Measurement of $T_{20}$ in Elastic Electron-Deuteron Scattering

M. Bouwhuis,1 R. Alarcon,2 T. Botto,1 J. F. J. van den Brand,1,3 H. J. Bulten,3 S. Dolfini,2 R. Ent,5,6 M. Ferro-Luzzi,1 D. W. Higinbotham,8 C. W. de Jager,1,5,8 J. Lang,7 D. J. J. de Lange,1 N. Papadakis,1 I. Passchier,1 H. R. Poolman,1 E. Six,2 J. J. M. Steijger,1 N. Vodinas,1 H. de Vries,1 Z.-L. Zhou4

1 Nationaal Instituut voor Kernfysica en Hoge-Energie Fysica, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands
2 Department of Physics, Arizona State University, Tempe, AZ 85287, USA
3 Department of Physics and Astronomy, Vrije Universiteit, 1081 HV Amsterdam, The Netherlands
4 Department of Physics, University of Wisconsin, Madison, WI 53706, USA
5 Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
6 Department of Physics, Hampton University, Hampton, VA 23668, USA
7 Institut für Teilchenphysik, Eidgenössische Technische Hochschule, CH-8093 Zürich, Switzerland
8 Department of Physics, University of Virginia, Charlottesville, VA 22901, USA

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We report on a measurement of the tensor analyzing power $T_{20}$ in elastic electron-deuteron scattering in the range of four-momentum transfer from 1.8 to 3.2 fm$^{-1}$. Electrons of 704 MeV were scattered from a polarized deuterium internal target. The tensor polarization of the deuteron nuclei was determined with an ion-extraction system, allowing an absolute measurement of $T_{20}$. The data are described well by a non-relativistic calculation that includes the effects of meson-exchange currents.

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The deuteron, as the simplest nucleus, serves as a sensitive testing ground for a variety of nuclear models (non-relativistic \(2\), fully covariant \(3\)). The charge and current distributions inside the nucleus can be probed with elastic electron scattering at intermediate energies. Elastic electron scattering off the spin-1 deuteron is completely described in terms of three electro-magnetic form factors: the charge monopole $G_C$, the magnetic dipole $G_M$ and the charge quadrupole $G_Q$. Measurement of the unpolarized cross section yields the structure functions $A(G_C,G_M,G_Q)$ and $B(G_M)$. When the tensor analyzing power $T_{20}$ is also determined, all three form factors can be separated \(3\). A large body of data is available for $A$ and $B$ for values of the four-momentum transfer $Q$ of up to 12 fm$^{-1}$, while $T_{20}$ has been measured up to 4 fm$^{-1}$, albeit with limited accuracy. The observable $T_{20}$ contains an interference between $G_C$ and $G_Q$ and is thus sensitive to the effects of short-range and tensor correlations in the ground-state wave function of the deuteron. In this paper absolute measurements are presented on the analyzing powers in the $^2H(e,e'd)$-reaction for $Q$-values between 1.8 and 3.2 fm$^{-1}$ with a high accuracy.

The cross section for elastic electron-deuteron scattering with unpolarized electrons and tensor-polarized deuteron nuclei can be expressed as $A$

\[
\sigma = \sigma_0 \left[ 1 + \frac{A_T^T P_{zz}}{\sqrt{2}} \right], \quad \text{with (1)}
\]

\[
A_T^T = \sum_{i=0}^{2} d_{2i} T_{2i} \quad \text{and} \quad d_{20} = \frac{3 \cos^2 \theta^* - 1}{2},
\]

\[
d_{21} = -\sqrt{\frac{3}{2}} \sin 2\theta^* \cos \phi^*, \quad d_{22} = \sqrt{\frac{3}{2}} \sin^2 \theta^* \cos 2\phi^*,
\]

with $\sigma_0$ the unpolarized cross section, $T_{2i}$ the tensor analyzing powers and $P_{zz}$ the degree of tensor polarization. The polarization axis of the deuteron is defined by the angles $\theta^*$ and $\phi^*$ in the frame where the $z$-axis is along the direction of the three-momentum transfer $\vec{q}$ and the $x$-axis is perpendicular to $z$ in the scattering plane.

The experiment was performed using a 704 MeV electron beam in the AmPS storage ring \(4\) and a tensor-polarized deuteron internal target \(5\) at NIKHEF. By stacking several pulses of electrons, produced by the medium-energy accelerator, circulating currents of up to 150 mA were stored in the ring. A beam life time in excess of 2000 s was obtained by compensating synchrotron radiation losses with a 476 MHz cavity.

