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Measurement of p_{zz} of the Laser-Driven Polarized Deuterium Target

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Abstract

The question of whether nuclei are polarized as a result of H—H (D—D) spin-exchange collisions within the relatively dense gas of a laser-driven source of polarized hydrogen (deuterium) can be addressed directly by measuring the nuclear polarization of atoms from the source. The feasibility of using a polarimeter based on the $D + T \rightarrow n + {}^4He$ reaction to measure the tensor polarization of deuterium in an internal target fed by the laser-driven source has been tested. The device and the measurements necessary to test the spin-exchange polarization theory are described.

Introduction

The laser-driven polarized hydrogen/deuterium source (LDS), which is described elsewhere[1], has been demonstrated recently[2] at flow rates of polarized hydrogen up to 1.7×10^{18}/s with $\geq$ 50% electron polarization. Deuterium polarizations of $\geq$ 40% have been demonstrated up to flow rates of 0.9×10^{18}/s. Compared to conventional atomic beam sources, which have not produced hydrogen flow rates larger than 8×10^{16}/s with 95% polarization, the optical pumping technique can polarize rapidly relatively dense samples of the hydrogen isotopes. Such a source is of general interest for atomic, plasma, nuclear, and high energy physics. One specific use of the LDS which has recently received much attention is as the source of polarized nuclei for an internal target in an electron storage ring. The Argonne laser-driven polarized deuterium internal target will be installed in the VEPP-3 electron storage ring (Novosibirsk, Russia) in 1994 for a measurement of the tensor analyzing power in electron-deuteron scattering at high momentum transfer[3].

For this application one must polarize the target nuclei, and to date only the electron polarization of the hydrogen and deuterium atoms from the laser-driven source has been measured. Given the recent progress in the development of the source[2], the most important outstanding question concerning its viability as a polarized target for nuclear physics experiments is the nuclear polarization achievable with the system. Recently Walker and

Anderson[4] suggested that in a dense sample of polarized hydrogen (deuterium, tritium) H–H spin-exchange collisions drive the system to a spin-temperature distribution of the magnetic substates, effectively transferring polarization from the electrons to the nuclei. If this suggestion is correct, the nuclei can be polarized without inducing RF transitions, a significant technical advantage. Measurements of the electronic polarization of both hydrogen and deuterium as a function of density and magnetic holding field indicate that the calculation of Walker and Anderson may be correct[2], but the definitive test will be a direct measurement of the nuclear polarization. To this end, a polarimeter has been set up at Argonne National Laboratory to measure the tensor polarization of deuterium from an internal target fed by the LDS. The device is described here, along with the series of measurements that will be done to test the predictions of Walker and Anderson.

Determination of p_{zz}

The polarimeter used at Argonne is based upon a working apparatus developed and tested with polarized deuterium from an atomic beam source by Price and Haeberli[5] at U. of Wisconsin-Madison. The polarimeter uses the low energy $D + T \rightarrow n +^4 He$ reaction, which displays an anisotropy in the angular distribution of the outgoing neutrons if the deuterium ions are tensor polarized. At low energy the $D(T,n)^4He$ reaction can proceed through both $J^\pi = 3/2^+$ and $J^\pi = 1/2^+$ resonances in ^5He. The unpolarized cross section has a broad resonance peak centered at a deuteron energy of 110 keV corresponding to the $J^\pi = 3/2^+$ channel, which dominates the cross section at low energy. The expression for the cross section for a tensor-polarized incident deuteron beam is

$$\sigma(\theta) = \sigma_0(\theta)\left(1 - \frac{f}{4}p_{zz}(3\cos^2\theta - 1)\right). \qquad [1]$$

σ_0 is the unpolarized cross section, which is isotropic, θ is the angle between the direction of the outgoing neutron and the spin of the deuteron in the center-of-mass system, p_{zz} is the tensor polarization of the deuteron, and the dilution factor f accounts for the small admixture of the $J^\pi = 1/2^+$ reaction channel, which has no tensor analyzing power. The dilution factor has been measured and found to be nearly unity ($f \approx 0.96$) for ion energies in the range used for the polarimeter[6]. The neutron anisotropy R, defined as

$$R = \frac{\sigma(0^\circ)}{\sigma(90^\circ)} = \frac{1 - \frac{f}{2}p_{zz}}{1 + \frac{f}{4}p_{zz}}, \qquad [2]$$

