Spin-Exchange Optical Pumping as a Source of Spin-Polarized Atomic Deuterium

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Optical pumping of potassium atoms followed by spin-exchange scattering with deuterium atoms in a high magnetic field was found to produce an intense, highly spin-polarized beam of atomic deuterium. In particular, the atomic polarization of deuterium was determined to be $(73 \pm 3)\%$ at an intensity of 2.1×10^{17} atoms/s.

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In the past few years, the possibility of using dilute polarized gases as polarized nuclear targets in particle storage rings has driven the quest for intense spin-polarized beams of atoms. We report the first results of a high intensity source of polarized deuterium atoms suitable for such targets that is based upon spin-exchange optical pumping in a high magnetic field. Thus far there have been proposals to use internal polarized gas targets [1] at the VEPP-3 and NEP rings at Novosibirsk, the UNK ring [2] at Serpukov, the HERA ring [3] at DESY, the cooler ring [4] at Indiana University Cyclotron Facility, and the electron stretcher rings [5] at MIT-Bates, NIKHEF, and Saskatoon. With a conventional atomic beam source [6] which can produce an intensity of $\sim 1.5 \times 10^{16}$ polarized deuterium atoms/s, the resulting target thickness, even with the use of storage cells, renders many such exciting experiments impractical.

In addition to nuclear and high-energy physics, there is a strong interest in atomic physics for a dense highly polarized gas of atoms. A simple electron-polarized hydrogen target is useful for experiments in atomic physics; for example, charge exchange in such a target can be used to form hydrogenlike heavy ions for the study of parity nonconservation [7]. Resonance experiments with polarized heavy ions to measure hyperfine structure in few-electron systems can provide a stringent test of atomic structure calculations [8]. In addition, the target can be used for detailed studies of state-selective electron capture [9]. Again, present conventional atomic beam sources are insufficient for these experiments.

Although the principle [10] of spin-exchange optical pumping has been known for some time, previous attempts [11] to develop this process into a practical source of polarized atoms have met with limited success because of radiation trapping in the optically pumped alkali atoms. In the present work, we demonstrate that performing the spin-exchange optical-pumping process in a high magnetic field has the potential to lead to a polarized deuterium source of unprecedented performance. The central idea is that alkali atoms can be readily polarized by optical pumping and that this polarization can be transferred to deuterium by spin-exchange scattering between the alkaki and deuterium. The rate equations [12] for optical-pumping spin exchange in a high magnetic field (where only the electron-spin polarization is important) lead to a simple relation for the deuterium atomic polarization, P_e. In terms of the alkali polarization, P_a,

$$P_e = \frac{\gamma_{\mathrm{SE}}}{\gamma_{\mathrm{SE}} + \gamma_R} P_a , \tag{1}$$

where γ_{SE} is the spin-exchange rage and γ_R is the deuterium spin-relaxation rate. The spin-exchange rate depends on the spin-exchange cross section and the alkali density, whereas the relaxation rate depends on all polarization losses, e.g., collisions with the cell walls and loss of polarized atoms out of the cell. The main problem with optical-pumping spin exchange at low field is that high alkali polarization is limited to very low alkali density ($\ll 10^{12}$ atoms/cm^3) by radiation trapping. This typically limits the spin-exchange rate to 300 s^{-1}. The radiation trapping limit at high field, however, is known [13] to occur at higher alkali densities ($\lesssim 10^{13}$ atoms/cm^3) because of the increased spacing between the σ and π light absorption due to Zeeman splitting. Thus, by applying a high field, high alkali polarization can be maintained at higher alkali density corresponding to a higher spin-exchange rate.

In the present experiment, potassium was optically pumped at 770.1 nm using approximately 2 W of 770.1-nm light from an Ar-ion–pumped Ti-sapphire laser operating in a single mode. The experimental arrangement is shown schematically in Fig. 1. The laser photons passed through a $\frac{1}{4}$-wave plate and the central axis of a dipole magnet pole tip before impinging on a drifilm-coated [14] Pyrex cell (22 mm diam×45 mm length). The magnetic field was set to 2.2 kG, in order to permit a rapid and convenient change in frequency from σ^+ to σ^- circularly polarized light, since the level spacing in K at this field is equal to the free spectral range of the intracavity thick etalon. Atomic deuterium effused into the

