Evidence for Nuclear Tensor Polarization of Deuterium Molecules in Storage Cells

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Deuterium molecules were obtained by recombination, on a copper surface, of deuterium atoms prepared in specific hyperfine states. The molecules were stored for about 5 ms in an open-ended cylindrical cell, placed in a 23 mT magnetic field, and their tensor polarization was measured by elastic scattering of 704 MeV electrons. The results of the measurements are consistent with the deuterium molecules retaining the tensor polarization of the initial atoms. [S0031-9007(97)02449-6]

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In nuclear and high-energy physics, measurements of spin-dependent scattering can provide important information on the largely unknown charge form factor of the neutron [1], and the spin structure of the nucleon [2] and few-body nuclei [3]. The measurement of analyzing powers and spin-correlation parameters in scattering from polarized nuclei can be optimally performed by scattering particles from pure and highly polarized gas targets in particle storage rings. Recently, several such experiments were carried out at IUCF [4,5], NIKHEF [6], BINP [7], and DESY [8], while new experiments have been proposed [9,10]. Although this novel technique has many advantages, in that spin-dependent scattering from chemically and isotopically pure atomic species of high polarization can be realized, it provides a challenge for attaining sufficient luminosities, especially when polarized hydrogen or deuterium is used. Furthermore, there exist many mechanisms that can depolarize the target atoms, mainly through the interaction of the electron spin with external fields associated with the stored particle beam and/or the presence of container walls. This has prompted a significant effort in the past few years devoted to the production of intense polarized atomic beams of hydrogen and deuterium [11–13], the development of suitable coatings [14,15] to preserve the nuclear polarization of these atoms, and the realization of polarimeters [16,17] that can precisely measure the nuclear polarization of the target species.

In the present paper, we investigate the possibility of producing nuclear polarized deuterium molecules by the recombination of atoms prepared in specific hyperfine states. If successful, this technique has the potential to allow the creation of polarized targets of unprecedented performance. The targets would be significantly more dense, and in addition, the nuclear polarization would be more robust due to the noble-gas structure of the electron cloud of the deuterium molecule.

In our experiment, an atomic beam source (ABS) is used to prepare deuterium atoms in specific combinations of hyperfine states [18]. Figure 1 shows that the ABS consists of a radio frequency (rf) dissociator, a cooled nozzle, collimators, sextupole magnets, and rf transition units. It provides a flux of 1.2×10^{16} deuterium atoms s^{-1} in two hyperfine states. A medium-field (MFT) and a strong-field transition unit (SFT) [19] are used to prepare atoms in hyperfine states $|m_I = 0, m_J = +\frac{1}{2}\rangle$ and $|0, -\frac{1}{2}\rangle$, or $|-1, +\frac{1}{2}\rangle$ and $|+1, -\frac{1}{2}\rangle$. Here, I and J represent the nuclear and electron spin of the deuterium atom, respectively. The degree of vector and tensor polarization is defined as $P_z = n_+ - n_-$ and $P_{zz} = n_+ + n_- - 2n_0$, respectively, where n_+, n_0, and n_- are the relative populations of the various nuclear spin projections on the direction of the magnetic field. The substate population is alternated every 10 s, changing the tensor polarization of the deuterium atoms between -2 and $+1$, while keeping the vector polarization at zero. Note that, for the used combinations of hyperfine states, the electron polarization of the ensemble of deuterium atoms was kept constant ($P_e = 0$). This choice eliminates uncertainties due to P_e-dependent processes (e.g., recombination).