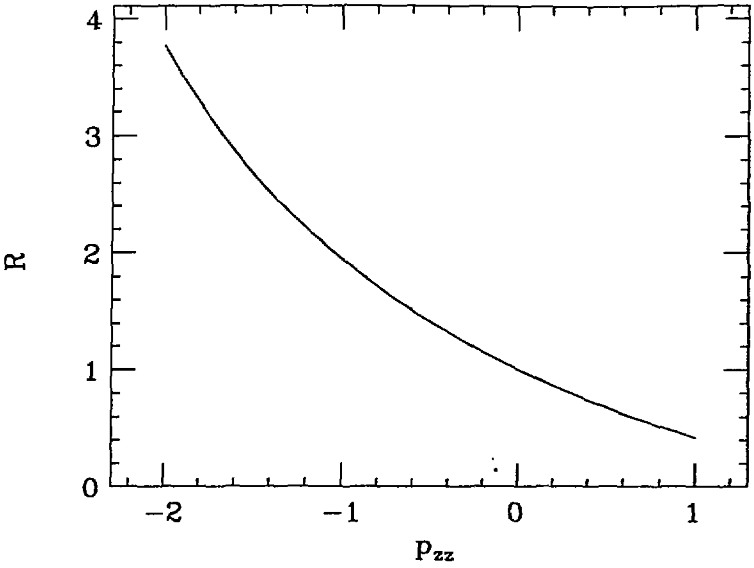

Figure 1. Neutron anisotropy as a function of tensor polarization.

is plotted as a function of p_{zz} in Figure 1.

The apparatus is shown schematically in Figure 2. The polarized deuterium flows from the optical pumping cell through a glass transport tube and a teflon getter, which removes the potassium, into the storage cell. A solenoidal coil surrounding the storage cell creates the magnetic holding field that serves both to decouple the electronic and nuclear spins and as a guide field for the ions to prevent them from hitting the cell walls. The storage cell is 48 cm long and 19 mm in diameter. The longitudinal holding field is 330 Gauss over most of the length of the storage cell; the value at the center of the cell where the atoms enter from the LDS is 270 Gauss. A small hole opposite the entrance port allows $\sim$ 10% of the atoms to leak out of the cell to be analyzed by a sextupole magnet and quadrupole mass spectrometer which serves as an electron polarimeter. The storage cell is coated with Drifilm to reduce recombination at the surface and is heated to 140° C to prevent any potassium entering the cell from condensing on the surface where it would cause molecular recombination.

Electrons from an electron gun are accelerated to $\sim$ 2 kV and pass through the storage cell, ionizing the deuterium. The ions follow the magnetic field lines to the end of the storage cell, where they are either reflected by a positive potential at the electron gun end or extracted and accelerated towards a tritiated titanium foil target at the other end. A Wein filter ($\vec{E} \times \vec{B}$) between the storage cell and the tritium target acts as a velocity se-

