First Measurement of the Tensor Structure Function $b_1$ of the Deuteron.

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The HERMES experiment has investigated the tensor spin structure of the deuteron using the 27.6 GeV/c positron beam of HERA. The use of a tensor polarized deuteron gas target with only a negligible residual vector polarization enabled the first measurement of the tensor asymmetry $A_{1,2}^t$ and the tensor structure function $b_1^d$ for average values of the Bjorken variable $0.01 < \langle x \rangle < 0.45$ and of the negative of the squared four-momentum transfer $0.5 \text{ GeV}^2 < \langle Q^2 \rangle < 5 \text{ GeV}^2$. The quantities $A_{1,2}^t$ and $b_1^d$ are found to be non-zero. The rise of $b_1^d$ for decreasing values of $x$ can be interpreted to originate from the same mechanism that leads to nuclear shadowing in unpolarized scattering.

Inclusive deep-inelastic scattering (DIS) of charged leptons from the deuteron, a spin-1 object, is described by eight structure functions, twice as many as required to describe DIS from a spin-1/2 nucleon. The three leading-twist structure functions relevant to this discussion can be written within the Quark-Parton Model as:

$$F_1 = \frac{1}{2} \sum_q e_q^2 [q_T^+ + q_T^-]$$
$$g_1 = \frac{1}{2} \sum_q e_q^2 [q_T^+ - q_T^-]$$
$$b_1 = \frac{1}{2} \sum_q e_q^2 [2q_T^+ - q_T^+ - q_T^-]$$

where $q_T^m(q_T^m)$ is the number density of quarks with spin up(down) along the $z$ axis in a hadron(nucleus) with helicity $m$ moving with infinite momentum along the $z$ axis. Reflection symmetry implies that $q_T^m = q_T^{-m}$. The sums run over quark and antiquark flavors $q$ with a charge $e_q$ in units of the elementary charge $e$. Both structure functions and quark number densities depend on the Bjorken variable $x$ which can be interpreted as the fraction of the nucleon momentum carried by the struck quark in the infinite-momentum frame, and $-Q^2$, the square of the four-momentum transfer by the virtual photon.

The polarization-averaged structure function $F_1$ describes the quark distributions averaged over the target spin states. The polarization-dependent structure function $g_1$ describes the imbalance in the distribution of quarks with the same $q_T^m$ or opposite $q_T^m$ helicity with respect to that of the parent hadron. It can be measured only when both beam and target are polarized. The tensor structure function $b_1$ does not exist for spin-1/2 targets and vanishes in the absence of nuclear effects, i.e., if the deuteron simply consists of a proton and neutron in a relative $S$-state. It describes the difference in the quark distributions between the helicity-0, $q_0 = (q_0^+ + q_0^-)/2q_T$, and the averaged non-zero helicity $q_1 = (q_1^+ + q_1^-)/2q_T$, states of the deuteron. The measurement does not require a polarized beam. Since the magnitude of $b_1^d$ was expected to be small, it was usually ignored in the extraction of $g_1^d$ and, as a consequence, of the neutron structure function $g_1^n$ derived from deuteron and proton data. This is in general not a priori justified. This paper reports the first measurement of $b_1^d$ performed by the HERMES collaboration using a data set taken with a positron beam and a tensor-polarized deuteron target, and an integrated luminosity of 42 pb$^{-1}$.

The HERMES experiment was designed to investigate the internal spin structure of nucleons and nuclei by deep-inelastic scattering of polarized positrons and electrons by polarized gaseous targets (e.g., hydrogen, deuterium and helium-3) internal to the HERA-$e^-$ storage ring. The positrons (electrons) circulating in the ring become transversely polarized by the emission of spin-flip synchrotron radiation. A longitudinal beam polarization is generated at HERMES by the use of a pair of spin rotators before and after the experiment. Beam polarization is employed for the simultaneous $g_1^d$ measurement and for studies on beam related systematic effects on $b_1^d$.

A feature of HERMES unique among polarized DIS experiments is its atomic-gas target that is not diluted by non-polarizable material. The target cell is an opened elliptical aluminum tube internal to the beam line (40 cm long, 75 µm in wall thickness), which is used to confine the polarized gas along the beam. A magnetic field surrounding the target and aligned with the beam provides the quantization axis for the nuclear spin. A sample of gas was continuously drawn from the cell and analyzed to determine the atomic and molecular abundances and the nuclear polarization of the atoms. An atomic beam source (ABS) generates a deuteron atomic beam and selects the two hyperfine states with the desired nuclear polarization to be injected into the cell. This system allows the selection of substates with pure tensor polarization $P_{z_+} = (n^+ + n^- - 2n^0)/(n^+ + n^- + n^0)$ and at the same time vanishing vector polarization $P_z = (n^+ - n^-)/(n^+ + n^- + n^0)$, a combination which is not possible for solid-state polarized targets. Here $n^+$, $n^-$, $n^0$ are the atomic populations with positive, negative and
zero spin projection on the beam direction, respectively. Every 90 seconds the polarization of the injected gas is changed; for the $l_1^b$ measurement the four injection modes listed in Table 1 were continuously cycled. Note that the vector+ and vector− modes are also employed for the $g_1^d$ measurement.

