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 $A_{zz}^d$ and the tensor structure function $b_1^d$ for average values of the Bjørken variable $0.01 < x < 0.45$ and of the negative of the squared four-momentum transfer $0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$. The quantities $A_{zz}^d$ 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.

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zero spin projection on the beam direction, respectively. Every 90 seconds the polarization of the injected gas is changed; for the \( b^d \) measurement the four injection modes listed in Table I were continuously cycled. Note that the vector+ and vector− modes are also employed for the \( g^d \) measurement.

The HERMES detector \( [4] \) 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 \( ±170 \) mrad horizontal and \( ±40 \) to \( ±140 \) mrad 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 Čerenkov detector, a leadglass 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 mrad 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

\[
\frac{d^2\sigma}{dx dQ^2} \approx \frac{d^2\sigma}{dx dQ^2} \left[ 1 - P_z P_B D A^d + \frac{1}{2} P_{zz} A^d \right].
\]

Here, \( \sigma \) is the unpolarized cross section, \( A^d \) is the vector and \( A^d_z \) 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. I and in the following Eq. II, the fractional correction (\( \lesssim 0.01 \)) arising from the interference between longitudinal and transverse photo-absorption amplitudes, which leads to the structure function \( g^d \), is neglected. Four independent polarized yields were measured (see Table II for the \( \sigma^zz \) and \( \sigma^zz \) when the target spin is parallel and anti-parallel to that of the beam, respectively, \( \sigma^\alpha \) when the target has a mixture of helicity-1 states, and \( \sigma^0 \) when the target is in the helicity-0 state.

The tensor asymmetry is extracted as

\[
A^d_z = \frac{2\sigma^1 - 2\sigma^0}{3\sigma U P_{zz}},
\]

where \( \sigma^1 = (\sigma^zz + \sigma^\alpha + \sigma^\alpha) / 3 \) is the average over the helicity-1 states, \( \sigma U = (2\sigma^1 + \sigma^0) / 3 \) is the polarization-averaged yield and \( \sigma^zz = (P_{zz}^2 + P_{zz}^2 + P_{zz}^2 - 3P_{zz}^0) / 9 \) is the effective tensor polarization. In Eq. II, the vector component due to \( A^d_z \) nearly cancels out: a residual vector polarization not more than 0.02 is achieved both for the \( \sigma^0 \), \( \sigma^\alpha \) and the averaged (\( \sigma^zz + \sigma^zz \)) / 2 measurements, (see Table I). 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 \( g^d \) can be extracted from the vector asymmetry \( A^d_z \) as

\[
\frac{g^d}{F^d} \approx A^d_z \approx \frac{c_{zz} (\sigma^zz - \sigma^zz)}{|P_z P_B| D (\sigma^zz + \sigma^zz)},
\]

with \( c_{zz} = (\sigma^zz + \sigma^zz) / 2\sigma U \).

In all previous determinations of \( g^d \) the contribution of the tensor asymmetry \( A^d_z \) 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 \( A^d_z \) on the existing \( g^d \) data.

For the determination of \( A^d_z \), about 3.2 million inclusive events obtained with a tensor-polarized deuteron target are selected, by requiring as in the HERMES \( g^d \) analysis \( S \) a scattered positron with 0.1 GeV < \( Q^2 \) < 20 GeV\(^2\) and an invariant mass of the virtual-photon nucleon system \( W > 1.8 \) 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 \( A^d_z \) is calculated according to Eq. II. 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 \( [1] \).

The asymmetry \( A^d_z \) 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 migration of the events

| Target state | Hyper. state | Atomic popul. | Tensor term | Vector term | Meas. yield |
|-------------|-------------|---------------|-------------|-------------|------------|
| vector+     | 1 + [6]     | \( n^+ \)     | 0.80 ± 0.03 | +0.45 ± 0.02 | \( \sigma^\alpha \) |
| vector−     | 3 + [4]     | \( n^- \)     | 0.85 ± 0.03 | −0.45 ± 0.02 | \( \sigma^\alpha \) |
| tensor+     | 3 + [6]     | \( n^+ + n^- \)| 0.80 ± 0.03 | 0.00 ± 0.01 | \( \sigma^\alpha \) |
| tensor−     | 2 + [5]     | \( n^0 \)     | −1.65 ± 0.05| 0.00 ± 0.01 | \( \sigma^0 \) |
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 \[16\]. 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 \[9\]. The coherent and quasi-elastic radiative tails are estimated using parameterizations of the deuteron form factors \[11\] and \[12\], and corrected for the tracking inefficiency and Fermi motion effects. It was later realized that the same mechanism that leads to the well known effect of nuclear shadowing in unpolarized scattering \[21\].

