Measurement of the spin-dependent structure function $g_1(x)$ of the deuteron

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We report on the first measurement of the spin-dependent structure function $g_1^d$ of the deuteron in the deep inelastic scattering of polarised muons off polarised deuterons, in the kinematical range $0.006 < x < 0.6$, $1 \text{ GeV}^2 < Q^2 < 30 \text{ GeV}^2$. The first moment, $F_1^d = \int_0^1 g_1^d dx = 0.023 \pm 0.020 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$, is smaller than the prediction of the Ellis–Jaffe sum rules. Using earlier measurements of $g_1^p$, we infer the first moment of the spin-dependent neutron structure function $g_1^n$. The difference $F_1^p - F_1^n = 0.20 \pm 0.05 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$ agrees with the prediction of the Bjorken sum rule, $F_1^p - F_1^n = 0.191 \pm 0.002$.

In the past 15 years, two experimental determinations of the spin-dependent structure function $g_1^p(x)$ of the proton were made from measurements of cross section asymmetries in deep inelastic scattering of longitudinally polarised leptons by longitudinally polarised protons. The first was an experiment at SLAC [1] in which polarised electrons with energies between 6 and 21 GeV were used and which covered the kinematic range $0.1 < x < 0.7$, where $x$ is the Bjorken scaling variable. The second was an experiment at CERN [2] in which polarised muons of 100, 120 and 200 GeV energy were used, and which covered the $x$ range $0.01 < x < 0.7$. The result of these experiments disagrees with the prediction of the Ellis–Jaffe sum rule [3] for the proton and indicates that in the quark–parton model, the spins of quarks and antiquarks contribute little to the spin of the proton. In a large number of papers, a variety of theoretical ideas were proposed to explain this unexpected result [4]. Several experiments are presently being carried out or prepared at CERN [5], SLAC [6], and DESY [7] to measure the spin structure function of the neutron.

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13 Supported by Comision Interministerial de Ciencia y Tecnologia.
14 Supported by the Department of Energy.
15 Supported by KBN.
16 Supported by the National Science Foundation of the Netherlands.
17 Supported by Bundesministerium für Forschung und Technologie.
18 Supported by the National Science Foundation.
19 Supported by Monbusho International Science Research Program.
20 Supported by the US–Israel Binational Science Foundation, Jerusalem, Israel.
and to repeat the proton measurement with improved accuracy.

In this paper, we present first results from a measurement of the cross section asymmetry for the deuteron,

\[ A^d = \frac{\sigma^{1-} - \sigma^{1+}}{\sigma^{1+} + \sigma^{1-}}. \]

In this expression, \( \sigma^{1\pm} \) are the cross sections for inclusive deep inelastic scattering of longitudinally polarised muons off longitudinally polarised deuterons, for antiparallel (parallel) orientation of beam and target polarisations. From this asymmetry, we evaluate the spin-dependent structure function \( g_1^d(x) \), which we then use to test the prediction of the Ellis–Jaffe sum rules [3]. In combination with the earlier results from measurements with proton targets, our data allow us to evaluate the first moment of the structure function \( g_1^d(x) \) of the neutron and to test the Bjorken sum rule [8].

The experiment uses a polarised muon beam, a polarised deuteron target, a spectrometer to measure the scattered muon, and a beam polarimeter. The target and the spectrometer are based on the apparatus built by the EMC Collaboration [2,9], but have been upgraded to reduce systematic uncertainties [5,10]. The polarimeter is new and will be described in a forthcoming publication [11].

For this experiment, we have used a beam of positive muons with an average energy of 100 GeV [12], a spill time of 2.4 s and a period of 14.4 s. The beam intensity was \( 4 \times 10^7 \) muons per spill. The incident muon momentum is measured on an event-by-event basis.

The polarised target in the present experiment uses the same cryogenic components as the EMC target [2,13,14]. A superconducting solenoid provides a magnetic field of 2.5 T parallel to the beam direction. A dilution refrigerator cools the target to a temperature of about 500 mK during polarisation, and to 50 mK during frozen spin operation. The target is divided in two halves, each 40 cm long and 5 cm in diameter, separated by 20 cm. The longitudinal polarisations in the two halves are opposite in sign so that data can be recorded for both polarisation directions simultaneously.

The target material is deuterated butanol with an admixture of paramagnetic molecules. Dynamic Nuclear Polarisation (DNP) is obtained by applying microwaves at a frequency close to the resonance of the paramagnetic electrons. The typical deuteron polarisation was about 0.25 until it was discovered that a substantial increase in the polarisation can be obtained by modulating rapidly the microwave frequency over a range of 30 MHz [15]. In this way, deuteron polarisations larger than 0.40 have been routinely obtained. The polarisation is measured using 10 NMR coils embedded in the target material. The integrated NMR absorption signals were calibrated in thermal equilibrium at 1.1 K. This allows us to measure the polarisation to an accuracy of about 0.02.