The atoms are injected into a windowless T-shaped cylindrical storage cell with 15 mm diameter and 400 mm length. A magnetic holding field of 23 mT is applied over the entire cell region by using two electromagnets. A small fraction of the injected atoms is sampled in a Breit-Rabi polarimeter (BRP) consisting of a sextupole magnet, a chopper, and a quadrupole mass spectrometer (QMS). It is used to determine the hyperfine composition of the target gas. Figure 2 shows that the MFT provides a 1-4 Zeeman

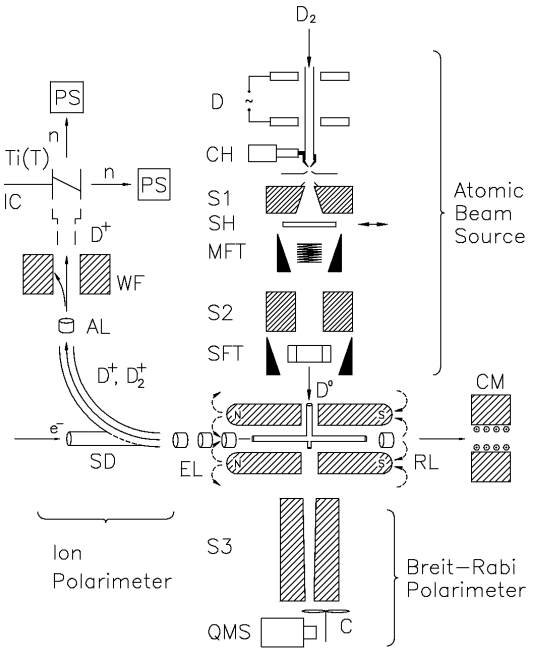

FIG. 1. Schematic outline of the atomic beam source, Breit-Rabi polarimeter, internal target, and ion-extraction system. All components, except the neutron detectors (PS), correction magnet (CM), and target holding field magnet, are inside the vacuum system. D: rf dissociator; CH: cold head; S1, S2,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

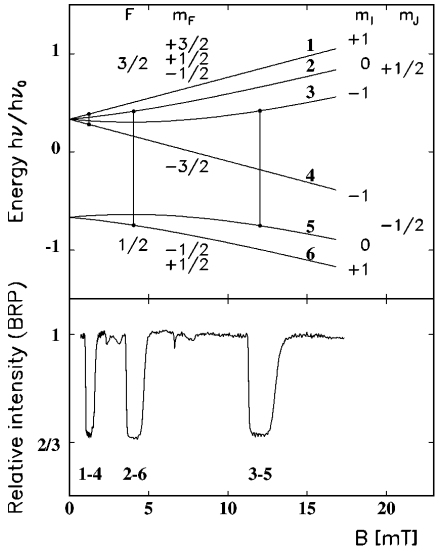

FIG. 2. Top panel: hyperfine structure of deuterium as a function of the static field B. The lines indicate the Zeeman transitions used in the present experiment. Bottom panel: response of the BRP as a function of the central magnetic field in the MFT and SFT.

transition, while the SFT provides either a 2-6 or a 3-5 transition. Each transition involves a collective change of the nuclear- and electron-spin orientation. Therefore, a decrease of $1/3$ in the amount of atoms detected by the QMS with a high-frequency transition unit on, indicates a 100% efficiency of the transition. The 1-4, 2-6, and 3-5 transitions occur with an efficiency of 0.97 ± 0.01, 1.02 ± 0.02, and 0.99 ± 0.02, respectively [19]. Consequently, deuterium atoms in well-controlled mixtures of hyperfine states are injected into the storage cell.

Two different storage cells were used in our experiment: an uncoated copper cell, and an ultrapure aluminum cell coated with a solution of PTFE3170 liquid Teflon diluted with water [20]. The copper cell was constructed from 10 μm thick copper [21] foil and cleaned with trichloroethane before manufacturing. No precaution was taken to avoid natural oxidation of the surface. The PTFE-coated aluminum cell was cooled to approximately 180 K. The copper cell was kept at room temperature. The atoms (molecules) spend about 3 (5) ms in the storage cell, while undergoing about 300 wall bounces. On wall contact, the polarized deuterium atoms will largely recombine to molecules on a copper surface [14], whereas on a PTFE-coated cell surface recombination is strongly suppressed.

