Measurement of Tensor Analyzing Powers for Elastic Electron Scattering from a Polarized ^{2}H Target Internal to a Storage Ring

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We report an absolute measurement of the tensor analyzing powers T_{20} and T_{22} in elastic electron-deuteron scattering at a momentum transfer of 1.6 fm^{-1}. The novel approach of this measurement is the use of a tensor polarized ^{2}H target internal to an electron storage ring, with *in situ* measurement of the polarization of the target gas. Scattered electrons and recoil deuterons were detected in coincidence with two large acceptance nonmagnetic detectors. The techniques demonstrated have broad applicability to further measurements of spin-dependent electron scattering. [S0031-9007(96)01269-0]

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Measurements of spin-dependent electron scattering have the potential to greatly enhance our understanding of nucleon and nuclear structure. For example, spin observables in elastic, quasielastic, and deep-inelastic scattering from polarized deuterium are predicted to provide important information on the effects of *D*-wave components in the ground state of ^{2}H [1], the largely unknown charge form factor of the neutron [2], and the neutron spin structure functions [3]. This has prompted development of both polarized ^{2}H targets for use with internal [4] or external beams [5] and polarimeters for measuring the polarization of recoiling hadrons [6]. Indeed the first round of measurements of spin-dependent e-^{2}H scattering has been carried out at Novosibirsk [7,8], Bonn [9], MIT-Bates [10,11], and SLAC [12].

The measurement of analyzing powers and spin-correlation parameters in spin-dependent electron scattering from polarized nuclei is optimally performed by scattering electrons from a pure and highly polarized target. Polarized internal gas targets in electron storage rings have the advantage that spin-dependent scattering from chemically and isotopically pure atomic species of high polarization can be realized. They offer rapid polarization reversal and flexible orientation of the nuclear spin direction by using low magnetic holding fields, a low thickness at high luminosity which allows for the detection of low-energy recoiling hadrons, and access to a broad kinematic range by using large acceptance detectors. For polarized deuterium one has the additional ability to reverse the tensor polarization, P_{zz}, at fixed vector polarization, P_z, and vice versa. Subsequently, small systematic errors can be expected.

The first pioneering measurements [7,8] with a polarized deuterium internal target have been carried out at VEPP-3 in Novosibirsk. They realized a target with a thickness limited to about 3×10^{11} atoms cm^{-2} [8] as viewed by their detectors. Recently, this was increased by an order of magnitude [13]. Since many mechanisms can depolarize the target nuclei in the storage cell, and no polarimeters were available to measure the target polarization *in situ,* they normalized one datum to a theoretical prediction, setting the scale for the other data points [8].

The electron spin-averaged cross section for elastic electron-deuteron scattering can be expressed [1] as

$$\sigma = \sigma_0\Big[1 + \frac{1}{\sqrt{2}} P_{zz}\Big(\frac{3\cos^2\theta^* - 1}{2} T_{20} - \sqrt{\frac{3}{2}}\sin 2\theta^* \cos\phi^* T_{21} + \sqrt{\frac{3}{2}}\sin^2\theta^* \cos 2\phi^* T_{22}\Big)\Big].$$

Here, σ_0 is the unpolarized cross section, and the degree of tensor polarization is defined as $P_{zz} = n_+ + n_- - 2n_0$, where n_+, n_0, and n_- are the relative populations of the various nuclear spin projections on the direction of

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the magnetic holding field. The polarization direction of the deuteron is defined by the angles θ^* and ϕ^* in the frame where the z axis is along the direction of the virtual photon and the y axis is defined by the vector product of the incoming and outgoing electron momenta.

Elastic electron scattering from the deuteron is completely described by the G_C, G_Q, and G_M form factors. Cross section measurements yield the structure functions $A(G_C, G_Q, G_M)$ and $B(G_M)$, which combined with $T_{20}(G_C, G_Q, G_M)$ allow the determination of these form factors [1]. The present data set for elastic e-^{2}H scattering and the isoscalar charge form factor of the three-body system pose an interesting puzzle [14] for the few-body theory: there exists *no* theoretical model capable of describing all measurements simultaneously. T_{20} has only a limited data set, and accurate measurements of this observable are required to address this issue. In addition, a measurement of T_{22} provides a stringent consistency check, since the value of T_{22} can be unambiguously determined from unpolarized elastic electron scattering.

We have performed an experiment to measure the tensor analyzing powers T_{20} and T_{22}, at the Amsterdam Pulse Stretcher Ring [15] at NIKHEF with 565 MeV electrons. Several beam bunches were stacked into the ring, yielding currents up to 120 mA and a lifetime exceeding 15 min.

