has been measured in polarized deep inelastic experiments on the proton. The asymmetry  $A_1$  has been extracted from these measurements by neglecting the contribution of the  $A_2$  term. In this paper we present data on  $A_{\perp}$ , which makes it possible to extract  $A_1$  and  $A_2$  with no approximations [Eqs. (6) and (7)]. The  $A_1$  results have been published in Ref. [14]. In this Letter, we present the results for the asymmetry  $A_2$ , and for the structure function  $g_2$ .

The experiment was carried out at the CERN SPS by scattering 100 GeV longitudinally-polarized muons off transversely-polarized protons. The polarized target and the spectrometer used for these measurements are basically the same as those used to measure longitudinal asymmetries, and have been described in a previous publication [14]. The new SMC target incorporates a sufficiently strong dipole field of 0.5 T [15], in which the proton polarization can be maintained transverse to the beam direction. The two cells of the butanol target, each 60 cm long, were longitudinally polarized along a solenoid field of 2.5 T by dynamic nuclear polarization (DNP). When high polarization was reached, the proton spins were ‘frozen’ at a base temperature of about 60 mK, and rotated to a transverse (vertical) direction by applying the additional dipole field and reducing the longitudinal field to zero. Upwards (downwards) transverse polarization was achieved by choosing the initial longitudinal polarization parallel (antiparallel) to the beam direction. The spins were reversed 10 times during the 17 days of data-taking. The transverse field was always applied in the same direction to avoid different acceptances. As it was not possible to measure the polarization in the transverse spin direction at 0.5 T, it was measured before and after each reversal in the solenoid field at 2.5 T. The loss of polarization was less than 1% over a period of 12 h. The average polarization

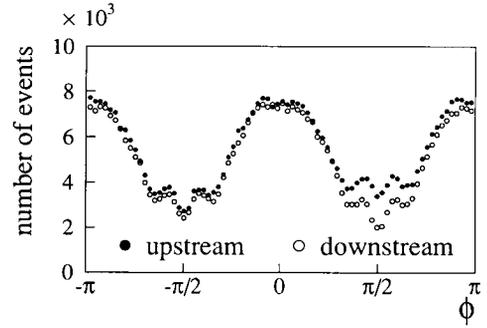


Fig. 1. The event distribution as a function of the azimuthal angle  $\phi$ , for interactions in the upstream and downstream targets. The value  $\phi = 0$  corresponds to a scattered muon with transverse momentum parallel to the target polarization. The observed distribution mainly reflects the trigger acceptance.

was  $P_T = 0.80 \pm 0.04$ .

The deflection of the incoming muons caused by the transverse dipole field was 2.25 mrad, and was compensated by an additional magnet, installed 7 m upstream of the target. The reconstruction software was modified to account for the curvature of the beam tracks in the region between the two sets of scintillator hodoscopes used to determine their direction. Track reconstruction and vertex fitting inside the dipole field were tested by a Monte Carlo simulation, and were found to perform just as well as in the case of the solenoid field used for longitudinal asymmetry measurements.

The incident muons mostly come from pion decay and are naturally polarized in the longitudinal direction. The average beam polarization at 100 GeV was determined from the positron energy spectrum in the decay  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ , and found to be  $P_B = -0.82 \pm 0.06$  [16,17], in good agreement with the Monte Carlo simulation of the beam transport [18].

The events were required to satisfy  $y < 0.9$ ,  $E_{\mu'} > 15 \text{ GeV}$ , and  $\nu > 10 \text{ GeV}$ , in order to avoid large radiative corrections, to eliminate muons originating from the decay of pions produced in the target, and events with poor kinematic resolution. A total of  $8.7 \times 10^5$  events was obtained in the range  $0.006 < x < 0.6$  and  $1 < Q^2 < 30 \text{ GeV}^2$ . The event distribution as a function of the angle  $\phi$  is shown in Fig. 1. Most events are collected in the regions where the angle  $\phi$  is close to zero or  $\pi$  because the trigger conditions predominantly select muons scattered in a direction close to the vertical plane. This optimizes our measurement,

because only muons scattered in a plane close to the polarization plane contribute effectively to the asymmetry.