In order to minimise systematic errors, we reversed the polarisation directions in the two target halves at regular time intervals. For most of our data the spins were reversed every 8 hours by rotating the field direction using the 0.2 T transverse field of a new superconducting dipole coil wound on the microwave cavity. In addition, the relative orientation of the solenoid field and the target polarisation was changed at least once per week with DNP.

In the first stage of the muon spectrometer, charged particles are momentum analysed with a conventional large-aperture dipole magnet and several sets of proportional and drift chambers. Hadrons are absorbed in an iron wall. Downstream of this wall streamer tubes, drift tubes, proportional chambers and scintillator hodoscopes are used for muon identification and triggering.

The beam polarisation is determined from the shape of the energy spectrum of the positrons from the decay \( \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \). Downstream of the muon spectrometer, a 30 m long muon decay path is defined between a shower veto hodoscope which identifies the \( \mu^+ \) and a dipole magnet where the momentum of the \( e^+ \) is measured using multiwire proportional chambers. Identification of the decay positrons is done using the energy deposited in a lead glass calorimeter. Radiative corrections are taken into account. For 100 GeV positive muons, the beam polarisation is found to be \( P_\mu = -0.82 \pm 0.06 \), in good agreement with Monte Carlo simulations of the beam transport [12].

Off-line event reconstruction programs determine the kinematics of the incident and scattered muon and the vertex position. Starting from the scattered muon identified downstream of the absorber wall in
the muon spectrometer, the upstream trajectory is reconstructed up to the interaction point. The average vertex resolution is 3 cm in the direction of the beam and 0.3 mm in the transverse plane. This permits a good identification of the events originating from the upstream and downstream target cells.

A Monte Carlo simulation was developed for our experimental set-up using the GEANT program [16]. The detailed description of the apparatus includes the resolutions and efficiencies of all detectors. The simulation uses the distribution of incident muons recorded during the data taking. The Monte Carlo program has been used to test the event reconstruction, to determine smearing due to finite resolution and to estimate systematic errors.

We report here on data taken in 1992, covering the kinematic range $1 \text{ GeV}^2 < Q^2 < 30 \text{ GeV}^2$ and $0.006 < x < 0.6$. Cuts were applied on kinematic variables in order to minimise smearing effects, to limit the size of radiative corrections, and to reject muons originating from the decay of pions produced in the target. After cuts, the data sample amounts to $3.2 \times 10^6$ events with an average deuteron polarisation $P_T = 0.35$.

The measured event yields from the two target cells can be expressed in terms of the cross section asymmetry $A^d$:

$$N_u = n_u \Phi a_u \sigma_0 (1 - f P_u P_d A^d),$$

$$N_d = n_d \Phi a_d \sigma_0 (1 - f P_u P_d A^d),$$

where the subscripts u and d refer to the upstream and downstream target cells, $n$ is the number of target nucleons, $\Phi$ the beam flux, $a$ the apparatus acceptance, $\sigma_0$ the unpolarised cross section, $f$ the fraction of the event yield from the deuterons in the target material (dilution factor), and $P_u$ and $P_{ud}$ are the beam and target polarisations. The sign of the polarisation of both the target and the incident muon is defined to be positive when parallel to the beam direction. With this definition, $P_u$ is negative for the $\mu^+ \tau$ beam, and $P_d$ and $P_{ud}$ are of opposite sign. Cuts are applied to ensure that the beam flux $\Phi$ is the same for both target cells. The dilution factor is $f \approx 0.19$, and the raw asymmetry $f P_u P_d A^d$ is of order $10^{-3}$.

The longitudinal virtual photon asymmetry $A^d_L$ is related to the muon-deuteron asymmetry $A^d$ by [17]

$$A^d_L = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{A^d}{D} - \eta A^d,$$
Table 1
Results on the virtual photon asymmetry $A_1^d$ and on the spin structure function $g_1^d$ of the deuteron. The first error is statistical, the second one is systematic.