Scattered electrons were detected in an electromagnetic calorimeter [16] consisting of six layers of CsI(Tl) blocks covering a solid angle of 180 msr. Two plastic scintillators, one in front of the CsI(Tl) blocks, one sandwiched between the first two layers, provided the electron trigger. The total energy resolution obtained (about 8%) was sufficient to distinguish quasielastic events from inelastic events, in which a pion was produced. Two sets of wire chambers, one adjacent to the scattering chamber, one in front of the first trigger scintillator, were used for track reconstruction. The central angle of the electron detector was positioned at 35°. This resulted in a coverage in the four-momentum transfer range $1.3 < q < 1.8$ fm^{-1} with a cross section and acceptance weighted average of $\bar{q} = 1.58$ fm^{-1}.

The recoil deuterons were detected in a range telescope [17], consisting of 15 layers of 1 cm thick plastic scintillator preceded by 1 layer of 2 mm thickness. The detector was positioned at a central angle of 80°, and covered a solid angle of nearly 300 msr. The range telescope was preceded by two sets of wire chambers for track reconstruction. The minimum energy of the detected deuterons was 19 MeV.

Figure 1 shows a schematic layout of the target area of the experiment. An atomic beam source (ABS) consisting of an rf dissociator, a cooled nozzle, collimators, sextupole magnets, and rf transition units, provides a flux of 1.2×10^{16} deuterium atoms s^{-1} (for two hyperfine states), injected into a windowless T-shaped cylindrical storage cell, with 15 mm diameter and 400 mm length, cooled down to 100 K. A medium-field and a strong-field transition unit [18] were used to alternate every 10 s the tensor polarization of the injected deuterons between -2 and $+1$, while keeping the vector polarization at zero. The target thickness obtained with this ABS, visible to the detectors, amounted to 2×10^{13} atoms cm^{-2}. This constitutes about an order of magnitude increase over previous experiments [8,13].

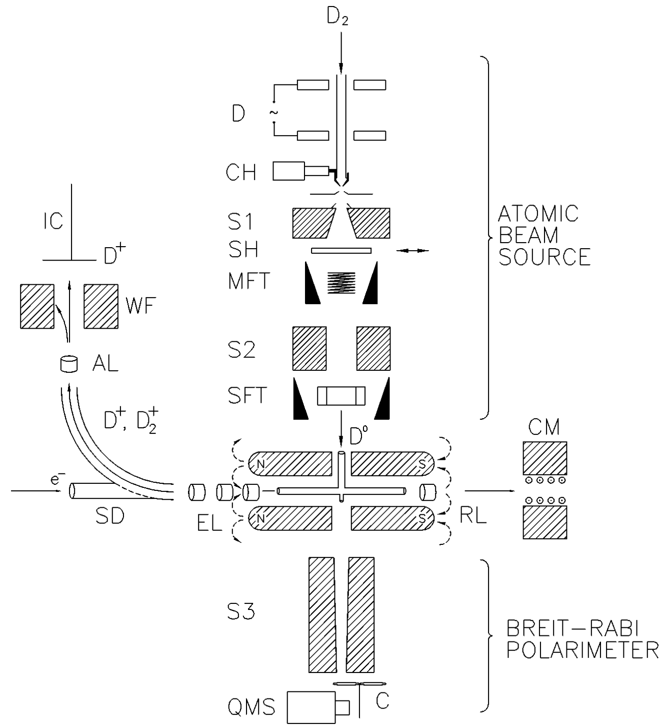

FIG. 1. Schematic outline of the atomic beam source, Breit-Rabi polarimeter, internal target, and ion-extraction system. All components, except the target holding field and correction magnets, are inside the vacuum system. D: rf dissociator; CH: cold head; S1, S2, S3: sextupole magnets; MFT, SFT: medium- and strong-field transition units; SH: shutter; C: chopper; QMS: quadrupole mass spectrometer; CM: correction magnet; RL: repeller lens; EL: triplet of ion-extraction lenses; SD: spherical deflector; AL: electrostatic lens; WF: Wien filter; IC: ion collector.

A magnetic holding field of 30 mT is applied over the entire target cell region by using two electromagnets. A correction magnet is added to counterbalance the target holding field and to preserve a closed orbit in the storage ring. The holding field coils are provided with two holes, one for injection of the deuterium atoms into the storage cell, one to sample a small fraction of these atoms in a Breit-Rabi polarimeter (BRP). This polarimeter consists of a sextupole magnet, a chopper, and a quadrupole mass spectrometer (QMS).

The BRP proved useful to optimize the intensity of atoms injected into the storage cell as a function of, e.g., nozzle temperature, deuterium flow into the rf dissociator, and sextupole fields. Furthermore, it was used to test the performance of the high-frequency transition units.