The cells were placed in the Amsterdam Pulse Stretcher ring at NIKHEF. Several pulses of 704 MeV electrons were stacked into the ring, yielding currents up to 120 mA and a lifetime exceeding 15 min. The relative amount of atoms and molecules in the two cells was determined by analyzing the fraction of the gas, ionized by the electron beam. Note that, for ultrarelativistic electrons, the ratio of ionization cross sections for molecules and atoms is 2 [22]. The produced ions were prevented from reaching the walls of the storage cell by confining them with a 23 mT longitudinal magnetic field (see Fig. 1). They were, on the one side of the cell, reflected by an electrostatic repeller lens and, on the other side, extracted by using a triplet of lenses and a spherical deflector. A Wien filter separated the atoms from molecules, and we determined the atomic fraction, $\chi = n_{\mathrm{D}}/(n_{\mathrm{D}} + 2n_{\mathrm{D}_2})$, where n_i is the areal target density of the species. The atomic fraction was corrected for a $2 \pm 1\%$ contribution from dissociative ionization of the molecules by the 704 MeV electrons. This contribution was determined by measuring the atomic fraction for a pure molecular (unpolarized) deuterium sample [23]. In addition, the transmission efficiency of the D^+ and D_2^+ ions through the electrostatic setup was determined by injecting known mixtures of H_2 and D_2 gases. The ratio of H_2^+ and D_2^+ ion currents, measured after the Wien filter, was consistent with the prepared mixture ratios to within 3% [23]. We found for the PTFE-coated aluminum (bare copper) cell $\chi = 0.71 \pm 0.02$ (0.26 ± 0.03).

The molecules, $n_{\mathrm{D}_2^{\mathrm{unp}}}$, coming from background gas or from the nozzle will be unpolarized, and only the molecules, $n_{\mathrm{D}_2^{\mathrm{rec}}}$, originating from recombination are potentially polarized. Their contribution was determined

by turning on and off the sextupole electromagnets, as well as by flowing background gas. For the PTFE-coated aluminum (uncoated copper) cell, we found that about 85% (35%) of the molecules in the target cell are due to the molecular beam, residual gas in the target chamber, and diffused flow from the ABS into the feed tube, while about 15% (65%) of the molecules in the storage cell originated from recombination of atoms on the walls. Figure 3 shows the normalized ion current as a function of the magnitude of the Wien filter magnetic field. The peaks at lower and higher magnetic field correspond to D^+ and D_2^+, respectively. It is seen that the PTFE-coated cell contains mostly atoms, whereas a substantial molecular contribution from recombined atoms is realized in the uncoated copper cell. The hatched area represents the contribution of atoms and recombined molecules.

The tensor polarization of the target gas can be written as

$$P_{zz}^{\mathrm{tot}} = \frac{n_{\mathrm{D}} P_{zz}(\mathrm{D}) + 2n_{\mathrm{D}_2^{\mathrm{rec}}} P_{zz}(\mathrm{D}_2^{\mathrm{rec}})}{n_{\mathrm{D}} + 2n_{\mathrm{D}_2^{\mathrm{rec}}} + 2n_{\mathrm{D}_2^{\mathrm{unp}}}}. \quad (1)$$

The nuclear tensor polarization of the deuterium atoms, $P_{zz}(\mathrm{D})$, has been determined by accelerating the atomic ions, produced by the circulating electrons, to 60 keV, which are then used to bombard a tritiated foil [16]. The reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$ was used to measure the tensor polarization directly. For the atoms in the PTFE-coated aluminum (uncoated copper) cell we found $P_{zz}^{+}(\mathrm{D}) = +0.523 \pm 0.005$ ($+0.434 \pm 0.027$) and $P_{zz}^{-}(\mathrm{D}) = -1.037 \pm 0.007$ (-0.974 ± 0.035), where the error represents the statistical accuracy. The deviation from maximum polarization can be explained by the effects of the finite target B field, the $80 \pm 5\%$ state-4 rejection efficiency of the second sextupole [23], and polarization losses in the cell due to atomic spin flip transitions on the walls and spin-exchange collisions.

