A LASER DRIVEN SOURCE OF SPIN POLARIZED ATOMIC HYDROGEN AND DEUTERIUM

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ABSTRACT

Recent results from a laser-driven source of polarized hydrogen (H) and deuterium (D) are presented. The performance of the source is described as a function of atomic flow rate and magnetic field. The data suggest that because atomic densities in the source are high, the system can approach spin-temperature equilibrium although applied magnetic fields are much larger than the critical field of the atoms. We also observe that potassium contamination in the source emittance can be reduced to a negligible amount using a teflon-lined transport tube.

INTRODUCTION

Experiments have been performed and have been proposed that use stored internal targets of H and D atoms within electron storage rings [1]. Sources of polarized H and D, namely the ultra cold source and the atomic beam source, are described in these proceedings [2]. The laser driven source of polarized H and D described herein relies on the technique of spin-exchange optical pumping where photon angular momentum is transferred to target nuclei via spin-exchange collisions with polarized potassium atoms. The principle of spin-exchange optical pumping has long been known [3], however, early attempts to develop this idea into a practical source have met with limited success as a result of radiation trapping [4]. Recently it was reported that high D polarization could be obtained by performing spin-exchange optical pumping in a high magnetic field thereby alleviating the ill effects of radiation trapping [5]. In this paper, we report the first polarized H results from the Argonne laser-driven source. Source performance is described as a function of H and D atomic flow rate and magnetic field. Also, we report greatly reduced potassium contamination in source emittance using a teflon-lined transport tube.

EXPERIMENTAL TECHNIQUE

The laser-driven source apparatus is described in refs. [5,6]; only a short description of the source is given here. Molecular H (or D) is dissociated in an rf inductive discharge and sent into a drifilm-coated spin-exchange cell containing potassium vapor. The potassium is optically pumped and polarized with a single-

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frequency titanium sapphire laser in the presence of a high magnetic field. Electron spin is transferred to H (D) atoms during collisions with polarized potassium atoms;

$$H(\uparrow) + K(\downarrow) = H(\downarrow) + K(\uparrow) \quad (1)$$

H (D) atoms leave the spin-exchange cell and travel through a transport tube to a vacuum chamber that contains an electron-spin polarimeter. The polarimeter consists of a quadrupole mass analyzer (QMA) and a permanent sextupole magnet which focuses electron "spin-up" atoms and defocuses electron "spin-down" atoms. Atomic polarization is determined by comparing QMA signals when the pump laser is blocked and then directed into the spin-exchange cell [5]. The QMA is also used to measure degree of dissociation.

FLOW RATE AND MAGNETIC FIELD RESULTS

The performance of the source has been investigated as a function of flow rate. Figure 1 shows measured H and D atomic polarization values as a function of total intensity of atoms. Polarization values were obtained over similar dissociator region pressures where degree of dissociation (Df) was high and nearly constant (≈75%). Maximum H flow rate exceeds that of D by a factor of approximately $\sqrt{2}$ as a result of increased dissociator conductance for H. The data were obtained with a magnetic field of 4.4 kGauss and with approximately 3 Watts of pump laser power incident upon the spin-exchange cell. The potassium sidearm was maintained at 188°C resulting in a potassium density within the spin-exchange cell of approximately $4x10^{11}$ atoms/cm^3. Higher H and D polarization values are obtained by increasing the potassium density within the spin-exchange cell [6], however higher sidearm temperatures are undesirable as that would require maintaining the spin-exchange cell and transport tube at temperatures > 250°C [7]. High atomic polarization ($P_e \approx 80\%$) is measured for both H and D at a flow rate of $2x10^{17}$ atoms/second. Polarization values decrease with increasing flow, however D polarization is observed to decrease more rapidly than H polarization.

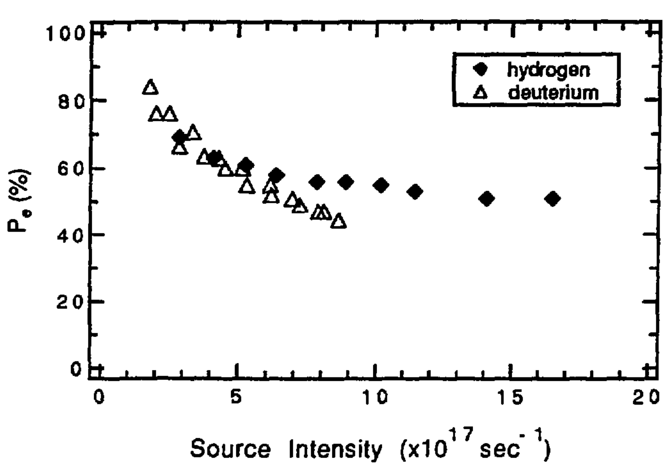

Figure 1. H and D atomic polarization as a function of total source intensity.

