Measurement of Tensor Analyzing Power in Electron-Deuteron Elastic Scattering

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An internal-target technique was used to make the first measurements of the tensor analyzing power T_{20} of electron-deuteron elastic scattering in the four-momentum-transfer range of 2–3 fm^{-1}. Polarized deuterium atoms were confined within a storage cell in the VEPP-3 electron storage ring in Novosibirsk to achieve a total target thickness of 3×10^{12} cm^{-2}, 15 times greater than was previously possible with an atomic-beam target alone. The results for T_{20} are in agreement with reasonable models of the deuteron wave function.

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A long-standing issue in nuclear physics is the electromagnetic structure of the deuteron, the simplest nucleus. Elastic electron-deuteron scattering is determined completely in the one-photon-exchange approximation by the monopole (G_C), quadrupole (G_Q), and magnetic (G_M) form factors of the deuteron. The momentum-transfer dependence of these form factors is expected[1-3] to provide information about the deuteron wave function, and is sensitive to isoscalar meson-exchange currents, relativistic effects, and quark degrees of freedom. The monopole form factor is particularly sensitive to the model of the deuteron in the range of four-momentum transfer $3<Q<6$ fm^{-1}, where it is predicted to pass through zero. These form factors appear in the spin-averaged cross section in the form $A(Q^2)+B(Q^2)\times\tan^2(\theta/2)$, in which A depends on G_C, G_Q, and G_M, B depends on G_M alone, and θ is the electron scattering angle. This expression is not as sensitive to the underlying deuteron structure as the individual form factors, which are separable only through the use of polarization measurements.

Polarization techniques in electron scattering[4] have been successfully employed to study the deuteron in only three published experiments: one at MIT-Bates,[5] with a recoil polarimeter, and two at Novosibirsk,[6] with a polarized deuterium gas jet target. We present here the first results of a measurement of the asymmetry in elastic electron scattering by a tensor-polarized deuteron target, in which the polarized atoms were contained within a storage cell in an electron storage ring.[7] Although polarized hydrogen atoms have been stored in cells before, most notably by Barker *et al.*[8] and Kleppner *et al.*,[9] this work represents the first application of storing polarized nuclei as a target in a storage ring. The performance of the storage cell in such an environment is of great interest because its success may lead to many other experiments,[10] hitherto not practical. The present results demonstrate the feasibility of this novel technique.

Elastic electron scattering from tensor-polarized deuterium is described by the cross section[4]

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma_0}{d\Omega}[1+T_{20}t_{20}+2T_{21}\,\mathrm{Re}(t_{21})+2T_{22}\,\mathrm{Re}(t_{22})] \tag{1}$$

in which $d\sigma_0/d\Omega$ is the scattering cross section for an unpolarized deuteron target, T_{20}, T_{21}, and T_{22} are the components of the tensor analyzing power in a spherical basis, and t_{20}, t_{21}, and t_{22} are the corresponding tensor-polarization parameters of the target. T_{20} may be expressed in terms of the deuteron form factors:

$$T_{20}=-\sqrt{2}[X(X+2)+Y/2]/[1+2(X^2+Y)] \tag{2}$$

in which $X=\frac{2}{3}\tau(G_Q/G_C)$, $Y=\frac{1}{3}\tau(G_M/G_C)^2f(\theta)$, $f(\theta)=[1+2(1+\tau)\tan^2(\theta/2)]$, and $\tau=Q^2/4m_d^2$. The expression for t_{20} is

$$t_{20}=(p_{zz}/\sqrt{2})P_2(\hat{\mathbf{n}}\cdot\hat{\mathbf{q}})\,, \tag{3}$$

where $p_{zz}=1-3n_0$ is the Cartesian tensor polarization, n_0 is the fraction of deuterium atoms with a spin projection of zero, P_2 is the second Legendre polynomial, and $\hat{\mathbf{q}}$ and $\hat{\mathbf{n}}$ are unit vectors in the direction of $\mathbf{q}$ and the target polarization, respectively. For moderate momentum transfers, the terms in Eq. (1) involving T_{21} and T_{22} are relatively small, and the terms in Eq. (2) involving X are dominant. Thus, the asymmetry term $T_{20}t_{20}$ is sensitive to the ratio of G_Q and G_C, and to the zero crossing of G_C. Furthermore, the isoscalar nucleon form factors largely cancel in this ratio, so that T_{20} is determined mostly by the structure of the deuteron.

The experiment was performed at the 2-GeV electron storage ring VEPP-3 in Novosibirsk. Electron bunches of length 30 cm and cross section 5×1 mm circulated at a frequency of 4 MHz to create a current of 0.1–0.2 A. Polarized deuterium atoms from an atomic-beam source[11] were injected into an open-ended tube, coaxial with the electron beam in the ring, to form an internal target. Scattered electrons were detected in coincidence with recoil deuterons or protons by drift chambers and scintillation counters, as shown in Fig. 1.