A drop of 1/3 in the amount of atoms detected by the QMS with high-frequency transition units on, indicates a 100% efficiency of the transition. These measurements also proved that the polarization of the injected atoms was not lost in passing through the target holding field magnets, where the field components have zero crossings. In addition, the BRP was used to set the holding field strength such as to avoid resonant electron beam-induced depolarization of the target atoms.

Ions, produced by the electron beam, were extracted and analyzed [4] (see Fig. 1). These ions were prevented from reaching the walls of the storage cell by a longitudinal holding field. They were on the one side of the cell reflected by an electrostatic repeller lens, on the other side extracted by using a triplet of lenses and a spherical deflector. A Wien filter separated the atoms from molecules, and the atomic fraction measured with an ion collector amounted to 0.71 ± 0.02. By turning on and off the sextupole electromagnets as well as by flowing background gas, we found that up to 25% of the molecules in the storage cell originated from the recombination of atoms on the Teflon coated walls. A ±3.6% systematic uncertainty was included in the error bars to accommodate that these molecules can be completely unpolarized or as polarized as the deuterium atoms from which they originate. $P_{zz}(D^+)$ has been determined in a separate measurement where ions were produced by a 1 kV e gun, and were accelerated to 50 keV to bombard a tritiated foil [4]. The reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$ was used to measure the target tensor polarization directly. The nuclear polarization amounted to $P_{zz}^+(D^+) = +0.664 \pm 0.019 \pm 0.017$ and $P_{zz}^-(D^+) = -1.215 \pm 0.036 \pm 0.023$. Combining these results with the data from the ion-extraction system, the nuclear tensor polarization of the target has been determined with the same weighting over target gas and electron beam density as in the actual experiment. The net polarization, including molecular dilution, is then $P_{zz}^+ = +0.488 \pm 0.014 \pm 0.030$ and $P_{zz}^- = -0.893 \pm 0.027 \pm 0.052$, where the first (second) error represents the statistical (systematic) accuracy.

The left panel in Fig. 2 shows a time difference spectrum between electrons and hadrons for the event sample with and without cuts on angular correlations. It is seen that an unambiguous separation of the deuterons from protons was obtained by differences in time of flight, in energy loss in the scintillators, and by requiring kinematic correlations between electron and deuteron events. The right panel in Fig. 2 shows the reconstructed vertex distribution along the storage cell for $^2\mathrm{H}(e,e'd)$ events. The expected triangular density distribution of the gas along the storage cell is observed, as illustrated by the curve obtained by a Monte Carlo technique. We also included in Fig. 2 the results from a run without gas flow from the ABS, established by inserting a shutter (shaded histogram). This unpolarized background amounts to 4% and was taken into account in the polarization determination.

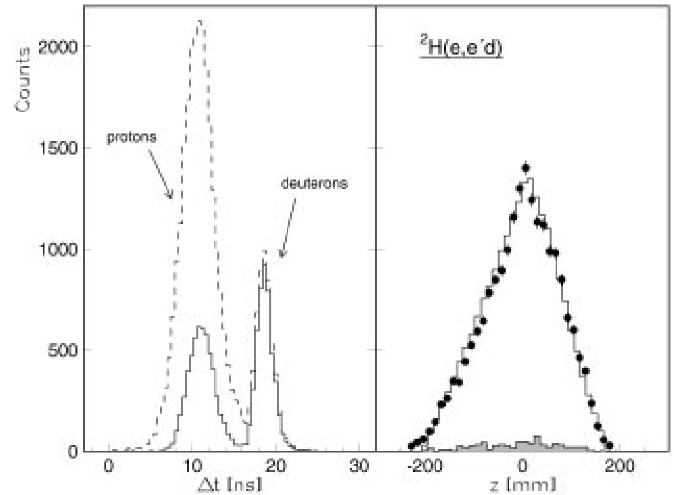

FIG. 2. Left panel: time difference between electrons and hadrons for the event sample with (solid histogram) and without (dashed histogram) cuts on angular correlations. Right panel: reconstructed vertex position along the beam axis for the reaction $^2\mathrm{H}(e,e'd)$. Both measurements with an atomic beam source (circles) and an empty storage cell (shaded histogram) are shown. The curve indicates the Monte Carlo prediction.