The performance of the source was also investigated as a function of magnetic field. A simple rate equation model that accounts only for optical pumping of potassium atoms and spin-exchange collisions between potassium and H (D) atoms predicts that H (D) polarization should not vary with changing magnetic field [8]. Figure 2 shows measured H and D atomic polarization values as a function of flow rate for three different magnetic field conditions in the spin-exchange cell. The data were obtained with approximately 3 Watts of pump laser power incident upon the spin-exchange cell. The potassium density within the spin-exchange cell was approximately equal to $4x10^{11}$ atoms/cm^3. The degree of dissociation over the range of flow rates tested was approximately 75%. H polarization is observed to be relatively insensitive to changing magnetic field; D polarization however depends significantly on magnetic field. The field dependence of the D data cannot be explained with the simple rate equation optical-pumping spin-exchange model.

Recently, it has been proposed that spin-exchange optical pumping in a high magnetic field can yield direct polarization of the nucleus without actively performing rf hyperfine transitions [9]. Although high magnetic fields generally weaken the influence of the hyperfine coupling between the nucleus and the electron, frequent H·H (D·D) collisions increase the total probability for a hyperfine interaction to occur. Under such a condition, atoms approach spin-temperature equilibrium and nuclei become polarized through hyperfine interaction with polarized electrons. A system approaches spin-temperature equilibrium in a time given by;

$$T_{st} = (1+(\frac{g_s \mu_B B}{\delta v_{hfs}})^2)T_H \quad (2)$$

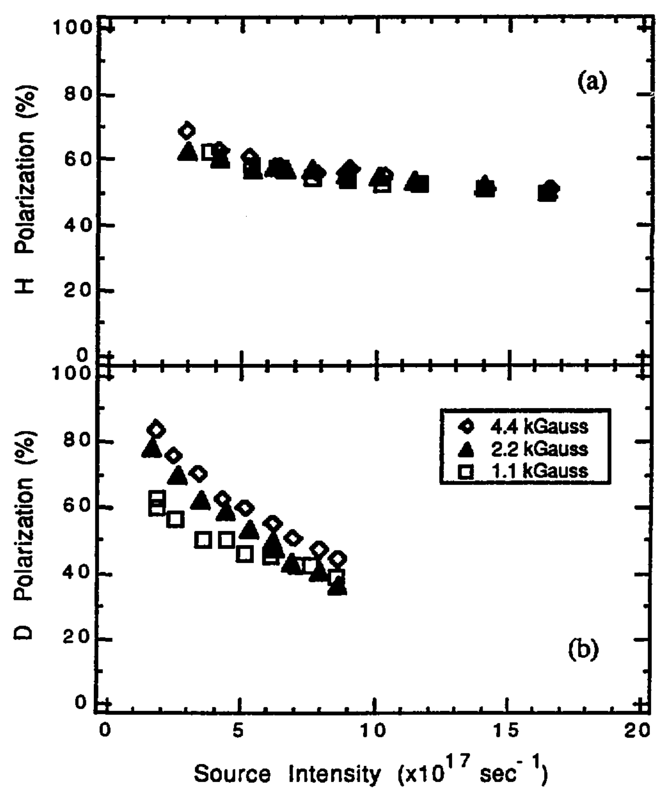

Figure 2 (a) H polarization as a function of total H intensity for three magnetic field conditions. (b) D polarization as a function of total D intensity for three magnetic field conditions.

where $\delta\nu_{hfs}$ is the ground-state hyperfine splitting in zero magnetic field, $g_s\mu_B B$ is the energy shift of the electron in a magnetic field B, and $T_H^{-1} = n_H < \sigma_{se}(HH) \cdot v >$ is the thermally averaged H·H spin-exchange rate, where n_H is the hydrogen density, $\sigma_{se}(HH)$ is the spin-exchange cross section equal to $2x10^{-15} cm^{-2}$ [10] and v is the thermally averaged velocity.

H and D polarization data obtained with the Argonne laser-driven source as a function of flow rate and magnetic field provide an excellent test of this novel feature of the spin-exchange process since densities within the source are high and because the large difference in the magnetic moments of the nuclei will give very different rates for approach to spin-temperature equilibrium. For comparable flow rates, H will approach spin-temperature equilibrium more quickly than D because of the comparatively larger hyperfine splitting for H ($\delta\nu_{hfs}(H)$=1420 MHz, $\delta\nu_{hfs}(D)$=327 MHz). This statement is evident when calculating T_{st} values for flow rate and magnetic field conditions parameterized by Figure 2 and comparing these values to t_{dwell}, the dwell time of an atom in the spin exchange cell. Atoms approach spin-temperature equilibrium when $T_{st} << t_{dwell}$. For H atoms, T_{st} values are less than t_{dwell} for both high and low field conditions ($0.03 < T_{st} < 3.0$ msec; $t_{dwell}(H) = 5$ msec). As a result, H polarization is relatively insensitive to changing field in Figure 2a. Thus, H atoms approach spin-temperature equilibrium for each of the three magnetic field conditions tested. For D atoms, T_{st} values can be made both less than and greater than t_{dwell} ($0.43 < T_{st} < 67$ msec; $t_{dwell}(D) = 7$ msec). As a result, D polarization in Figure 2b is observed to be highly sensitive to changing magnetic field. D atoms approach spin-temperature equilibrium only for low field conditions.