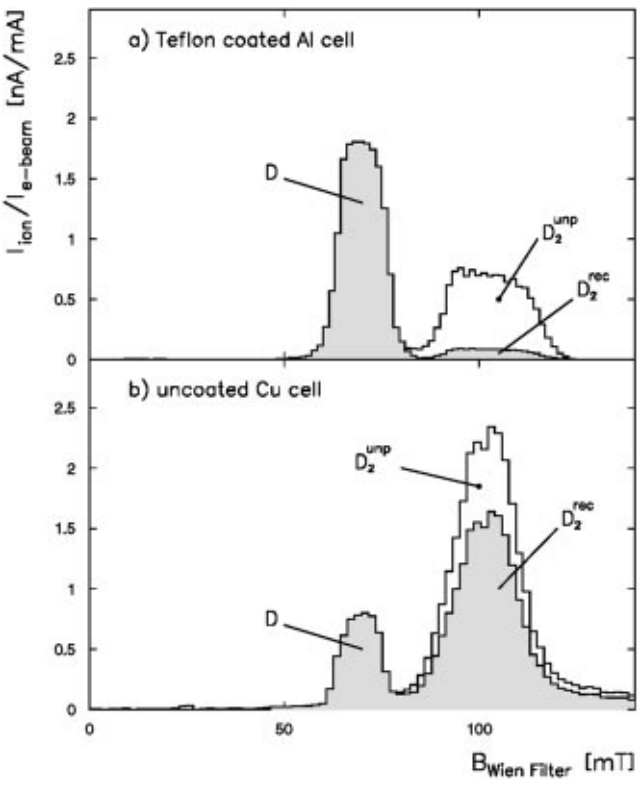

FIG. 3. Normalized ion current as a function of the magnitude of the Wien filter magnetic field. The peaks at lower and higher magnetic field correspond to D^+ and D_2^+, respectively. Results are shown for PTFE-coated aluminum (a) and uncoated copper (b) cells. The hatched area represents the contribution of atoms and molecules which recombined in the storage cells. The unhatched contribution D_2^{unp} represents unpolarized molecules originating from residual D_2 gas and from an undissociated molecular beam.

The tensor polarization of D_2 molecules cannot be measured with the above described polarimeter. It was found that the data for $P_{zz}(\mathrm{D}_2)$ given in Ref. [14] cannot be interpreted to give the tensor polarization of the molecules in the storage cell due to the unknown spin precession angle of the remaining electron in the D_2^+ molecular ion. In passing through the magnetic (fringe) field, the hyperfine interaction then causes uncertainties in the orientation of the nuclear spin at the position of the ^{3}H foil (they applied no magnetic field at this foil). Therefore, we determined the tensor polarization of the molecules by measuring the asymmetry, $A = \frac{N^+ - N^-}{2N^+ + N^-}$, for elastic electron-deuteron scattering at 704 MeV incident energy. Here, N^+ (N^-) are the yields of scattered electrons for deuterium nuclei with tensor polarization P_{zz}^{+} (P_{zz}^{-}). Kinematics were selected where the spin is directed along the momentum transferred by the electron to the nucleus and the yields are sensitive to the tensor analyzing power T_{20} [3]. The target thickness obtained with this ABS amounts to 2×10^{13} atoms cm^{-2}. Scattered electrons are detected in an electromagnetic calorimeter [24] consisting of six layers of CsI(Tl) blocks and two plastic scintillators covering a solid angle of 180 msr. The central angle of the electron detector is positioned at 45°. This results in a coverage in four-momentum transfer between $1.8 < q < 3.2$ fm^{-1} with a cross section and acceptance weighted average of $\bar{q} = 2.3$ fm^{-1}.