The deuterium storage cell, installed in a straight section of VEPP-3, was an aluminum tube 940 mm in length, with an elliptical cross section of 24×46 mm. These dimensions minimize the effect of the storage ring during beam injection. Recoil deuterons passed through 100-μm exit windows etched in the sides of the cell, and 60-μm Ti exit windows on the vacuum chamber. An Al tube 10 mm in diameter and 60 mm long provided the inlet for polarized atoms from an atomic-beam source, which produced 10^{16} atoms/s, with tensor polarization p_{zz} close to unity. The total thickness of atoms in the cell was approximately 3×10^{12} cm^{-2}, 15 times greater than the thickness of the atomic beam. After 400 collisions on average with the cell wall, an atom would exit through either end of the tube into the vacuum chamber. The interior of the cell was coated with drifilm[12] to inhibit deuterium-atom depolarization during collisions with the cell wall. Based on the measurements of target polarization, the probability of depolarization per collision is estimated at 0.1%. In the portion of the cell visible to the detectors, a 0.7-kG field was applied to align the polarization along one of two directions orthogonal to the electron beam ($\mathbf{n}_1,\mathbf{n}_2$), as shown in Fig. 1. A solenoidal field of greater than 0.3 kG was applied to the remainder of the cell in order to inhibit depolarization[13] by the time-varying magnetic fields of the electron-beam pulses. Directly opposite the inlet tube was a slit in the cell wall through which a small portion of the atomic beam entered a polarization monitor, consisting of a Rabi magnet followed by a movable vacuum gauge to observe the exit-beam profile.[11]

The particle-detection apparatus[14] consisted of four nearly identical detection systems, placed symmetrically around the electron-beam axis, as indicated in Fig. 1. Each system was used to detect electrons with scattering angle θ between 10° and 22° and in a 40° range of azimuthal angle, in coincidence with recoil deuterons scattered between 68° and 80°. Electron and deuteron trajectories were measured in two separate sets of drift chambers, each containing six planes. Three thin plastic scintillators (4, 10, and 10 mm thick) were placed behind the deuteron drift chambers and were followed by either a 20-cm-thick plastic scintillator or a 16-cm NaI counter. A single, 10-mm-thick plastic scintillator was installed behind a 5-radiation-length Pb converter following the electron drift chambers.

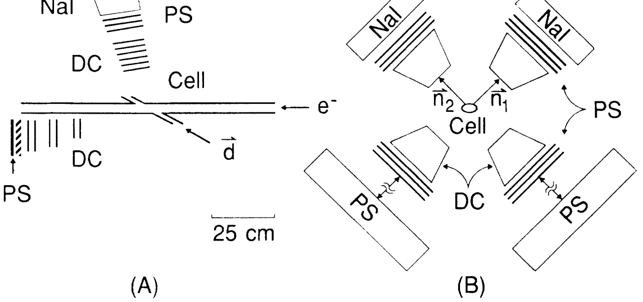

FIG. 1. Storage cell and apparatus for the detection of scattered particles. (a) Side view of one electron-deuteron detector pair and (b) axial view of all four deuteron detectors. DC denotes drift chambers; PS denotes plastic scintillator.

Data acquisition was organized into 1-2-h runs following each injection of electrons into the storage ring. The sign of p_{zz} was reversed every 200 s, and the magnitude was constantly monitored. The direction of the magnetic guide field was switched only during the time between runs. The electron-beam current was separately integrated for each of the four polarization states. The integrated charge for each state, summed over all runs, varied by less than 4% from an average value of 95 kC. The event trigger required large coincident signals in the deuteron and electron scintillators, as well as a minimum number of hits in the drift chambers, which suppressed background events from stray beam-related particles. Surviving background events were eliminated off-line by enforcing constraints on the location of the scattering vertex.

A crucial task for the data analysis was the separation of elastically scattered deuterons from the much greater flux of protons from inelastic scattering. This separation used time of flight, differences in dE/dX in the scintillation counters, and the kinematical correlation between the electron and deuteron scattering angles and energies. These cuts eliminated 99.5%–99.98% of the protons, thus reducing the proton contamination to 2%–6% of the events, depending on θ. This was small enough to be ignored. The resulting elastic-scattering events for each detector system and each polarization state were separated into three bins according to which of the final three scintillation counters stopped the deuteron. These results were divided by the integrated charge to obtain the experimental scattering rates.