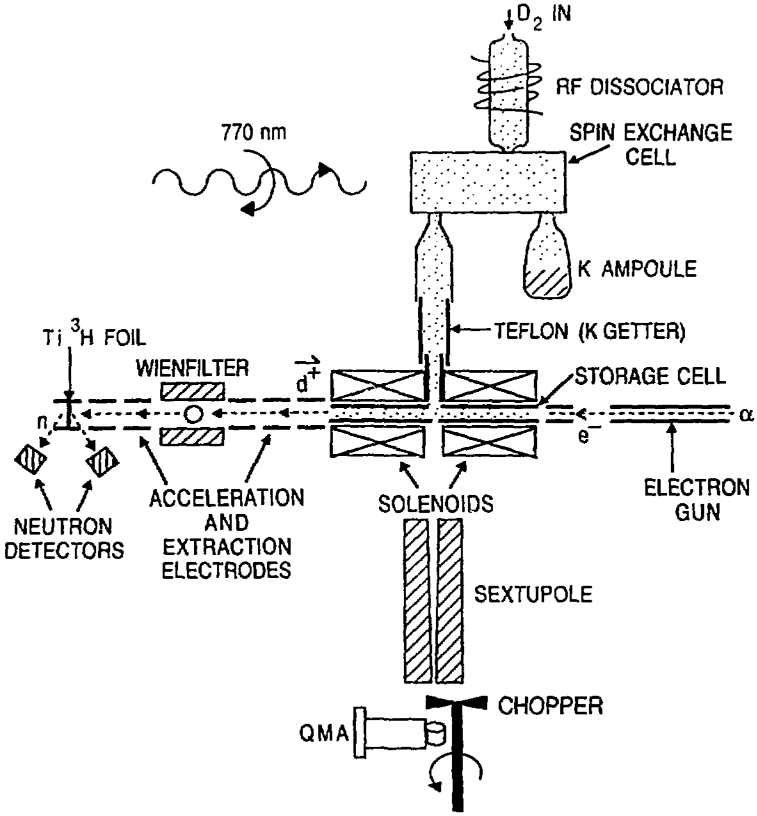

Figure 2. Schematic of the laser-driven source, the deuteron nuclear polarimeter, and the electron polarimeter.

lector to separate deuterium atoms and molecules. The spin direction, which is parallel to the solenoidal holding field in the storage cell, precesses in the B-field of the Wein filter according to the relationship

$$\frac{d\vec{S}}{dt} = \frac{g\mu_N}{\hbar}\vec{S} \times \vec{B}, \qquad [3]$$

where $g = 0.857$ is the Landé g-factor for the deuteron. The spin rotates $\sim 40°$ in the field used in the measurements described here. The tritium foil is mounted inside an electrostatic lens maintained at 30 kV. Outgoing neutrons are detected in two NE110 scintillators ($7.6 \times 5.1 \times 3.8$ cm) placed outside the vacuum chamber at $\theta = 0°$ and $\theta = 90°$. Initial tests of the polarimeter with unpolarized deuterium show that the measurements are reproducible to better than $\Delta R/R = 0.01$. Corrections for the finite detector size are less than 1%. The largest systematic uncertainty is expected to be the determination of the deuteron spin orientation at the tritium foil. This can be found by moving the detectors to find the maximum value of R.

Tests of the Spin-Temperature Prediction

According to Walker and Anderson, in a dense sample of polarized hydrogen, deuterium, or tritium spin-exchange collisions drive the system to a spin-temperature distribution of the magnetic substates where the relative population density of a sublevel with total angular momentum magnetic quantum number m_F is

$$\rho(m_F) = e^{\beta m_F}/N. \qquad [4]$$

Both N and β depend upon the total angular momentum stored in the system. Even in a large magnetic field the system is driven towards a spin temperature distribution, although the time constant to reach equilibrium is larger at higher field.

The experimental consequences of this prediction are marked. The optical pumping process transfers angular momentum from photons to the electrons in an atom, so if this prediction is true then both the vector and tensor polarization of the deuterons will be nonzero, while the nuclear polarizations will be identically zero if this mechanism is not at work. If D–D spin-exchange collisions redistribute the angular momentum between the atoms and nuclei, then optical pumping with either σ_+ or σ_- light will tend to deplete the $m_I = 0$ state, resulting in $p_{zz} > 0$ for either helicity pumping light. Figure 3 shows the values of the electron, vector, and tensor polarizations of deuterium in a population that has a spin temperature distribution with temperature parameter β in the limit of $B \gg B_{crit}$, where the critical field B_{crit} for deuterium is 117 Gauss. Since an electronic polarization of $\sim 50\%$ is observed currently with the LDS, we should measure a tensor polarization of $\sim +0.3$ if the system is in spin temperature equilibrium. The limit for the tensor polarization achievable with a spin temperature distribution is $+1.0$. In Figure 3 one also sees the interesting feature that the vector polarization of the deuteron is larger than the electron polarization for a spin temperature distribution, so an electron polarization of 50% corresponds to a vector polarization of $p_z = 65\%$.