The recoil deuterons are detected in a range telescope [25] consisting of 15 layers of 1 cm thick plastic scintillator preceded by 1 layer of 2 mm thickness. An unambiguous separation of the deuterons from protons is obtained by differences in time of flight, in energy loss in the scintillators, and by requiring kinematic correlations between electron and deuteron events. The detector is positioned at a central angle of 62°, and covered a solid angle of nearly 300 msr. Both detectors are preceded by two sets of wire chambers for track reconstruction. The minimum energy of the detected deuterons is 19 MeV.

In a background-free measurement of the reaction $^2\mathrm{H}(e,e'd)$, we found for the elastic electron scattering asymmetries $A^{\mathrm{PTFE}} = -0.232 \pm 0.014$ and $A^{\mathrm{Cu}} = -0.183 \pm 0.043$, where the superscripts PTFE and Cu denote that the measurements were carried out with the PTFE-coated aluminum cell and the copper cell. As

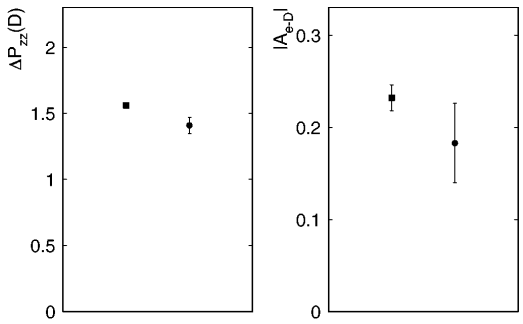

FIG. 4. Left panel: tensor polarization, $\Delta P_{zz}(\mathrm{D})$, of the atoms. Right panel: absolute value of the elastic electron-deuteron scattering asymmetry. Data are given for both the PTFE-coated aluminum (squares) and the uncoated copper cell (circles).

a check on false asymmetries, we measured the asymmetry for unpolarized target gas and obtained $A_{\mathrm{unp}} = 0.000 \pm 0.014$.

Figure 4 shows the tensor polarization, $\Delta P_{zz}(\mathrm{D}) \equiv P_{zz}^{+}(\mathrm{D}) - P_{zz}^{-}(\mathrm{D})$, of the atoms and the absolute value of the elastic electron-deuteron scattering asymmetry for both the PTFE-coated aluminum and the copper cell. All previous internal-target experiments with polarized hydrogen or deuterium (e.g., Refs. [5–8]) have used storage cells with special surfaces, consisting of drifilm or PTFE. However, we observe a significant asymmetry with an uncoated copper cell. It is concluded that the molecules retain most of the tensor polarization of the parent atoms. Compared to a PTFE-coated aluminum surface, atoms exhibit a 10% polarization loss on copper. Since molecules originate from recombination of these atoms, we expect a similar polarization loss for molecules, and thus for A^{Cu}. Assuming that the ratio of molecular over atomic tensor polarization is the same for the copper and the PTFE-coated aluminum cell, we obtain for the nuclear tensor polarization of the molecules from recombined atoms $\Delta P_{zz}(\mathrm{D}_2^{\mathrm{rec}}) = (0.81 \pm 0.32) \times \Delta P_{zz}(\mathrm{D})$. Such a high polarization indicates the possibility of developing a polarized molecular target. Here, the paired electrons in a hydrogen and/or deuterium molecule are chemically stable, and interact weakly with the spin of the nucleus. This may allow one to develop a robust polarized H_2/D_2 target, insensitive to beam-induced depolarization, polarization losses due to spin-exchange collisions, and radiation damage of the cell surface.

In summary, combining the asymmetries obtained from elastic electron-deuteron scattering, the atomic-to-molecular ratios measured with the Wien filter and the atomic nuclear tensor polarizations seen in the ion-extraction polarimeter, we find that molecules produced by recombination of atoms retain most of the atomic nuclear tensor polarization in a copper cell. The techniques discussed here may have broad applicability to future developments in spin-dependent scattering experiments.

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