<table>
<thead>
<tr>
<th>$x$ range</th>
<th>$(x)$</th>
<th>$(Q^2)$ (GeV$^2$)</th>
<th>$A_1^d$</th>
<th>$g_1^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.006–0.010</td>
<td>0.009</td>
<td>1.2</td>
<td>$-0.029 \pm 0.071 \pm 0.013$</td>
<td>$-0.554 \pm 1.347 \pm 0.251$</td>
</tr>
<tr>
<td>0.010–0.020</td>
<td>0.015</td>
<td>1.7</td>
<td>$-0.046 \pm 0.046 \pm 0.015$</td>
<td>$-0.490 \pm 0.493 \pm 0.155$</td>
</tr>
<tr>
<td>0.020–0.030</td>
<td>0.025</td>
<td>2.5</td>
<td>$-0.032 \pm 0.059 \pm 0.018$</td>
<td>$-0.198 \pm 0.360 \pm 0.100$</td>
</tr>
<tr>
<td>0.030–0.040</td>
<td>0.035</td>
<td>3.1</td>
<td>$-0.098 \pm 0.073 \pm 0.021$</td>
<td>$-0.417 \pm 0.312 \pm 0.078$</td>
</tr>
<tr>
<td>0.040–0.060</td>
<td>0.050</td>
<td>3.7</td>
<td>$+0.096 \pm 0.067 \pm 0.025$</td>
<td>$+0.283 \pm 0.197 \pm 0.060$</td>
</tr>
<tr>
<td>0.060–0.100</td>
<td>0.079</td>
<td>4.6</td>
<td>$+0.013 \pm 0.070 \pm 0.030$</td>
<td>$+0.023 \pm 0.127 \pm 0.043$</td>
</tr>
<tr>
<td>0.100–0.150</td>
<td>0.123</td>
<td>5.6</td>
<td>$+0.144 \pm 0.095 \pm 0.037$</td>
<td>$+0.162 \pm 0.107 \pm 0.031$</td>
</tr>
<tr>
<td>0.150–0.200</td>
<td>0.173</td>
<td>6.9</td>
<td>$+0.168 \pm 0.143 \pm 0.042$</td>
<td>$+0.128 \pm 0.109 \pm 0.024$</td>
</tr>
<tr>
<td>0.200–0.300</td>
<td>0.241</td>
<td>9.0</td>
<td>$+0.245 \pm 0.154 \pm 0.046$</td>
<td>$+0.122 \pm 0.077 \pm 0.017$</td>
</tr>
<tr>
<td>0.300–0.400</td>
<td>0.343</td>
<td>12.0</td>
<td>$+0.170 \pm 0.286 \pm 0.050$</td>
<td>$+0.047 \pm 0.080 \pm 0.010$</td>
</tr>
<tr>
<td>0.400–0.600</td>
<td>0.470</td>
<td>15.5</td>
<td>$+0.031 \pm 0.456 \pm 0.054$</td>
<td>$+0.004 \pm 0.059 \pm 0.005$</td>
</tr>
</tbody>
</table>

uncertainty, we have carefully analysed the variations of all detector efficiencies between pairs of data sets preceding and following a polarisation reversal. The largest possible contribution to the systematic uncertainty was then estimated by a Monte Carlo simulation using the largest efficiency variations observed within these pairs. In a second method the same variations were artificially imposed on the experimental data. The acceptance changes obtained with both methods are in good agreement and lead to an upper limit $\Delta r/r < 2 \times 10^{-3}$. The systematic error on $A_1^d$ is then given by

$$\Delta A_1^d = \frac{1}{4 f_P P_T D} \frac{\Delta r}{r} . \quad (5)$$

Additional systematic errors arise from the uncertainties on the beam and target polarisations, the dilution factor, the radiative corrections, the momentum measurement, the depolarisation factor $D$, and from a small contamination of protons in the target. The individual systematic errors are combined in quadrature (table 1).

In order to check the consistency of our data, we divided them into different subsets according to a variety of criteria (e.g. data taking periods, radial vertex position, events reconstructed in different parts of the spectrometer). The asymmetries from such subsets were in agreement with each other.

The longitudinal spin structure function $g_1^d(x)$ is obtained from the asymmetry $A_1^d$ by the relation

$$g_1^d(x) = \frac{A_1^d(x) F_2^d(x, Q^2)}{2x \left[ 1 + R(x, Q^2) \right]} . \quad (6)$$

We adopt here the convention that $g_1^d$ and $F_2^d$ are the average structure functions of the nucleon in the deuteron. We have taken $F_2^d(x, Q^2)$ and $R(x, Q^2)$ at the average $Q^2$ of the data, $Q^2 = 4.6$ GeV$^2$. The values of $F_2^d(x, Q^2)$ were taken from the NMC parametrisation [20] and those of $R$ from a global fit of the SLAC data [21]. Uncertainties in $F_2$ and $R$ are included in the systematic error. The results are shown in fig. 2 and are also given in table 1. The data indicate that for $x < 0.04$, $g_1^d$ becomes negative.