The asymmetries were obtained separately for each target cell. The raw asymmetry  $A_m$  is measured in bins of  $x$ ,  $Q^2$ , and  $\phi$  from the number of scattered muons ( $N_1, N_2$ ) in the azimuthal directions ( $\phi, \pi - \phi$ ), and the corresponding counts ( $N'_1, N'_2$ ) evaluated after a reversal of the polarization. Assuming that the ratio of the spectrometer acceptances at angles  $\phi$  and  $\pi - \phi$  is the same during the periods before and after polarization reversal, we obtain

$$\sqrt{\frac{N_1 N_2}{N_2 N'_1}} = \frac{1 + A_m(x, Q^2, \phi)}{1 - A_m(x, Q^2, \phi)}. \quad (11)$$

The transverse asymmetry is then

$$A_{\perp}(x, Q^2) = \frac{1}{\cos \phi} \frac{A_m(x, Q^2, \phi)}{P_B |P_T| f}, \quad (12)$$

where  $P_B$  and  $P_T$  are the beam and target polarizations, and  $f$  is the fraction of polarizable protons in the target material ( $f \cong 0.12$ ). The values of  $A_{\perp}$  corresponding to the same  $x$  and  $Q^2$  are averaged over the  $\phi$  intervals, and over the five subsamples defined by the ten polarization reversals.

The asymmetry  $A_2$  is extracted from  $A_{\perp}$  and  $A_{\parallel}$  in  $(x, Q^2)$  bins, using Eqs. (6) and (7). For  $A_{\parallel}$  we use previous measurements on longitudinally polarized targets [19,20,14]. These experiments have published  $A_1$ , extracted through the relation  $A_1 = A_{\parallel}/D$ , where the  $A_2$  contribution is neglected. We parametrize the  $A_1$  data and recover  $A_{\parallel}$  through the same relation.

Since no  $Q^2$  dependence is observed within the errors, we present the average of  $A_2$  in each bin of  $x$  (see Table 1). If the  $\bar{g}_2$  contribution can be neglected in Eq. (1) and  $A_1$  is independent of  $Q^2$ ,  $\sqrt{Q^2} A_2$  is expected to scale. However, if we average  $\sqrt{Q^2} A_2$ , instead of  $A_2$ , we obtain the same results.

The dominant systematic error on  $A_{\perp}$  is the variation of the ratio of acceptances in the upper and lower parts of the spectrometer between polarization reversals. The resulting false asymmetries have been studied using real data and a Monte Carlo simulation, and found to be negligible compared to the statistical error. Radial effects and overall variations in detector efficiencies do not cause false asymmetries because they affect the upper and lower part of the spectrometer in

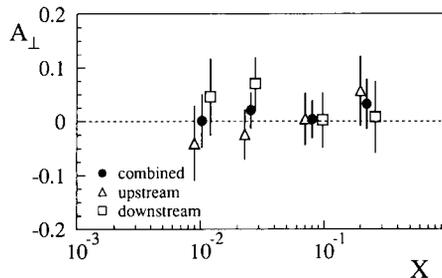


Fig. 2. The transverse cross-section asymmetry  $A_{\perp}$  as a function of  $x$  for interactions in the upstream and downstream targets and for the combined data. The error bars represent the statistical errors.

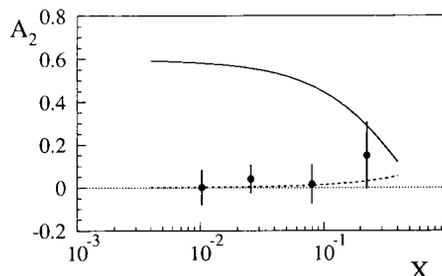


Fig. 3. The asymmetry  $A_2$  as a function of  $x$ . The solid line shows  $\sqrt{R}$  from the SLAC parametrization [12], and the dashed line the results obtained with  $\bar{g}_2 = 0$  in Eq. (1). The error bars represent statistical errors, only.

the same way. The radiative corrections to  $A_{\perp}$  were calculated with the method of Ref. [21] and found to be smaller than 0.001.