Whether the polarized atoms from the LDS have a spin temperature distribution depends upon the equilibration rate, which is given in Reference 5 as

$$\frac{1}{T_{ST}} = \frac{(h\nu_{hfs})^2}{(h\nu_{hfs})^2 + (g_s\mu_B B)^2} n < \sigma_{se} v > . \qquad [5]$$

$h\nu_{hfs}$ is the ground state hyperfine splitting in zero field, $g_s\mu_B B$ is the field-dependent electron energy shift, and $n < \sigma_{se} v >$ is the thermally-averaged

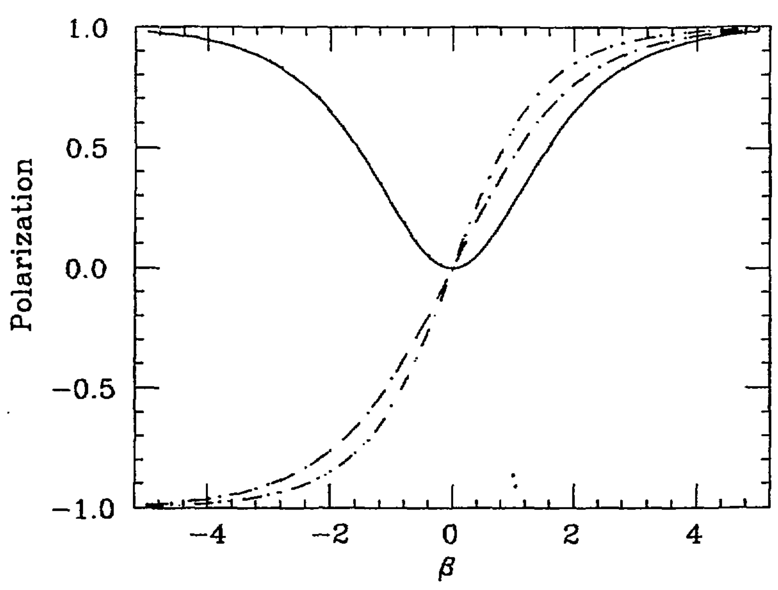

Figure 3. The electron (dash), vector (dotdash), and tensor (solid) polarizations for deuterium atoms in spin-temperature equilibrium as a function of the temperature parameter β.

H−H (D−D) spin exchange rate, which depends upon the density n, the velocity v, and the spin-exchange cross section[7], $\sigma_{se} = 2 \times 10^{-15}/\text{cm}^2$. The hyperfine splitting for hydrogen is 1420 MHz, for deuterium is 327 MHz, and for tritium is 1517 MHz, so spin-temperature equilibrium is reached much faster in hydrogen and tritium than in deuterium. From equation 5 it is clear that T_{ST} decreases with increasing density and increases with decreasing B-field. For the LDS, the dwell time of deuterium atoms in the spin-exchange cell is 7 ms, and the time for deuterium to reach spin temperature equilibrium in the spin-exchange cell is estimated to vary from $0.4 < T_{ST} < 70$ ms for the range of densities and magnetic fields where the LDS is operated. This is an interesting region to study because it should be possible to observe the transition to a spin temperature distribution.

A series of measurements are planned to ascertain whether the deuterium target can be polarized without the use of RF transition units. The target polarization p_{zz} will be measured for both σ_+ and σ_- pumping light as a function of flow ($2 - 10 \times 10^{17}$/s) and magnetic holding field in the spin-exchange cell (0.8 – 4 kG). In addition, RF transitions can be induced and the value of p_{zz} measured. If the system is driven to spin-temperature equilibrium in the transport tube then the transitions should not result in a higher value of p_{zz}.

Perhaps the most important consequence of a verification of the predictions of Walker and Anderson is that it would be demonstrated that the laser-driven source is capable of easily producing high flows of vector polarized hydrogen and deuterium with polarizations $> 50\%$. Another interesting possibility that becomes feasible is that one could polarize hydrogen, deuterium, or tritium nuclei in a sealed system; an experiment which makes use of this technique to construct a sealed polarized tritium target was recently proposed[8]. Finally, these tests will allow us to optimize the achievable polarization figure of merit, $p_{zz}^2 f$, where f is the flow rate, for experiments requiring tensor polarized deuterium.

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