The azimuthal asymmetry due to $T_{20}t_{20}$ is manifested as a difference in the scattering rates for neighboring detector systems; the rates for detectors on opposite sides of the electron beam should be equal. If the sign of p_{zz} is switched, this asymmetry will change sign, and if the direction of the guide field is switched, the asymmetry is rotated by 90°. With four systems, two polarization directions, and two values of p_{zz}, there are many possible ways to compute an asymmetry. This allows a direct check of the systematic uncertainties arising from possible differences in the various detector systems, errors in the guide-field orientation, or unequal magnitudes of p_{zz}. All such tests resulted in asymmetries that were self-consistent, within their statistical uncertainty. By averaging the asymmetries computed for different detector systems, any residual systematic errors are substantially reduced. We therefore define the experimental asymmetry to be

$$a_{\text{expt}} = [(S^2_{1+} - S^2_{1-} - S^2_{2+} + S^2_{2-}) - (S^1_{1+} - S^1_{1-} - S^1_{2+} + S^1_{2-})] \Big/ \sum S^i_{jk} \tag{4}$$

in which S^i_{jk} is the sum of the counting rates in the detector systems facing the directions $\pm n_i$, with the magnetic guide field pointing in direction n_j, and the sign of p_{zz} given by k. Equation (4) was used to compute the values of a_{expt} presented in Table I for the three deuteron energy bins. Each result is quoted at an effective momentum transfer $\bar{Q}$ computed in the plane-wave impulse approximation from the Paris potential.

To determine T_{20} from these data, it is necessary to know the average value of p_{zz} for the target. The average polarization for nuclei in the storage cell was reduced through dilution by the unpolarized residual gas, by atomic depolarization associated with wall collisions, and by depolarizing transitions[13] induced by the high-frequency magnetic field of the passing electron-beam bunches. Lacking an exact calculation of these effects, we determined p_{zz} by normalizing the datum at the lowest value of Q to the theoretical value of T_{20} given by the Paris potential.[3] The asymmetry we would have measured with perfect polarization, a'_{expt}, is then given by a_{expt}/p_{zz}. We thus find that $p_{zz} = 0.572 \pm 0.053$. This is a higher polarization than was expected from initial tests of the drifilm coating in a low magnetic field[12] and from the previous work with a jet target. The improved performance may be attributed[15] to the strong magnetic holding field used in this experiment.

Finally, a correction was made for the terms in Eq. (1) involving T_{21} and T_{22}. These corrections were obtained by integrating the predictions of the Paris potential over the acceptance of the apparatus, and respectively amount to +10% and −1.7% of the total asymmetry for $\bar{Q} = 2.93$ fm^{-1}, the worst case. The resulting values of T_{20} are listed in Table I and plotted in Fig. 2. The systematic uncertainty in these values is dominated by the spread in theoretical values for T_{20} at the normalization point (5%) and the uncertainty in the placement of cuts to select elastic-scattering events (2%–7%). Other sources of systematic uncertainty include the uncertainty in $\bar{Q}$, uncertainty in detector acceptances, efficiencies, and dead times, and uncertainty in the magnetic-field orientation. Estimates for these uncertainties were combined in quadrature to yield the second error values in Table I.

TABLE I. Experimental results.

$\bar{Q}$ (fm^{-1})	a_{expt}	a'_{expt}	T_{20}
1.97	0.140 ± 0.013	0.245 [a]	−0.538 [a]
2.49	0.189 ± 0.038	0.330 ± 0.073	$-0.77 \pm 0.16 \pm 0.07$
2.93	0.309 ± 0.077	0.539 ± 0.14	$-1.32 \pm 0.32 \pm 0.11$

[a] Normalized to predictions from the Paris potential.

It can easily be seen that the present results agree well with the theoretical predictions of several widely used deuteron wave functions. In this range of Q, there is not much difference between the theories, because G_C is still large. One of the main differences between the two sets of theoretical predictions[1,2] shown in Fig. 2 is that isoscalar meson-exchange corrections have been explicitly included in the work of Sitarski, Blunden, and Lomon and not included in the calculations of Chung *et al.* To distinguish between theories will require data at higher momentum transfers. These results are limited to $Q < 3$ fm^{-1} because of the relatively low luminosity available with the present target. Work is currently in progress to extend these measurements to larger Q by using a higher-density storage cell and ultimately an optically pumped source of polarized deuterium with at least an order-of-magnitude increase in flux. In addition, new results with a polarimeter at MIT-Bates are expected to be forthcoming in the high-momentum-transfer region.[16]