The resulting values for  $A_{\perp}$  are shown in Fig. 2, for four intervals of  $x$ . They are consistent for the two parts of the target and are compatible with zero.

The corresponding values of  $A_2$  are presented in Fig. 3 and Table 1. The limit imposed by the positivity condition (Eq. (9)) is also shown in Fig. 3. The present measurements constrain the asymmetry function  $A_2$  to values much smaller than the positivity limit. At 90 % confidence level, we obtain  $A_2 < 0.16$  for  $x < 0.15$ , and  $A_2 < 0.4$  for  $x > 0.15$ . These improved limits have been used in Ref. [14] for the evaluation of  $g_1$ . The expected values of  $A_2$  obtained by considering only the first term of  $g_2$  in Eq. (1) are also shown in Fig. 3, and are in good agreement with the data. They have been calculated from the values of  $g_1$  from Refs. [19,20,14] assuming that  $g_1$  scales with  $F_1$ . Additional sources of systematic errors in  $A_2$  are the parametrization of longitudinal asymmetries,

Table 1

Results on the spin asymmetry  $A_2$  and the structure functions  $g_2$  and  $g_2^{ww}$ , where  $g_2^{ww}$  has been calculated from the results of Ref. [19,20,14]. Only the statistical errors are given.

$x$ interval	$\langle x \rangle$	$\langle Q^2 \text{ (GeV}^2\text{)} \rangle$	$A_2$	$g_2$	$g_2^{ww}$
0.006 – 0.015	0.010	1.4	$0.002 \pm 0.083$	$1.2 \pm 61$	$0.73 \pm 0.10$
0.015 – 0.050	0.026	2.7	$0.041 \pm 0.066$	$7.0 \pm 12$	$0.47 \pm 0.09$
0.050 – 0.150	0.080	5.8	$0.017 \pm 0.091$	$0.2 \pm 2.9$	$0.15 \pm 0.02$
0.150 – 0.600	0.226	11.8	$0.149 \pm 0.156$	$0.5 \pm 0.8$	$-0.10 \pm 0.02$

and the uncertainty in  $R$ . Both effects are smaller than 10 % of the statistical error.

The values obtained for  $g_2$  are listed in Table 1, together with those of  $g_2^{ww}$  (Eq. (2)) evaluated at the same  $x$  and  $Q^2$ . The two sets are compatible within the statistical errors. Therefore the present data do not show evidence for  $\bar{g}_2$  to be different from zero. The limited accuracy of the present data does not allow sensitive tests of specific predictions, such as the partial cancellation between the two terms of  $g_2$  predicted by the bag models of Refs. [3,6]. Large contributions of  $\bar{g}_2$  close to the positivity limit are excluded in the  $x$  range covered. However,  $\bar{g}_2$  about one order of magnitude larger than  $g_2^{ww}$  would still be allowed within the statistical errors.

When the minimum  $Q^2$  requirement is reduced to  $0.5 \text{ GeV}^2$ , the data with  $Q^2 < 1 \text{ GeV}^2$  in the lowest  $x$ -bin yield  $A_2 = 0.05 \pm 0.10$ , which is consistent with the value for  $Q^2 > 1 \text{ GeV}^2$ . If we neglect the  $Q^2$  dependence within the kinematic range of the present data, the results of Table 1 can be used to calculate the limits for the integral of  $g_2$ ,

$$-0.9 < \int_{0.006}^{0.6} g_2 dx < 1.9, \quad (13)$$

at 90 % confidence level. We do not attempt the evaluation of the first moment of  $g_2$ , in order to test the Burkhardt–Cottingham sum rule, because we are not aware of theoretical predictions for the behaviour of  $g_2$  as  $x \rightarrow 0$ .

In summary, we have presented the first measurement of transverse asymmetries in deep inelastic lepton–proton scattering. The virtual-photon asymmetry  $A_2$  is found to be significantly smaller than its positivity limit  $\sqrt{R}$ . This result reduces the uncertainty in the determination of the structure function

$g_1$  from longitudinal polarization measurements. In addition, bounds are obtained for the spin-dependent structure function  $g_2$ , which exclude large twist-3 contributions.

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