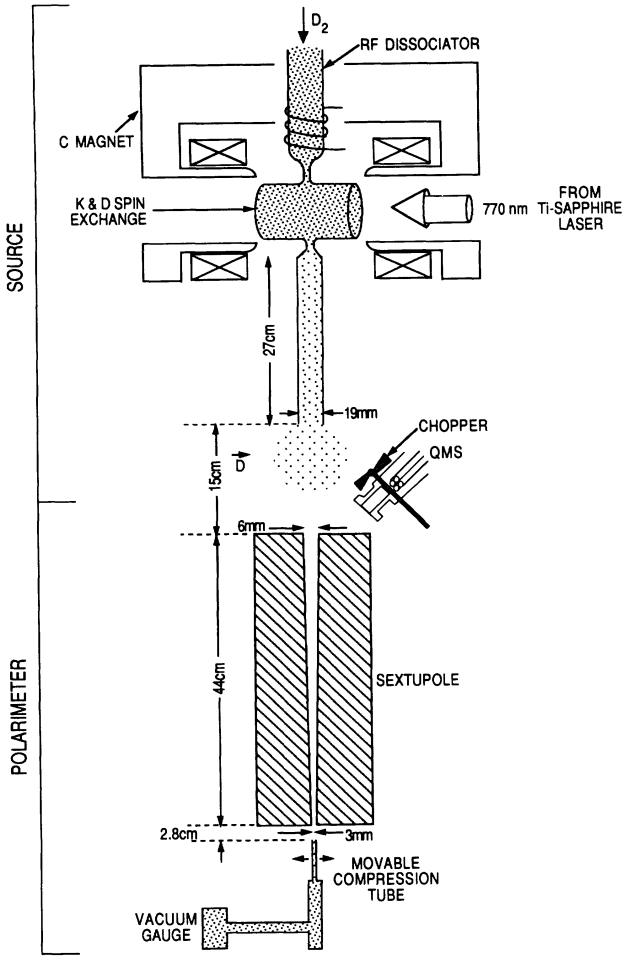

FIG. 1. Schematic diagram of the high-field optically pumped spin-exchange source and the polarimeter.

cell from an rf dissociator tube and K was introduced through a small (1.2 mm diam) hole in the side of the cell. In the present tests, the K density, determined from the temperature of the reservoir, was 1.7×10^{12} atoms/cm^3 corresponding to a flow of 9.4×10^{14} atoms/s. The deuterium density in the cell was 8.6×10^{13} atoms/cm^3, estimated from a flow of 2.1×10^{17} deuterium atoms/s. This flow is measured by a differential pressure gauge over a known conductance [15]. This leads to an estimated spin-exchange rate $\gamma_{SE}=1700\ s^{-1}$. This spin-exchange rate is more than a factor of 6 higher than could be achieved at low field.

The atoms exited the cell through a small hole (2.8 mm diam) and then traveled through a drifilm-coated Pyrex exit tube (19 mm diam×276 mm length). The spin-exchange cell and the exit tube are maintained at a temperature of 240 °C to inhibit alkali deposition on the glass walls. The polarization of the atoms exiting from this transport tube was measured with a permanent sextupole magnet followed by a compression tube with a vacuum gauge as indicated in Fig. 1. The principle of this polarimeter is that the sextupole focuses spin-up atoms and defocuses spin-down atoms. Thus, when the optical-pumping spin exchange is performed with σ^+ (σ^-) light, one would expect to see a signal in the compression tube detector that corresponds to all (none) of the atoms for 100% deuterium polarization; if the laser light is blocked, the signal would correspond to half of the atoms. The compression tube detector could be scanned across the focus of the sextupole, thereby permitting measurement of the background from ambient atoms and molecules in the vacuum chamber. In order to minimize this background, three differentially pumped vacuum regions were employed. A typical value for the ambient pressure as measured by the compression tube was 3×10^{-8} torr. To extract the polarization of the atoms in the beam, it was also necessary to determine the amount of molecular deuterium that entered the compression tube as a molecular beam emanating from the transport tube. This was determined by measuring the compression tube signal when the rf dissociator was off and by measuring the molecular fraction, i.e., the ratio of the yield of mass-4 molecules (D_2) with the dissociator on to that with the rf off. The molecular fraction was measured nearly simultaneously with the polarization by passing a small amount of chopped beam from the exit of the transport tube through a quadrupole mass spectrometer (QMS) as indicated in Fig. 1. In the present case, the molecular fraction was found to be 0.35 ± 0.03.

The results for a magnetic field of 2.2 kG for three conditions of laser light (σ^+, σ^-, and no light) are shown in Fig. 2. Clearly, from the observation of the three distinct curves shown in Fig. 2(a), the polarization of the deuterium atoms is large. In order to see the beneficial effect of the high magnetic field, the polarization at the same potassium density was measured at low field (~30 G). The corresponding curves are shown in Fig. 2(b) and the resulting polarization is only 5% to 10%.