No contribution from the hitherto unmeasured double spin-flip structure function \(\Delta\) \[14\] is considered here, being kinematically suppressed for a longitudinally polarized target \[17\]. The structure function \(F^d_2\) is calculated as \(F^d_2 = F^d_2(1 + F^d_2/F^p_2)/2\) using the parameterizations of the precisely measured structure function \(F^p_2\) \[10\] and \(F^p_2/F^p_2\) ratio \[17\]. In Eq. \(a\), \(R = \sigma_L/\sigma_T\) is the ratio of longitudinal to transverse photo-absorption cross sections \[18\] and \(\nu\) is the virtual-photon energy. The results for \(b^d_1\) are listed together with those for \(A^d_{zz}\) in Table II.

The particle identification efficiency and the target polarization measurement give negligible contributions to the systematic uncertainty. The normalization uncertainty of the radiative corrections 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\(\sigma^\parallel = \sigma^\parallel + \sigma^\perp\), and tensor\(^{\ast}\), \(\sigma^\ast\) replaced by \(\sigma^{\ast\ast}\) in Eq. \(2\), 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 \(A^d_{zz}\) results.

The tensor structure function \(b^d_1\) is extracted from the tensor asymmetry using the relations \[18\] \[27\]

\[
 b^d_1 = -\frac{3}{2} A^d_{zz} R^d_1; \quad R^d_1 = \frac{(1 + Q^2/\nu^2) F^d_2}{2x(1 + R)}.
\] 

No contribution from the hitherto unmeasured double spin-flip structure function \(\Delta\) \[14\] is considered here, being kinematically suppressed for a longitudinally polarized target \[17\]. The structure function \(F^d_2\) is calculated as \(F^d_2 = F^d_2(1 + F^d_2/F^p_2)/2\) using the parameterizations of the precisely measured structure function \(F^p_2\) \[10\] and \(F^p_2/F^p_2\) ratio \[17\]. In Eq. \(a\), \(R = \sigma_L/\sigma_T\) is the ratio of longitudinal to transverse photo-absorption cross sections \[18\] and \(\nu\) is the virtual-photon energy. The results for \(b^d_1\) are listed together with those for \(A^d_{zz}\) in Table II.

The \(x\)-dependence of \(b^d_1\) is displayed in Fig. 2. The data show that \(b^d_1\) is different from zero for \(x < 0.1\), its magnitude rises for decreasing values of \(x\) and, for \(x \gtrsim 0.03\), becomes even larger than that of \(g^d_1\) at the same value of \(Q^2\).

Because the deuteron is a weakly-bound state of spin-1/2 nucleons, \(b^d_1\) was initially predicted to be negligible, at least at moderate and large values of \(x\) (\(x > 0.2\)) \[14\] \[20\], where it should be driven by nuclear binding and Fermi motion effects. It was later realized that \(b^d_1\) 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 \(F^d_1\), due to the same mechanism that leads to the well known effect of nuclear shadowing in unpolarized scattering \[21\].

![FIG. 1: The tensor asymmetry \(A^d_{zz}(x)\). The error bars are statistical and the shaded band shows the systematic uncertainty.](image)

| \(x\) | \(Q^2\) | \(A^d_{zz} \pm \delta A^d_{zz}\text{stat} \pm \delta A^d_{zz}\text{sys}\) | \(b^d_1 \pm \delta b^d_1\text{stat} \pm \delta b^d_1\text{sys}\) |
|-------|---------|---------------------------------|---------------------------------|
| \(\text{GeV}^2\) | \(10^{-2}\) | \(10^{-2}\) | \(10^{-2}\) | \(10^{-2}\) |
| 0.012 | 0.51 | -1.06 | 0.52 | 0.26 | 11.20 | 5.51 | 2.77 |
| 0.032 | 1.06 | -1.07 | 0.49 | 0.36 | 5.50 | 2.53 | 1.84 |
| 0.063 | 1.65 | -1.32 | 0.38 | 0.21 | 3.82 | 1.11 | 0.60 |
| 0.128 | 2.33 | -0.19 | 0.34 | 0.29 | 0.29 | 0.53 | 0.44 |
| 0.248 | 3.11 | -0.39 | 0.39 | 0.32 | 0.29 | 0.28 | 0.24 |
| 0.452 | 4.69 | 1.57 | 0.68 | 0.13 | -0.38 | 0.16 | 0.03 |
FIG. 2: The tensor structure function presented as (top) $b_1^d(x)$ and (middle) $xb_1^d(x)$. The error bars are statistical and the shaded bands show the systematic uncertainty. The bottom panel shows the average value of $Q^2$ in each $x$-bin.

