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RECENT DEVELOPMENTS IN LASER-DRIVEN POLARIZED SOURCES

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ABSTRACT: Recent progress in the performance of laser-driven sources of polarized hydrogen and deuterium is described. The current status of the prototype source, I = $2.5 \times 10^{17} s^{-1}$, polarization = 0.29 (including atomic fraction), is comparable to classical Stern-Gerlach sources. A scheme to improve source performance by approximately an order of magnitude, using a combination of optical-pumping spin-exchange and RF transitions, is outlined.

INTRODUCTION

The development of high-density targets of polarized hydrogen and deuterium is central to the study of spin-dependent structure in nuclei. While such targets are of general interest, two experiments in particular motivate our development of polarized internal gas targets of hydrogen and deuterium: a) measurement of tensor analyzing power in electron-deuteron elastic scattering [1] and b) measurement of spin-dependent structure functions of the neutron and proton [2] . In both experiments, the desired figure of merit for the target is $np_{zz}^2 \approx np_z^2 \geq 10^{14}$nuclei/cm^2. In order to achieve this thickness, the proposed scheme is to feed a windowless storage cell [3] by a polarized source. At present, two options for the polarized source are being actively pursued, namely, the Stern-Gerlach source [4] at Heidelberg and the laser-driven source at Argonne [5].

The laser-driven polarized source is based on the principle of spin-exchange optical pumping. In this method, optical pumping creates a spin-polarized alkali atom, which, via spin-exchange collisions will polarize the electron of the hydrogen or deuterium atom. The nucleus of the H or D atom becomes polarized at low magnetic fields via the hyperfine interaction. This technique has great potential, which can be understood by considering that the photon flux available from a standard Ti-sapphire laser at the potassium D1 resonance line is 3-4 watts. A conversion efficiency of only 10% would give polarized H/D atoms at a flux $\geq 10^{18} s^{-1}$, far exceeding the flux available from conventional sources, $3 \times 10^{16} s^{-1}$. In this paper, recent developments (using both potassium and sodium as the spin-exchange intermediate) which show the laser-driven source to be comparable to the benchmark Stern-Gerlach source [6] will be discussed.

EXPERIMENTAL

The prototype spin-exchange optical pumping system is shown schematically in Figure 1. An Ar^+-pumped dye laser system provides the radiation required to optically pump the alkali, either Na or K. The spectral density of the laser is tailored to match

the Doppler-broadened absorption profile of the alkali vapor, circularly polarized, and sent to the spin-exchange cell located near the center of the diagram.

The spin-exchange cell is constructed of pyrex as an integral unit with the rf-dissociator and alkali reservoir. The interior is coated with drifilm [7]. The entire cell is heated to $\sim 250°C$ to prevent alkali condensation and placed in a static holding field of 10G. The H/D flux is controlled and measured with a servo-driven needle valve. The alkali density is independently controlled by the reservoir temperature and quantified by measuring the integrated absorption coefficient with a probe laser. Typically the ratio of Na to D atoms is 0.1 to 0.3%. The mixture of alkali and D atoms exits the spin-exchange cell through a spout, after which a chopper and quadrupole mass spectrometer are used to determine the fraction of D atoms in atomic form (AF).

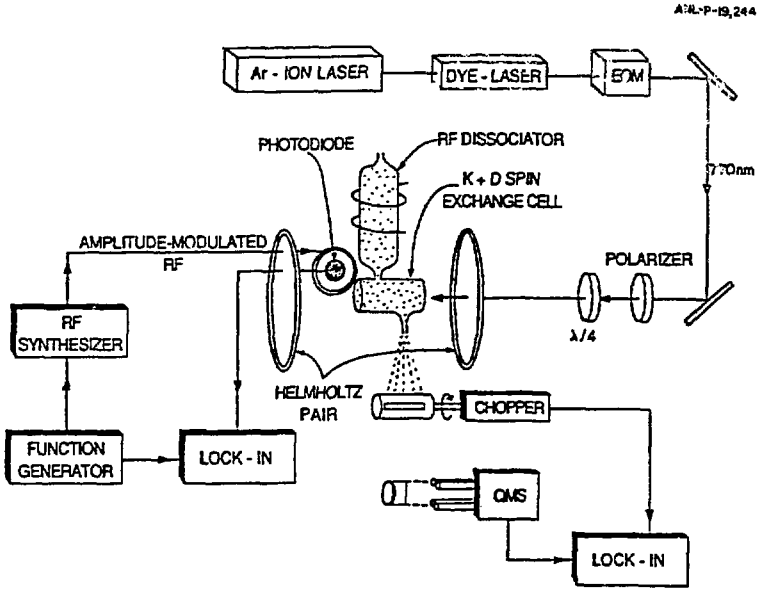

Figure 1. Schematic of the laser-driven source.

The equilibrium polarization of the atoms is measured by optical detection of magnetic resonance transitions between adjacent Zeeman sublevels [8]. That is, increased fluorescence from the optically-pumped alkali atoms is observed as a result of altering the relative populations of the magnetic sublevels, either directly or via spin-exchange collisions with deuterium atoms. A typical signal using the Zeeman technique is shown in Fig. 2. The asymmetry between $\sigma+$ and $\sigma-$ pumping reverses as expected. The polarizations shown on the figure are deduced using a spin-temperature model, where the populations of the magnetic sublevels are given by $N_{m_J} \propto e^{\beta m_J}$, where β is the spin temperature. From the figure, there appears to be an incomplete equilibration between the polarization of the alkali and deuterium atoms.