This improvement may not arise solely from suppression of radiation trapping [16]; there may also be a decrease in the loss of deuterium and potassium polarization from cell wall collisions. This would mean that γ_R in Eq. (1) is smaller than at low field. Further studies are necessary to isolate this effect. In particular, the K polarization must be measured independently from the deuterium polarization. It is not possible to measure the K polarization with the present polarimeter, since the K intensity from the source is more than a factor of 100 lower than the deuterium intensity. From Eq. (1) and taking $P_A=1$, an upper limit on γ_R is determined to be $630\ s^{-1}$.

In order to fully demonstrate the power of the present method, we compare the figure of merit for this source with that of the highest intensity deuterium source. The Novosibirsk deuterium source [6] has achieved 96% [(100% atomic polarization)×(96% atomic fraction)] at 1.5×10^{16} atoms/s while the present source has produced 47% [(73% atomic polarization)×(65% atomic fraction)]

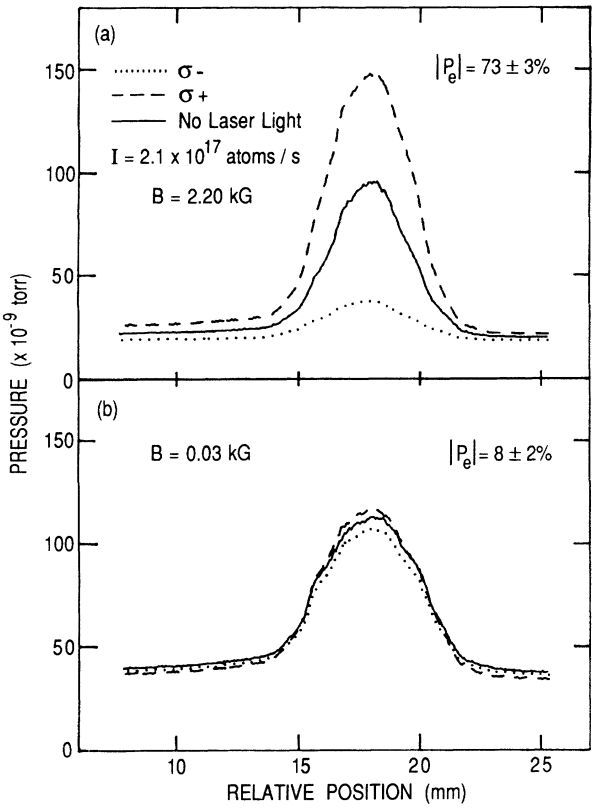

FIG. 2. (a) Signal from a scan of the compression tube and detector across the focal plane of the sextupole for three cases: (i) σ^+ laser light (dashed curve), (ii) no laser light (solid curve), and (iii) σ^- laser light (dotted curve) for a magnetic field of 2.2 kG. (b) Same as (a) with a 30-G magnetic field.

at 2.1×10^{17} atoms/s. Since the figure of merit is the square of the polarization times the intensity, the performance of the first high-field spin-exchange optically pumped source exceeds the best previous deuterium source by a factor of 3.4. For an experiment [8] that requires only polarized atoms, this figure-of-merit comparison is valid. Of course, for nuclear and high-energy experiments [1–5], the figure of merit must reflect the K dilution and thus would typically be a factor of only 1.7 greater than the conventional source.

Besides a higher figure of merit, the present source has a novel feature compared with the conventional atomic beam source, namely, that the polarization of the atoms can be reversed or can be made zero merely by changing the helicity of the light. For example, changing the helicity of the light allowed the atomic polarization to be measured without rf transitions in the present work. Polarization reversal for a conventional atomic beam source is more difficult since the source is based on the use of a magnetic sextupole. In this case, a reversal can be performed only by selecting different high-frequency rf transitions which typically involve changing the value of a magnetic field.

Although obtaining a high intensity of polarized deuterium atoms is an essential step, it is necessary to induce atomic transitions [17] in the source transport tube in order to obtain high nuclear polarization. A Monte Carlo calculation suggests that a nuclear polarization P_{zz} of 0.9 can be achieved for 100% polarized deuterium atoms by placing a medium-frequency rf transition unit over the output tube. With 100% efficiency, these rf transitions would give a maximum $P_{zz} = -1$ for σ^+ optical pumping and $+1$ for σ^- light.

A further improvement would be to increase the deuterium intensity by correspondingly increasing the laser power. In addition, it is believed that the molecular fraction can be decreased by minimizing contamination of the dissociator tube with drifilm.

In summary, the first test of a polarized deuterium source based on spin-exchange optical pumping in a high magnetic field has produced a figure of merit which significantly exceeds that of previously reported values [6] for a conventional atomic beam source. This work has significant implications for the many facilities planning internal polarized target experiments. Further development of this method should produce polarized targets with 10^{14}–10^{15} cm^{-2}, a thickness range which will render many new experiments feasible in atomic, nuclear, and high-energy physics.

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