Having established that an essentially background-free measurement of the reaction $^2\mathrm{H}(e,e'd)$ is possible, we determined the asymmetry $A = \sqrt{2}\,\frac{N^+ - N^-}{N^- P_{zz}^+ - N^+ P_{zz}^-}$, where N^+ (N^-) corresponds to the number of events measured for P_{zz}^+ (P_{zz}^-). The target spin vector was directed approximately parallel or perpendicular to the momentum transfer. The average spin angle was optimized for quasifree scattering kinematics, resulting for elastic scattering in $\bar{\theta}_\parallel^* = 15°$ and $\bar{\theta}_\perp^* = 89°$. We found $A_\parallel = -0.317 \pm 0.028$ and $A_\perp = 0.210 \pm 0.019$. Since the spin dependent cross section is dominated by T_{20}, we expect the asymmetry to follow the spin-angular dependence of the associated Legendre function $P_2^0 = \frac{1}{2}(3\cos^2\theta^* - 1)$. The predicted change of sign in the tensor asymmetry is clearly observed when changing the spin angle. As a check on false asymmetries, we measured the asymmetry for unpolarized target gas and obtained $A_{\mathrm{unpolarized}} = 0.000 \pm 0.014$.

The extracted value for T_{20} amounts to $\langle T_{20}\rangle = -0.401 \pm 0.024 \pm 0.028$. The 7% systematic error in T_{20} includes the uncertainties from the polarization measurement (6.6%) and the spin orientation angles (1.9%). Also included is the uncertainty from the correction for the small T_{21} and T_{22} contributions, which amounts to 0.7% and has been estimated from the existing data for $G_Q(Q^2)$ and $B(Q^2)$. The data for the two spin orientations also allow one to extract T_{22}, resulting in $\langle T_{22}\rangle = 0.022 \pm 0.019 \pm 0.003$. In Fig. 3 we compare the data for T_{20} and T_{22} with the results of other measurements and several state-of-the-art models [19–23]. We have included the results of experiments measuring T_{20} and T_{22} through the recoil polarization technique [10,11]. The variation in theoretical predictions for T_{20} shows that precise

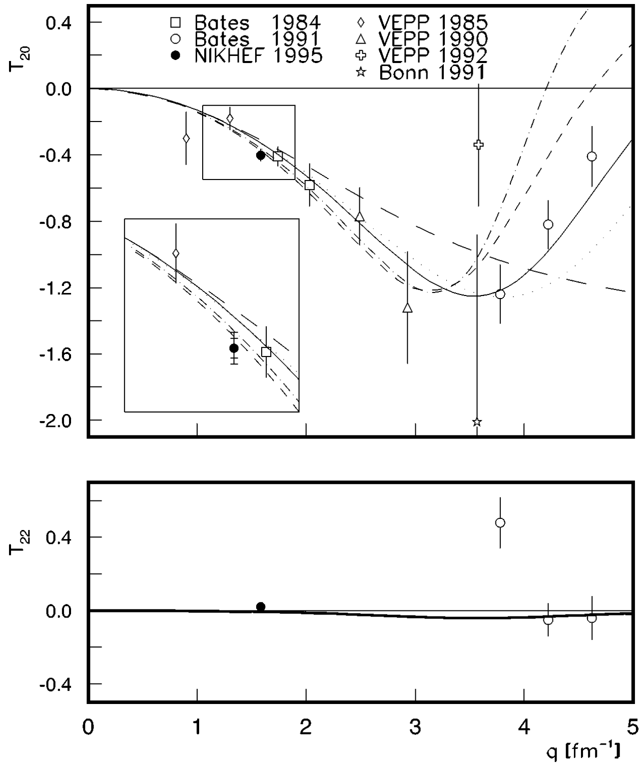

FIG. 3. Data and theoretical predictions for T_{20} and T_{22}, as a function of momentum transfer. Open circles are from Ref. [11], diamonds from Ref. [7], squares from Ref. [10], triangles from Ref. [8], crosses from Ref. [13], stars from Ref. [9], and the solid circles from the present experiment. The curves represent various theoretical models: short-dashed for the NRIA including MEC from Ref. [19] by using the Argonne V14 potential; solid from Ref. [20] for the RIA including $\rho\pi\gamma$ and $\omega\sigma\gamma$ contributions; dotted for the RIA from Ref. [21] by using the Bonn Q potential; dot-dashed for the coupled-channels calculation of Ref. [22] for IA + MEC and model D′; long-dashed for the PQCD prediction of Ref. [23]. The inset shows the results in the q (T_{20}) range from 1.05 fm^{-1} (-0.55) to 1.90 fm^{-1} (-0.10). The heavy curve in the bottom figure represents T_{22} calculated from a fit to the world data for $B(Q^2)$.

measurements up to $q = 4$ fm^{-1} can distinguish between the various models shown. The experimental techniques established here are sufficient to obtain such data, with small statistical and systematic uncertainties, within a reasonable time frame.

In summary, we have performed a measurement of the spin observables in elastic electron-deuteron scattering. We have obtained essentially background-free data to measure the asymmetry for target polarization both parallel and perpendicular to the momentum transfer, and derived the tensor analyzing powers T_{20} and T_{22} from these data. The techniques developed in this experiment have broad applicability to future measurements of spin-dependent electron scattering.

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