The integral of $g_1^d$ over the measured range of $x$ is
The integral \( \int_{x_m}^{1} g_1^d(x) \, dx \) as a function of the lower integration limit \( x_m \). The error bars are statistical only. The open point represents the extrapolation to large \( x \). The sum rule prediction is discussed in the text.

\[
\int_{x_m}^{1} g_1^d(x) \, dx \\
=-0.024 \pm 0.020 \text{ (stat.)} \pm 0.014 \text{ (syst.)}.
\]  

(7)

To estimate the integral in the unmeasured region at small \( x \), we fit the lowest three data points in \( x\) assuming a behaviour \( g_1^d(x) \propto x^{-\alpha} \), with \(-0.5 < \alpha < 0 \) [22]. This contribution amounts to \(-0.003 \pm 0.003\). To estimate the integral at \( x > 0.6 \), we use a parametrisation which is constrained to \( g_1^d(x) = 0 \) at \( x = 1 \). To estimate the uncertainty in this extrapolation, we use the bound \(|A_1| \leq 1\). This contribution amounts to \(0.002 \pm 0.004\). The result for the first moment of \( g_1^d(x) \) is thus (fig. 3)

\[
\Gamma_1^d = \int_{0}^{1} g_1^d(x) \, dx \\
= 0.023 \pm 0.020 \text{ (stat.)} \pm 0.015 \text{ (syst.)}.
\]  

(8)

The systematic errors on \( \Gamma_1^d \) are detailed in table 2.

The sum of the first moments of the spin structure functions \( g_1(x) \) of the proton and the neutron can be computed from the measured \( \Gamma_1^d \) using the relation \( \Gamma_1^p + \Gamma_1^n \simeq 2\Gamma_1^d/(1 - 1.5\omega_D) \), where \( \omega_D \) is the probability of the deuteron to be in a D-state. Using \( \omega_D = 0.058 \) [23], we find \( \Gamma_1^p + \Gamma_1^n = 0.049 \pm 0.044 \) (stat.) \pm 0.032 (syst.). The Ellis–Jaffe sum rules [3] predict \( \Gamma_1^p + \Gamma_1^n = 0.187 \pm 0.010 \) for \( \epsilon = 0.26 \). This is more than 2 standard deviations above the measured value.

The value of \( \Gamma_1^p + \Gamma_1^n \) can be expressed in terms of the SU(3) matrix elements \( a_0 \) and \( a_0 \) of the axial vector currents [2]. Using \( a_8 = (1/\sqrt{3})(3F_D - D) = 0.397 \pm 0.020 \) as derived from hyperon decay [24,2], we obtain

\[
a_0 = 0.05 \pm 0.16 \text{ (stat.)} \pm 0.12 \text{ (syst.)},
\]  

(9)

in agreement with the result from the measurement of \( \Gamma_1^p \): \( a_0 = 0.098 \pm 0.076 \) (stat.) \pm 0.113 (syst.) [2]. Using a more recent analysis of hyperon decay data [25], we obtain a similar result on \( a_0 \). In the quark–parton model, \( a_0 \) is proportional to the sum of the quark spin contributions \( \Sigma \) to the nucleon spin. Our result corresponds to

\[
\Sigma = \Delta u + \Delta d + \Delta s \\
= 0.06 \pm 0.20 \text{ (stat.)} \pm 0.15 \text{ (syst.)}.
\]  

(10)

Combining our result on \( \Gamma_1^d \) with \( \Gamma_1^p = 0.126 \pm 0.010 \) (stat.) \pm 0.015 (syst.) from ref. [2], we can determine the first moment of the neutron spin structure function:

\[
\Gamma_1^n = -0.08 \pm 0.04 \text{ (stat.)} \pm 0.04 \text{ (syst.)},
\]  

(11)

while the Ellis–Jaffe sum rule predicts \( \Gamma_1^n = -0.002 \pm 0.005 \). This allows us to test the sum rule for the difference \( \Gamma_1^p - \Gamma_1^n \) that was originally found by Bjorken.
and later derived as a rigorous QCD prediction [26]:

\[ \Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_A \left( 1 - \frac{\alpha_s(Q^2)}{\pi} \right) = 0.191 \pm 0.002 \]  

at \( Q^2 = 4.6 \text{ GeV}^2 \). From this experiment, we find:

\[ \Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \]  

in agreement with the prediction of the Bjorken sum rule.

In conclusion, we have performed the first measurement of the spin-dependent structure function \( g_1^d \) of the deuteron. The first moment of \( g_1^d(x) \) is smaller than the prediction obtained from the Ellis–Jaffe sum rules and indicates that the contribution of quark spins to the nucleon spin is compatible with zero. This is similar to the observation that the EMC made for the proton. Using the EMC data, we have inferred the integral of the structure function \( g_1^p(x) \) of the neutron. The difference of the first moments of the spin structure functions \( g_1 \) of the proton and the neutron is in good agreement with the prediction of the fundamental Bjorken sum rule.

References