This feature is described by coherent double-scattering models \cite{22, 23, 24, 25, 26, 27, 28, 29, 30}. The observed $b_1^d$ confirms qualitatively the double-scattering model predictions, except for the negative value at $(x) = 0.452$, 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 is tensor polarized \cite{29, 30}. From the $x$-behavior of $xb_1^d$ shown in Fig. 2, it can be seen that the first moment of $b_1^d$ is non-zero. A $2$-sigma result, $\int_{0.002}^{0.85} b_1(x)dx = (1.05 \pm 0.34 \text{ stat} \pm 0.35 \text{ sys}) \cdot 10^{-2}$, is obtained within the measured range, and a $1.7$-sigma result, $\int_{0.02}^{0.85} b_1(x)dx = (0.35 \pm 0.10 \text{ stat} \pm 0.18 \text{ sys}) \cdot 10^{-2}$, within the restricted $x$-range where $Q^2 > 1 \text{ GeV}^2$. The integrals are calculated after having $b_1^d$ evolved to $Q_0^2 = 5 \text{ GeV}^2$ by assuming a $Q^2$-independence of the measured $b_1^d/F_1^d$ ratio, $b_1^d(Q_0^2) = b_1^d/F_1^d \cdot F_1^d(Q_0^2)$.

In conclusion, HERMES has provided the first measurement of the tensor structure function $b_1^d$, in the kinematic domain $0.01 < \langle x \rangle < 0.45$ and $0.5 \text{ GeV}^2 < \langle Q^2 \rangle < 5 \text{ GeV}^2$. The function $b_1^d$ 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 $b_1^d$ 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 $b_1^d$ at low values of $x$ is in qualitative agreement with expectations based on coherent double-scattering models.

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\begin{thebibliography}{99}
\bibitem{1} P. Hoodbhoy \textit{et al.}, Nucl. Phys. B \textbf{312}, 571 (1989).
\bibitem{2} A. Pais, Phys. Rev. Lett. \textbf{19}, 544 (1967).
\bibitem{3} L. L. Frankfurt \textit{et al.}, Nucl. Phys. A \textbf{405}, 557 (1983).
\bibitem{4} HERMES Coll., K. Ackerstaff \textit{et al.}, Nucl. Instr. Meth. A \textbf{417}, 230 (1998).
\bibitem{5} A. Sokolov and L. Ternov, Sov. Phys. Doklady \textbf{8}, 1203 (1964).
\bibitem{6} HERMES Coll., A. Airapetian \textit{et al.}, Nucl. Instr. Meth. A \textbf{540}, 68 (2005).
\bibitem{7} E155 Coll., P. L. Anthony \textit{et al.}, Phys. Lett. B \textbf{553}, 18 (2003).
\bibitem{8} HERMES Coll., g1 paper, in preparation. C. Riedl, in \textit{Proc. of 16th International Spin Physics Symposium}, Trieste 2004, hep-ex/0411087.
\bibitem{9} I. V. Akushevich \textit{et al.}, hep-ph/9906408.
\bibitem{10} HERMES Coll., A. Airapetian \textit{et al.}, Phys. Rev. D \textbf{71}, 012003 (2005).
\bibitem{11} D. Abbott \textit{et al.}, Eur. Phys. J. A \textbf{7}, 421 (2000).
\bibitem{12} S. Stein \textit{et al.}, Phys. Rev. \textbf{12}, 1884 (1975).
\bibitem{13} Z.-L. Zhou \textit{et al.}, Phys. Rev. Lett. \textbf{82}, 687 (1999).
\bibitem{14} R. L. Jaffe \textit{et al.}, Phys. Rev. B \textbf{223}, 218 (1980).
\bibitem{15} E. Sather \textit{et al.}, Phys. Rev. D \textbf{42}, 1424 (1990).
\bibitem{16} H. Abramowicz \textit{et al.}, hep-ph/9712415.
\bibitem{17} NMC, P. Amaudruz \textit{et al.}, Nucl. Phys. B \textbf{371}, 3 (1992).
\bibitem{18} L. W. Whitlow \textit{et al.}, Phys. Lett. B \textbf{206}, 364 (1988).
\bibitem{19} G. A. Miller, in \textit{Electronuclear Physics with Internal Targets}, ed. R. G. Arnold (World Scientific, Singapore, 1989), p.30.
\bibitem{20} H. Khan \textit{et al.}, Phys. Lett. B \textbf{298}, 181 (1993).
\bibitem{21} M. Strikman, in \textit{Proceedings of the Symposium on Spin Structure of the Nucleon}, ed. V. H. Hughes and C. Cavata (World Scientific, Singapore, 1995), p.153.
\bibitem{22} N. N. Nikolaev \textit{et al.}, Phys. Lett. B \textbf{398}, 245 (1997).
\bibitem{23} J. Edelmann \textit{et al.}, Z. Phys. A \textbf{357}, 129 (1997).
\bibitem{24} J. Edelmann \textit{et al.}, Phys. Rev. C \textbf{57}, 3392 (1998).
\bibitem{25} K. Bora \textit{et al.}, Phys. Rev. D \textbf{57}, 6906 (1998).
\bibitem{26} F. E. Close \textit{et al.}, Phys. Rev. D \textbf{42}, 2377 (1990).
\bibitem{27} A. V. Efremov \textit{et al.}, Sov. J. Nucl. Phys. \textbf{36}, 557 (1982).
\end{thebibliography}