NOTICE

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HIGH FIELD OPTICAL-PUMPING
SPIN-EXCHANGE POLARIZED DEUTERIUM SOURCE

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ABSTRACT: Recent progress in the performance of laser-driven source of polarized deuterium is
described. Optical pumping of potassium atoms followed by spin exchange scattering with deuterium
atoms in a high magnetic field and RF transitions in a medium field was found to produce an intense,
highly spin-polarized beam of deuterium atoms. In particular, the atomic polarization of deuterium
was determined to be 73±3% at an intensity of 2.1×1017 Atoms/s. The RF transition efficiency was
measured and found to be 92±5%.

INTRODUCTION

The study of spin-dependent structure in nuclei using dilute polarized gases as polarized nuclear
targets in particle storage rings has driven an intense development of high density spin polarized
beams of atoms. While such targets are of general interest, two experiments in particular motivate
our development: measurement of tensor analyzing power in electron-deuteron elastic scattering
[1] and measurement of spin-dependant structure functions of the neutron and proton [2]. With a
conventional atomic beam source [3] which can produce an intensity of 2×1016 polarized deuterium
atoms/s, the resulting target thickness, even with the use of storage cells, will not reach the desired
figure of merit \( nP_{2s} = nP_{2} \geq 10^{14} \) nuclei/cm\(^2\) which renders the above experiments and many
others [4,5,6] impractical.

Although the principle [7] of spin-exchange optical-pumping has been known for some time,
previous attempts [8] 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 can 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 atoms. The rate equations [9] for optical-pumping spin-exchange in
a high magnetic field lead to a simple relation for the deuterium atomic polarization \( P_d \), in terms
of alkali polarization \( P_a \):

\[
P_d = \frac{\gamma_{se}}{\gamma_{se} + \gamma_{R}} \times P_a
\]

Where \( \gamma_{se} \) is the spin exchange rate and \( \gamma_{R} \) is the deuterium spin relaxation rate. The spin
exchange rate depends on the spin exchange cross section and the alkali density; where as the
relaxation rate depends on all polarization losses (collisions with walls and loss of polarized atoms
out of the cell). At low magnetic field, high alkali polarization is limited to very low alkali density
by radiation trapping (\( \ll 10^{12} \) atoms/cm\(^3\)). This typically limits the spin-exchange rate to 300 / s.
The radiation trapping limit at high field, however, is known [10] to occur at higher alkali densities
 (> 10^{13} \text{ atoms/cm}^3). Thus, by applying a high field, high alkali polarization can be maintained at higher alkali density corresponding to a higher spin exchange rate. The second essential step is to induce atomic transitions in order to obtain nuclear polarization. A Monte Carlo simulation suggests that a nuclear polarization p_{22} of .9 can be achieved for a 100% polarized deuterium atoms by placing an RF transition unit over a transport tube.

**EXPERIMENTAL**

In the present experiment, potassium was optically pumped at 770.1 nm using approximately 2 watts of 770.1-nm light from an Ar-ion pumped Ti-Sapphire laser operating a single mode, with the experimental arrangement is shown schematically in Fig-1. The laser photons passed through a 1/4-wave plate and the central axis of a dipole magnet pole tip before impinging on a debris coated [11] pyrex cell. 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 intra-cavity thick etalon. Deuterium atoms were injected into the cell from an RF dissociator tube and K was introduced through a small 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^{13} \text{ atoms/cm}^3, while the deuterium density in the cell was 8.6×10^{13} \text{ atoms/cm}^3, estimated from a flow of 2.1×10^{-7} \text{ deuterium atoms/s}. This leads to an estimated spin-exchange rate γ_{SE}=1700/s, a factor of six higher than the most achievable at low field. The atoms exited the cell through a small hole and then traveled through the RF transition region where a low magnetic field was set. A 20 gauss constant field was applied in addition to a 1 gauss/cm ramp field in order to drive two different atomic transitions, in the 20 MHz frequency region; for tensor polarization of deuterium one needs, in the above conditions, to perform a state 3 to state 4 transition and state 2 to state 3 transition for a circularly polarized light (1,...,6 are the hyperfine states of deuterium).

The polarization of the atoms exiting the RF transition 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 focusses spin-up atoms and defocusses spin-down atoms. Thus, when the optical-pumping spin-exchange is performed with σ_+(σ_-) light, and the RF transition unit is off, one would expect to see a signal in the compression tube detector that corresponds to all (none) of the atoms for 100% deuterium polarization. When the medium field and the RF transition power are switched on, a signal corresponding to only two third (one third for σ_-) of the atoms would be detected in the vacuum gauge for 100% RF transition efficiency. For either case, 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 for ambient atoms and molecules in the vacuum chamber. In order to minimize this background, three differentially pumped vacuum region were employed. A typical value for the ambient pressure as measured by the compression tube was 3×10^{-8} \text{ torr}. To extract the polarization of the beam it was also necessary to determine the amount of molecular deuterium that entered the compression 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 0.37 ± 0.03.
RESULTS AND DISCUSSION

We will first discuss the case of the atomic polarization of deuterium. From the detected signal in the compression tube $S_+, S_-$ and $S_0$ corresponding to $\sigma_+$, $\sigma_-$ and no light, one is able to compute the polarization of deuterium atoms in the following way:

$$P = \frac{S_+ - S_-}{S_+ + S_-} = \frac{S_+ - S_0}{S_0} = \frac{S_0 - S_-}{S_0}$$

where $S_+, S_-$ and $S_0$ are corrected from the molecular background.