POTASSIUM GETTER RESULTS

We observe that when a teflon sleeve is inserted into the transport tube of the laser-driven source, potassium contamination in the source emittance is reduced to a negligible amount. Potassium contamination is undesirable for internal target experiments described in ref.[1] because it dilutes the target with unpolarized potassium nuclei and necessitates the heating of the target cell to prevent potassium condensation and subsequent molecular recombination on the target cell wall. To investigate the extent to which the teflon sleeve acts as a potassium getter, a 10 cm long piece of teflon tubing (19 mm o.d., 17 mm i.d.) was inserted into the bore of the transport tube and the ratio of potassium atoms to hydrogen atoms in the source emittance was measured with the QMA described above. Also, the effect of the teflon sleeve on source polarization was monitored by measuring H polarization throughout the duration of the test.

Figure 3a shows the ratio of potassium atoms to H atoms in the source emittance measured during 140 hours of source operation. (Source operation was not continuous. Typically, the source would operate for six or seven hours followed by overnight shut-down and continued operation the next day.) Throughout the test, the total source intensity was constant to within 5% at $5x10^{17}$ atoms/second. The data were obtained with a magnetic field of 4.4 kGauss and with approximately 3 Watts of

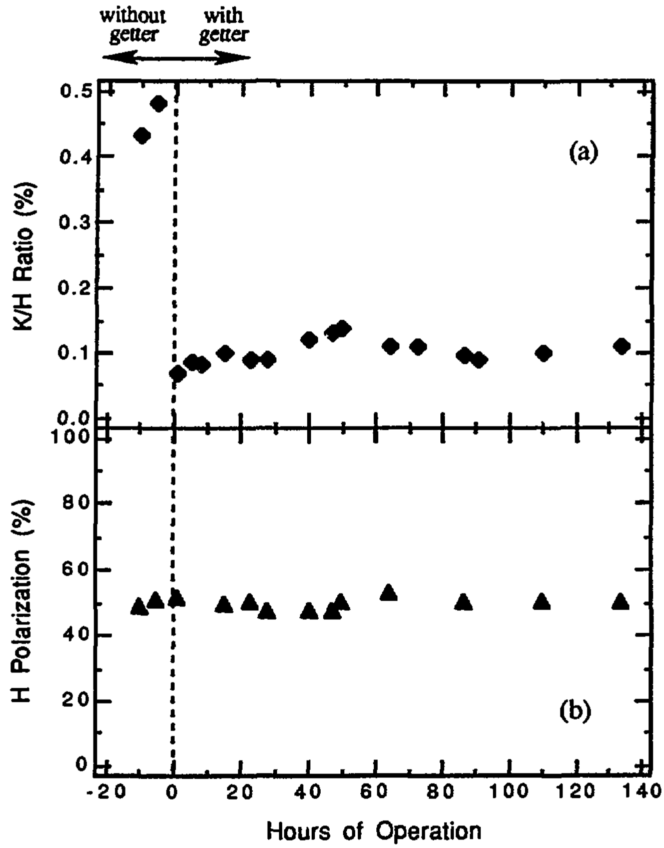

Figure 3 (a) Measured K/H ratio as a function source operation time. (b) H polarization as a function of source operation time.

pump laser power incident upon the spin-exchange cell. Before installation of the getter, approximately one potassium atom was detected in the source emittance for every 200 H atoms, corresponding to a K/H ratio of 0.5%. After installation of the getter, the K/H ratio was reduced by approximately a factor of five to a value of 0.1% . Monte Carlo simulations predict that 10% of the atoms detected with the electron-spin polarimeter travel from the source without hitting the transport tube wall. It is possible that the K/H ratio of 0.1% could be reduced further if attempts were made to ensure that all potassium atoms hit the teflon surface (e.g. future getter designs could incorporate a small bend). Figure 3b gives evidence that the teflon sleeve is not detrimental to maintaining high H polarization. Throughout the duration of the test, H polarization remained at a value of 50%.

CONCLUSIONS

The flow rate and field dependence of the D polarization data suggest that H and D atoms approach spin-temperature equilibrium in the source. This implies that nuclei become polarized without actively performing rf hyperfine transitions. For H atoms, high vector polarization at a flow rate of $1.6x10^{18}$ atoms/second (with a 75% degree of dissociation) can be inferred ($P_z = 51\%$), since vector polarization is equal to electron polarization ($P_e = P_z$) for H atoms in spin-temperature equilibrium. For D atoms in spin-temperature equilibrium (i.e. under low magnetic field conditions), a measured electron polarization of 50% at a flow rate of $6x10^{17}$ atoms/second (with a 75% degree of dissociation) would correspond to vector and tensor polarization of $P_z = 57\%$ and $P_{zz} = 27\%$, respectively. We are currently working towards measuring P_{zz} directly; our efforts are described in these proceedings [11].

Potassium contamination is reduced to a negligible amount using a teflon-lined transport tube and suggests the possibility of source operation with a cold target cell. These factors greatly enhance the figure of merit of a laser-driven target.

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