Nuclear-polarized deuteron gas was provided by an atomic beam source. Deuteron atoms are produced by means of an RF dissociator. Atoms with their electron spin up are focused into the target-cell feed tube by two sextupole magnets, whereas those with spin down are defocused. A medium- and a strong-field RF-unit induce transitions between the hyperfine states, resulting in a tensor polarization $P_{zz}^-$ ($P_{zz}^+$) of ideally -2 (+1) with zero vector polarization. The tensor polarization was flipped every 20 s between $P_{zz}^-$ and $P_{zz}^+$. The atomic beam is fed into an open-ended T-shaped dwell cell with a diameter of 15 mm and a length of 400 mm. The cell was cooled to approximately 150 K. With a flux of \(1.3 \times 10^{16}\) atoms/s in two hyperfine states into the cell an integrated target density was obtained of $2 \times 10^{13}$ atoms/cm$^2$. The direction of the deuteron polarization axis was defined by a magnetic holding field (B=23 mT) and chosen to be approximately 150 K. With a flux of \(1.3 \times 10^{16}\) atoms/s in two hyperfine states into the cell an integrated target density was obtained of $2 \times 10^{13}$ atoms/cm$^2$. The direction of the deuteron polarization axis was defined by a magnetic holding field (B=23 mT) and chosen to be...
parallel to the average three-momentum transfer.

Two polarimeters were available to study the polarization in the dwell cell. A small sample (10%) of the atomic beam was continuously analyzed by a Breit-Rabi polarimeter. The nuclear polarization of the atoms and the composition of the gas in the dwell cell was measured with an ion-extraction system. Ions, produced by the circulating electrons, were extracted from the beam line and transported through a Wien filter (an \(E \times B\) velocity selector). Since molecular and atomic deuterium ions have different velocities, measuring the ion current as a function of the Wien filter \(B\) field allows determination of the atomic fraction averaged over the target cell. The nuclear polarization can be determined by accelerating the ions onto a tritium target and using the field-(see [14] for an overview) it is possible to correct for these contributions. For example, \(T_{22}\) can be expressed in terms of \(A^T\) and \(B\) directly as \(T_{22} = -\frac{\sqrt{2}B}{8Q(\eta+1)(A+B\tan^2(\theta_{e}/2))}\) with \(\eta = \frac{Q^2}{4M_d}\) and \(M_d\) the mass of the deuteron. To investigate the sensitivity of the extraction procedure to the uncertainty in the input parameters (i.e., \(Q\), \(\theta_e\), \(d_{2i}\), \(A^T\), and \(B\)), these were varied independently within their error and the extraction repeated. The total error was taken to be the quadratic sum of the separate errors. Note that the main contribution to the systematic error in \(A_d^T\) comes from the systematic uncertainty in the polarization.

For the kinematically over determined elastic scattering reaction, requiring correlations between the scattering angles of the electron and the hadron reduces the number of protons even further.

Figure 2 shows the distribution of \(P_{id}\) and the coincidence timing \(\tau_p\) between the scattered electron and the recoiling hadron. To obtain this distribution \(\pm 2.5\) \(\sigma\) cuts were applied on their angular correlations. A clear separation is observed between protons and deuterons. The proton contamination was estimated to be 4.6 \%. Analysis of a proton sample has shown that these have an analyzing power much lower than that of the deuterons. Therefore, the proton contamination is treated as an unpolarized background.

In the event selection additional \(\pm 2.5\) \(\sigma\) cuts were applied on the coincidence time and on \(P_{id}\). An asymmetry \(A_d^T\) was formed for events that fall within a \(Q\)-bin, using the expression

\[
A_d^T = \sqrt{2} \frac{N^+ - N^-}{P_{zz}^+ N^+ - P_{zz}^- N^-}
\]

with \(N^+ (N^-)\) the number of events in the \(Q\)-bin considered when the target polarization was positive (negative). To correct for the fact that the direction of the holding field—and thus the spin orientation—varies over the length of the cell with respect to \(q\) the uncorrected tensor asymmetry \(A_d^T\) is weighted with \(d_{20}\) from Eq. (2).

Note from Eq. (1) that \(A_d^T\) contains small contributions from \(T_{21}\) and \(T_{22}\). Using the world data set for the unpolarized structure functions \(A\) and \(B\) (see [14] for an overview) it is possible to correct for these contributions. For example, \(T_{22}\) can be expressed in terms of \(A\) and \(B\) directly as \(T_{22} = -\frac{\sqrt{2}B}{8Q(\eta+1)(A+B\tan^2(\theta_{e}/2))}\) with \(\eta = \frac{Q^2}{4M_d}\) and \(M_d\) the mass of the deuteron. To investigate the sensitivity of the extraction procedure to the uncertainty in the input parameters (i.e., \(Q\), \(\theta_e\), \(d_{2i}\), \(A^T\), and \(B\)), these were varied independently within their error and the extraction repeated. The total error was taken to be the quadratic sum of the separate errors. Note that the main contribution to the systematic error in \(A_d^T\) comes from the systematic uncertainty in the polarization.