The HERMES detector [2] is a forward spectrometer with a dipole magnet providing a field integral of 1.3 Tm. A horizontal iron plate shields the HERA beam lines from this field, thus dividing the spectrometer into two identical halves with ±170 mm horizontal and ±40 to ±140 mm vertical acceptance for the polar scattering angle. Tracking is based on 36 drift chamber planes in each detector-half. Positron identification is accomplished using a likelihood method based on signals of four subsystems: a ring-imaging Cerenkov detector, a lead-glass calorimeter, a transition-radiation detector, and a preshower hodoscope. For positrons in the momentum range of 2.5 GeV/c to 27 GeV/c, the identification efficiency exceeds 98% and the hadron contamination is less than 0.5%. The average polar angle resolution is 0.6 mm and the average momentum resolution is 2%.

For a target state characterized by $P_z$ and $P_{zz}$, the DIS yield measured by the experiment is proportional to the double differential cross section of polarized DIS

$$
\frac{d^2\sigma_{P}}{dxdQ^2} \approx \frac{d^2\sigma}{dxdQ^2}
\left[1 - P_z P_B D A_1^d + \frac{1}{2} P_{zz} A_2^d\right].
$$

Here, $\sigma$ is the unpolarized cross section, $A_1^d$ is the vector and $A_2^d$ the tensor asymmetry of the virtual-photon deuteron cross section, $P_B$ is the beam polarization and $D$ is the fraction of the beam polarization transferred to the virtual photon. In Eq. 1 and in the following Eq. 4, the fractional correction ($\lesssim 0.01$) arising from the interference between longitudinal and transverse photo-absorption amplitudes, which leads to the structure function $g_2$ [7], is neglected. Four independent polarized yields were measured (see Table 1 for the values of the achieved polarizations): $\sigma^{\parallel}$ and $\sigma^{\perp}$ when the target spin is parallel and anti-parallel to that of the beam, respectively, $\sigma^{\theta}$ when the target has a mixture of helicity-1 states, and $\sigma^{\phi}$ when the target is in the helicity-0 state. The tensor asymmetry is extracted as

$$
A_2^d = \frac{2\sigma^{\parallel} - 2\sigma^{\perp}}{3\sigma^{\theta} P_{zz}},
$$

where $\sigma^{\parallel} = (\sigma^{\parallel} + \sigma^{\perp} + \sigma^{\theta})/3$ is the average over the helicity-1 states, $\sigma^{\theta} = (2\sigma^{\parallel} + \sigma^{\theta})/3$ is the polarization-averaged yield and $P_{zz}^{\text{eff}} = (P_z^2 + P_{zz}^2 + P_{zz}^2 - 3P_z^2)/9$ is the effective tensor polarization. In Eq. 4 the vector component due to $A_1^d$ nearly cancels out: a residual vector polarization not more than 0.02 is achieved both for the $\sigma^{\parallel}$, $\sigma^{\theta}$ and the averaged $(\sigma^{\parallel} + \sigma^{\perp})/2$ measurements, (see Table 1). Note that any contribution from residual vector polarization of the target is reduced to a negligible level by grouping together two sets of data with approximately the same statistics and opposite beam helicities.

The polarization-dependent structure function $g_1^d$ can be extracted from the vector asymmetry $A_1^d$ as

$$
\frac{g_1^d}{Q_1} \approx A_1^d \approx \frac{c_{zz}}{P_B D} \frac{(\sigma^{\parallel} - \sigma^{\perp})}{(\sigma^{\parallel} + \sigma^{\perp})},
$$

with $c_{zz} = (\sigma^{\parallel} + \sigma^{\perp})/2\sigma^{\theta}$.

(3)

In all previous determinations of $g_1^d$ the contribution of the tensor asymmetry $A_2^d$ was neglected, i.e. $c_{zz}$ was assumed to be equal to 1, in spite of the fact that the vector polarization of the target could only be generated together with a non-zero tensor polarization. The present measurement quantifies the effect of $A_2^d$ on the existing $g_1^d$ data.