The results for a magnetic field of 2.2 kG for three conditions of laser light ($\sigma_+$, $\sigma_-$ and no light) are shown in Fig-2.

![Figure 1:](image)

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

![Figure 2:](image)

(a) Signal from a scan of the compression tube and detector across the focal plane of the sextupole for three cases: (i) $\sigma_+$ light, (ii) no laser light (solid) and (iii) $\sigma_-$ light (dotted curve) for a magnetic field of 2.2 kG and RF transition power off.
(b) Same as Fig. 2(a) with a 30 G magnetic field.
Clearly, from the observation of the three distinct curves shown in Fig-2(a), the polarization of deuterium atoms is large: 73±3%. In order to see the beneficial effect of the high magnetic field, the polarization at the density of 6×10¹⁰ potassium atoms/cm³ 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 [12]; there may also be a decrease in the loss of deuterium and potassium polarization from cell wall collisions.

Only one RF transition (state 3 to state 4), can be seen by the sextupole. If one assumes that the second transition involved in the prototype is driven with the same efficiency ε₃₄ one has:

$$\varepsilon_{34} = \frac{3 P_{off} - P_{on}}{2 P_{off}}$$

where P_{off} and P_{on} are deuterium atomic polarizations with RF power off and RF power on respectively. The nuclear polarization is then:

$$P_{nuc} = \varepsilon_{33} \times \varepsilon_{34} \times P_0 = \varepsilon_{34}^2 \times P_0$$

For a 100% polarized deuterium atoms and a 100% RF transition efficiencies, the nuclear polarization would be +1 for $\sigma_+$ light and -1 for $\sigma_-$ light. The RF transition efficiency had already reached its saturation value (92±5%) for 2.6 watts of RF power, as it is shown in Fig. 3. However, one expects the transition efficiency to drop for higher power. In order to see the so-called adiabatic condition [13] the variation of the efficiency versus RF power was measured for .25 G/cm ramp field. The RF efficiency fall-off occurred as predicted, when the adiabatic condition was not satisfied (Fig-3). Thus we have demonstrated for the first time the feasibility of RF transitions for diffused beams.

Figure 3: RF transition efficiency versus RF power, for two cases: ramp field of 1 G/cm , $\sigma_+$ (diamonds), $\sigma_-$ (squares); ramp field of .25 G/cm
In order to fully demonstrate the power of the present method, we compare in Table-I the
figure-of-merit of this source with that of the Novosibirsk source. The projected figure-of-merit of
this source when the deuterium intensity is increased by correspondingly increasing the laser power
is also included in Table-I. In addition, it is believed that the molecular fraction can be decreased
by minimizing contamination of the dissociator tube with drt-film.

<table>
<thead>
<tr>
<th>Source</th>
<th>I/sec (x10^16)</th>
<th>Pz</th>
<th>eff*</th>
<th>F=I_p^2 * I (x10^16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novosibirsk</td>
<td>2</td>
<td>.9</td>
<td>.5</td>
<td>.81</td>
</tr>
<tr>
<td>ANL-91(HF)</td>
<td>21</td>
<td>.41=.63x.73x.9</td>
<td>1.</td>
<td>3.6</td>
</tr>
<tr>
<td>ANL-projected</td>
<td>40</td>
<td>.53=.8x.73x.9</td>
<td>1.</td>
<td>11.1</td>
</tr>
</tbody>
</table>

*Injection efficiency-estimate based on experience with source and storage cell at INP-
Novosibirsk.

Table 1

Besides a higher figure-of-merit, the present source has an additional advantage over a conven-
tional atomic beam source, namely that the polarization of the atoms can be reversed merely by
changing the helicity of the light, where as for the conventional ABS, it is more difficult since it
is performed by selecting different RF transitions.

In summary, the first test of 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 the
previously reported values [3] for a conventional atomic beam. Further development of this method
should produce polarized targets with 10^{14}-10^{15} atoms/cm^2, a thickness range which will render
many new experiments feasible.

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REFERENCES

[a] now at CRN-F67037 Strasbourg Cedex
[2] "A Proposal to Measure the Deep Inelastic Spin Dependent Structure Functions of the