### Table I. Result on \(A_d^T\), \(T_{20}(70^\circ)\) and \(G_C\) with statistical and systematic uncertainties, extracted from our \(T_{20}\) measurements and the world data on \(A\) and \(B\).

| \(Q\) [fm\(^{-1}\)] | \(A_d^T\) | \(T_{20}(70^\circ)\) (stat)(syst) | \(G_C\) (stat)(syst) |
|-----------------|--------|-------------------------------|-------------------|
| 2.03            | -0.683 | -0.713(0.082) (0.036)         | 0.163(0.003)(0.014) |
| 2.35            | -0.891 | -0.897(0.081) (0.045)         | 0.100(0.003)(0.009) |
| 2.79            | -1.383 | -1.334(0.223) (0.066)         | 0.035(0.015)(0.005) |

The observables \(A\), \(B\) and \(T_{20}\) provide three different combinations of the form factors \(G_C\), \(G_Q\) and \(G_M\), from which these can be extracted. The result for \(T_{20}\) was recalculated at \(\theta_e = 70^\circ\), to allow a direct comparison.
with the results of other experiments. The extracted values for $T_{20}$ and $G_C$ are shown in Table I and in Fig. 2. The new data on $T_{20}$ are each at least one $\sigma$ below the predictions of relativistic models. This confirms the findings of the previous NIKHEF experiment [15].

To evaluate the model sensitivity of the $T_{20}$ data sets a $\chi^2$-analysis was performed, for which the data measured most recently at Bates [14], using a calibrated recoil polarimeter, and those from the NIKHEF experiments were selected. The data from BINF have poor accuracy at low $Q$ [10] and poor discriminating power in the $Q$-range from 1 to 3 fm$^{-1}$ [17], since the $T_{20}$ values were extracted by normalizing one datum to a selected model prediction. The selected data sets are compared to the calculations of Wiringa [1], Mosconi [2], Hummel [3], Van Orden [4] and Buchmann [20]. The first two columns of Table II give the $\chi^2$-values when only the $T_{20}$ data of either experiment are considered. In addition, both these experiments yielded data on other tensor analyzing powers: in the 95 data run of NIKHEF $T_{22}$ was also determined, and the Bates experiment determined all tensor moments simultaneously. The last two columns of the table give the results when all data are taken into account.

The two data sets lead to different conclusions about the quality of the models. The NIKHEF set shows a preference for non-relativistic calculations with realistic NN-potentials, when only the $T_{22}$ are taken into account, mainly due to an inconsistency in one value of $T_{22}$. The then available data of either experiment are considered. In addition, both these experiments yielded data on other tensor analyzing powers: in the 95 data run of NIKHEF $T_{22}$ was also determined, and the Bates experiment determined all tensor moments simultaneously. The last two columns of the table give the results when all data are taken into account.

The normalization of each data set was varied within the quoted systematic uncertainty until a minimum value for the $\chi^2$ was obtained. The best description is given by the non-relativistic calculation of ref. [1] that includes the relevant corrections to the impulse approximation, which conforms to the conclusions from the NIKHEF data. It should be noted that especially the inclusion of meson-exchange currents is of great importance, both in describing the unpolarized and the polarized data.

TABLE III. $\chi^2/N$ analysis of the $A$ and the $B$ world data set.

| Model      | $A$  | $B$  | $A+B$ |
|------------|------|------|-------|
| Wiringa    | 5.6  | 5.9  | 5.7   |
| Mosconi    | 11.0 | 1.8  | 8.3   |
| Hummel     | 16.5 | 4.9  | 13.1  |
| Van Orden  | 72.7 | 2.7  | 52.0  |
| Buchmann   | 50.8 | 6.9  | 37.8  |

In conclusion, absolute measurements of the tensor analyzing power $T_{20}$ were performed in a $Q$-range from 1.8 to 3.2 fm$^{-1}$. This new data set, together with that of a previous measurement at NIKHEF, has provided additional stringent constraints on the deuteron form factors. Recently, an experiment [22] has been completed at Jefferson Laboratory, which will provide accurate data on $T_{20}$ in a $Q$-range from 4 to 6.5 fm$^{-1}$, thus covering the expected position [21] of the minimum in $G_C$. Further measurements in a $Q$-range of 2.1 to 4.4 fm$^{-1}$ will be performed at NIKHEF, which will allow a direct comparison with the MIT-Bates data.

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FIG. 1. Particle identification parameter $P_{id}$ (defined in the text) versus coincidence time $\tau_p$.

FIG. 2. Extracted values (solid triangles) of $T_{20}(70^\circ)$ (top) and $G_C$ (bottom) as a function of $Q$ compared to the world data and selected calculations. Data: solid triangles (present experiment), open squares [14], solid square [15], open diamond [16], open triangles [17], open circles [18], and open cross [19]. Curves: short-dashed [1], dash-dotted [2], full [3], long-dashed [4], dotted [20]. The shaded area indicates the size of the systematic errors from the present experiment.