For the determination of $A_2^d$, about 3.2 million inclusive events obtained with a tensor-polarized deuteron target are selected, by requiring in the HERMES $g_1^d$ analysis [8] a scattered positron with $0.1 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2$ and an invariant mass of the virtual-photon nucleon system $W > 1.8 \text{ GeV}$. The kinematic range covered by the selected data is $0.002 < x < 0.85$ and $0.1 < y < 0.91$, where $y$ is the fraction of the beam energy carried by the virtual photon in the target rest frame. The asymmetry $A_2^d$ is calculated according to Eq. 4. The number of events determined per spin state is corrected for the $e^+ e^-$ background arising from charge symmetric processes (the latter is negligible at high $x$ but amounts to almost 15% of the statistics in the lowest-$x$ bin) and normalized to the luminosity measured by Bhabha scattering from the target gas electrons [9].

The asymmetry $A_2^d$ is corrected for detector smearing and QED radiative effects to obtain the Born asymmetry corresponding to pure single-photon exchange in the scattering process. The kinematic measurement of the events

<table>
<thead>
<tr>
<th>Target state</th>
<th>Hyper. state</th>
<th>Atomic term</th>
<th>Nuclear term</th>
<th>Vector term</th>
<th>Measure term</th>
<th>Pzz, Pz</th>
<th>Pzz, Pb yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>vector+</td>
<td>[1, 2]</td>
<td>$n^+$</td>
<td>+0.80 ± 0.03</td>
<td>+0.45 ± 0.02</td>
<td>$\sigma^{\parallel}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vector-</td>
<td>[3, 4]</td>
<td>$n^-$</td>
<td>+0.85 ± 0.03</td>
<td>-0.45 ± 0.02</td>
<td>$\sigma^{\perp}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tensor+</td>
<td>[3, 6]</td>
<td>$n^+ n^-$</td>
<td>+0.89 ± 0.03</td>
<td>0.00 ± 0.01</td>
<td>$\sigma^{\theta}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tensor-</td>
<td>[2, 6]</td>
<td>$n^+$</td>
<td>-1.63 ± 0.05</td>
<td>0.00 ± 0.01</td>
<td>$\sigma^{\phi}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
due to radiative and detector smearing is treated using an unfolding algorithm, which is only sensitive to the detector model, the known unpolarized cross section, and the models for the background processes. The radiative background is negligible at high $x$ but increases as $x \to 0$ and reaches almost 50% of the statistics in the lowest-$x$ bin. The radiative corrections are calculated using a Monte Carlo generator based on RADGEN. The coherent and quasi-elastic radiative tails are estimated using parameterizations of the deuteron form factors and corrected for the tracking inefficiency due to showering of the radiated photons. The polarized part of the quasi-elastic radiative tail is neglected since there is no net tensor effect by inclusive scattering on weakly-bound spin-$1/2$ objects. The extracted tensor asymmetry $A_{12}^T$ is shown in Fig. 1 and listed in Table II.

It appears to be positive at high $x$ and is negative at low $x$, crossing zero at an $x$ value of about 0.2. In the lowest-$x$ bin, the asymmetry is zero at the 2-$\sigma$ level only after the subtraction of the radiative background. The magnitude of the observed tensor asymmetry $A_{12}^T$ does not exceed 0.02 over the measured range; from this result and using Eqs. 2 and 3, the fractional correction to the HERMES $g_1^p$ measurement due to the tensor asymmetry is estimated to be less than 0.01.

The particle identification efficiency and the target polarization measurement give negligible contributions to the systematic uncertainty. The normalization uncertainty between different injection modes of the ABS is $\approx 1 \times 10^{-3}$ and correlated over the kinematic bins. This uncertainty is estimated by the observed 2-$\sigma$ offset from zero of the asymmetry between averaged vector, $2\sigma = \sigma^+ + \sigma^-$, and tensor, $\sigma^T$ replaced by $\sigma^3$ in Eq. 4, non-zero helicity injection modes. The luminosity measurement is sensitive to possible residual polarization of the target gas electrons. The asymmetries obtained by normalizing the yields to the luminosity-monitor rates, or to the beam-current times the target-gas analyzer rates, are in good agreement within the quoted normalization uncertainty. The subtraction of the radiative background inflates the size of the statistical and the above mentioned systematic uncertainties by almost a factor of 2 at low $x$. The systematic uncertainty of the radiative corrections is $\approx 2 \times 10^{-3}$ for the three bins at low $x$ and negligible at high $x$. A possible misalignment in the spectrometer geometry yields an uncertainty $\approx 3 \times 10^{-3}$ in the bins where the asymmetry changes sign. All the contributions to the systematic uncertainty are added in quadrature. The two subsamples of data with opposite beam helicities were analyzed independently and gave consistent $A_{12}^T$ results.