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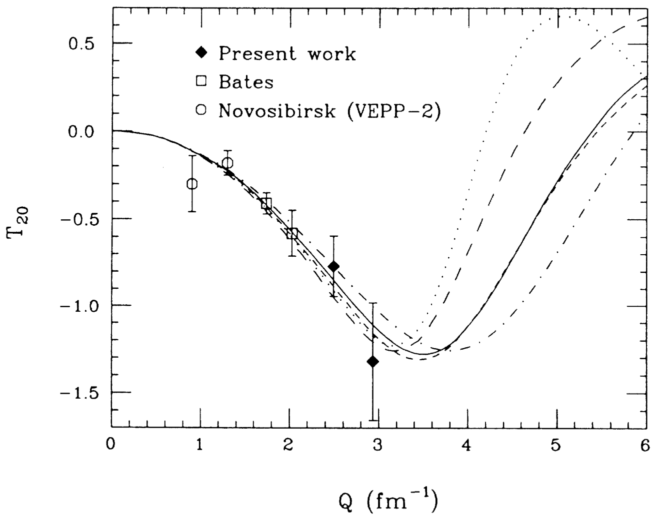

FIG. 2. Experimental results and theoretical predictions for T_{20} as a function of the momentum transfer. The squares are from Bates (Ref. 5), the circles are from Novosibirsk (Ref. 6), and the diamonds are the present work. The error bars represent statistical and systematic uncertainties added in quadrature. The solid, short-dashed, and dot-dashed lines are from Chung *et al.* (Ref. 1) and represent the Paris, Argonne V14, and Bonn Q potentials. The dotted and long-dashed lines are from the coupled-channel models C' and D' of Blunden *et al.* (Ref. 2).

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[1] P. L. Chung *et al.*, Phys. Rev. C **37**, 2000 (1988).

[2] W. P. Sitarski, P. G. Blunden, and E. L. Lomon, Phys. Rev. C **36**, 2479 (1987); P. G. Blunden *et al.*, Phys. Rev. C **40**, 1541 (1989).

[3] M. I. Haftel, L. Mathelitsch, and H. F. K. Zingl, Phys. Rev. C **22**, 1285 (1980).

[4] V. F. Dmitriev, S. G. Popov, and D. K. Toporkov, Institute of Nuclear Physics, Novosibirsk, Report No. 76-85, 1976 (unpublished); T. W. Donnelly and A. S. Raskin, Ann. Phys. (N.Y.) **169**, 247 (1986).

[5] M. E. Schulze *et al.*, Phys. Rev. Lett. **52**, 597 (1984).

[6] V. F. Dmitriev *et al.*, Phys. Lett. **157B**, 143 (1985); B. B. Wojtsekhowski *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 567 (1986) [JETP Lett. **43**, 733 (1986)].

[7] R. J. Holt, in *Proceedings of the Workshop on Polarized Targets in Storage Rings, Argonne, Illinois, 1984,* edited by R. J. Holt (ANL Report No. 84-50), p. 103.

[8] M. D. Barker *et al.*, in *Polarization Phenomena in Nuclear Physics—1980,* edited by G. G. Ohlsen *et al.*, AIP Conference Proceedings No. 69 (American Institute of Physics, New York, 1981), p. 931.

[9] D. Kleppner, H. C. Berg, S. B. Crampton, and N. F. Ramsey, Phys. Rev. **138**, A981 (1965).

[10] MIT-Bates Linear Accelerator Center report on Bates Planning Workshop for the South Hall Ring, 1989 (unpublished); HERMES Collaboration, DESY Report No. DESY-PRC-90-01, 1990 (unpublished); *Proceedings of the International Conference on Intersections Between Particle and Nucleon Physics, Steamboat Springs, Colorado, 1984,* edited by R. E. Mischke, AIP Conference Proceedings No. 123 (American Institute of Physics, New York, 1984), p. 499; T. Wise and W. Haeberli, *ibid.* 7, p. 249.

[11] A. V. Evstigneev, S. G. Popov, and D. K. Toporkov, Nucl. Instrum. Methods Phys. Res., Sect. A **238**, 12 (1985).

[12] L. Young *et al.*, Nucl. Instrum Methods Phys. Res., Sect. B **24/25**, 963 (1987); D. R. Swenson and L. W. Anderson, Nucl. Instrum. Methods Phys. Res., Sect. B **29**, 627 (1988).

[13] S. I. Mishnev *et al.*, in *Proceedings of the Eighth International Symposium on High Energy Spin Physics, Minneapolis, Minnesota, 1988,* AIP Conference Proceedings No. 187 (American Institute of Physics, New York, 1988), p. 1286.

[14] B. B. Wojtsekhowski *et al.*, Institute of Nuclear Physics, Novosibirsk, Report No. 88-120 (to be published).

[15] M. Tanaka, T. Ohshimi, K. Katori, M. Fujiwara, T. Itahashi, H. Ogata, and M. Kondo, Phys. Rev. A **41**, 1496 (1990).

[16] J. Cameron (private communication).