The tensor structure function $b_1^T$ is extracted from the tensor asymmetry using the relations

$$b_1^T = \frac{3}{2} A_{12}^T F_1^T ; \quad F_1^T = \frac{(1 + Q^2/\nu^2) F_2^T}{2x(1 + R)} \quad (5)$$

No contribution from the hitherto unmeasured double spin-flip structure function $A_{21}^T$ is considered here, being kinematically suppressed for a longitudinally polarized target. The structure function $F_2^T$ is calculated as $F_2^T = F_2^p (1 + F_2^p/F_2^n)/2$ using the parameterizations of the precisely measured structure function $F_2^p$ and $F_2^p/F_2^n$ ratio $[7]$. In Eq. 3, $R = \sigma_T/\sigma_T$ is the ratio of longitudinal to transverse photo-absorption cross sections [13] and $\nu$ is the virtual-photon energy. The results for $b_1^T$ are listed together with those for $A_{12}^T$ in Table II.

The $x$-dependence of $b_1^T$ is displayed in Fig. 4. The data show that $b_1^T$ is different from zero for $x < 0.1$, its magnitude rises for decreasing values of $x$, and for $x < 0.03$, becomes even larger than that of $g_1^p$ even at the same value of $Q^2$.

Because the deuteron is a weakly-bound state of spin-$1/2$ nucleons, $b_1^T$ was initially predicted to be negligible, at least at moderate and large values of $x$ ($x > 0.2$) [8, 19, 20], where it should be driven by nuclear binding and Fermi motion effects. It was later realized that $b_1^T$ could rise to values which significantly differ from zero as $x \to 0$, and its magnitude could reach about 1% of the unpolarized structure function $F_1^T$, due to the same mechanism that leads to the well known effect of nuclear shadowing in unpolarized scattering [3].

![Figure 1](image-url)

**TABLE II:** Measured values (in $10^{-2}$ units) of the tensor asymmetry $A_{12}^T$ and the tensor structure function $b_1^T$. Both the corresponding statistical and systematic uncertainties are listed as well.

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$</th>
<th>$A_{12}^T$</th>
<th>$b_1^T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[GeV$^{-2}$]</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>0.012</td>
<td>0.51</td>
<td>-1.06</td>
<td>0.52</td>
</tr>
<tr>
<td>0.032</td>
<td>1.06</td>
<td>-1.07</td>
<td>0.49</td>
</tr>
<tr>
<td>0.063</td>
<td>1.65</td>
<td>-1.32</td>
<td>0.38</td>
</tr>
<tr>
<td>0.128</td>
<td>2.33</td>
<td>-0.19</td>
<td>0.34</td>
</tr>
<tr>
<td>0.248</td>
<td>3.11</td>
<td>-0.39</td>
<td>0.30</td>
</tr>
<tr>
<td>0.452</td>
<td>4.00</td>
<td>-1.57</td>
<td>0.68</td>
</tr>
</tbody>
</table>
This feature is described by coherent double-scattering models. The observed $\mu_1^2$ confirms qualitatively the double-scattering model predictions, except for the negative value at $x = 0.25$, which, however, is still compatible with zero at the 2-sigma level. In the context of the Quark-Parton Model description, the sum rule $\int b_1(x) dx = 0$ is broken if the quark sea istensor polarized. From the $x$-behavior of $x b_1(x)$ shown in Fig. 4, it can be seen that the first moment of $b_1^0$ is non-zero. A 2-sigma result, $\int_{0.15}^{0.85} b_1(x) dx = (1.05 \pm 0.34 \text{ stat} \pm 0.35 \text{ syst}) \cdot 10^{-2}$, is obtained within the measured range, and a 1.7-sigma result, $\int_{0.17}^{0.85} b_1(x) dx = (0.35 \pm 0.10 \text{ stat} \pm 0.18 \text{ syst}) \cdot 10^{-2}$, within the restricted $x$-range where $Q^2 > 1 \text{ GeV}^2$. The integrals are calculated after having $b_1^0$ evolved to $Q^2 = 5 \text{ GeV}^2$ by assuming a $Q^2$-dependence of the measured $b_1^0 / F_1^N$ ratio, $b_1^0(Q^2) = b_1^0 / F_1^N \cdot F_1^N(Q^2)$.

In conclusion, HERMES has provided the first measurement of the tensor structure function $b_1^2$, in the kinematic domain $0.01 < x < 0.45$ and $0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$. The function $b_1^2$ is found to be different from zero for $x < 0.1$. Its first moment is found to be not zero at the 2-sigma level within the measured $x$ range. The $b_1^2$ measurement can be used to reduce the systematic uncertainty on the $g_1^D$ measurement that is assigned to the tensor structure of the deuteron. The behavior of $b_1^2$ at low values of $x$ is in qualitative agreement with expectations based on coherent double-scattering models.

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