The average deuterium polarization is expected to be measured well, since, the mean free path between D-alkali collisions is much larger than the cell dimensions ($\lambda =$

$1/\sigma_{se}n_A \approx 10^3$cm). However, the alkali polarization may be overestimated, since regions of the cell with high laser intensity are preferentially sampled. This is confirmed by probe laser measurements of differential $\sigma+, \sigma-$ absorption as a function of position in the cell. The calculated polarization transfer efficiency is thus an underestimate, and improvements in deuterium polarization can be expected with uniform high-power laser coverage of the cell.

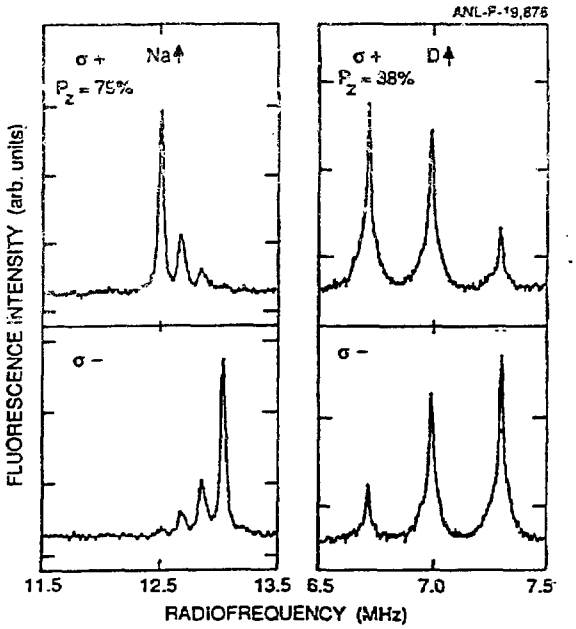

Figure 2. Typical fluorescence signal using Zeeman technique.

RESULTS AND DISCUSSION

In this section we discuss the evolution of the laser-driven source. Only deuterium will be discussed in detail, although tests have shown that hydrogen polarization essentially equivalent to deuterium vector polarization, p_z, can be obtained. Initial studies (ANL'88) were conducted using potassium as the spin-exchange intermediate. This choice was motivated by the ease with which one could distribute the output of a cw laser over the absorption profile of the K vapor (≈1.5 GHz Doppler + hyperfine) relative to other alkalis. The switch to Na (ANL'90) as the spin-exchange intermediate can be best understood by considering the processes which determine the deuterium polarization.

The processes in the spin-exchange cell can be modelled using a rate-equation approach, which leads to the following relationship for the efficiency of polarization transfer from the alkali to the D atom.

$$P_D = \frac{\gamma_{se} P_A}{\gamma_{se} + \Gamma}\left(1 - e^{-(\gamma_{se}+\Gamma)t}\right)$$

where γ_{se} = spin exchange rate = $\sigma_{se}\bar{v}n_A$, Γ =loss rate (depolarization + flow rate) and P_D, P_A = electron polarization of the deuterium and alkali, respectively.

In order to enhance the efficiency of polarization transfer, one should maximize the spin-exchange rate, i.e. n_A, and minimize the loss rate. However, due to radiation trapping, n_A can not be increased arbitrarily without a corresponding decrease in P_A. Radiation trapping at low B-fields is a less severe problem for Na than for K. The critical density (where the alkali polarization is degraded by roughly 50%) is more than a factor of two higher for Na than for K.

Table 1 shows the performance figures for the laser-driven source configurations at low fields using K (ANL'88) and Na (ANL'90) as the spin-exchange intermediates. In addition, it shows the corresponding parameters for the benchmark classical atomic beam source (Bonn). The first three columns concentrate solely on source performance p_z, I and atomic fraction (AF). The final two columns relate to the expected figure of merit ($F = Ip_z^2\mathrm{AF}^2\epsilon$) for internal target applications involving a storage cell, as indicated in the introduction. The injection efficiency, ϵ, into the storage cell (fourth column) is unity for the laser-driven source since the source and cell can be directly coupled. The figure of 0.5 given for the Bonn source is estimated from the experience of the ANL-Novosibirsk collaboration [1]. It may be an underestimate, but is included to indicate the non-trivial nature of efficient injection into the storage cell.

Table I. Performance figures for polarized H/D sources.

Source	p_z	Intensity ($\times 10^{17} s^{-1}$)	Atomic Fraction	Injection Efficiency	F (s^{-1})
ANL'88	0.25	0.6	0.80	1.0	0.24×10^{16}
ANL'90	0.38	2.5	0.75	1.0	2.0×10^{16}
Bonn	0.95	0.3	1.00	0.5	1.4×10^{16}

As can be seen, the switch from potassium to sodium increased the deuterium polarization, p_z, from 0.25 to 0.38, for the reasons previously discussed. Another very marked improvement is the source intensity. This is due primarily to the increased laser power. The incident photon fluxes for the K and Na cases were $\approx 8 \times 10^{17} s^{-1}$ and $\approx 3 \times 10^{18} s^{-1}$, respectively.

FUTURE PLANS

Although substantial gains have been posted with the change in alkali and additional laser power, the laser-driven source has not yet met the design goals: I = $4 \times 10^{17} s^{-1}, p = 0.5$. In particular, the p_{zz} obtained thus far, 0.15, yields a figure of merit similar to the existing source at Novosibirsk and must be improved an order of magnitude for the electron-deuteron elastic scattering experiments.

In order to increase the polarization (p_{zz}) and the intensity of the source, we plan a two-step process: optical-pumping spin-exchange with K at high field followed by RF transitions in a moderate field. The added complication of RF transitions subsequent to the spin-exchange is offset by the advantages of high-field optical pumping, namely, greatly reduced radiation trapping problems and better wall depolarization properties. The p_{zz} expected in this scheme is $p_{zz} = \epsilon_{24}\mathrm{AF}\ P_D$, where ϵ_{24} is the efficiency of the $4 \leftrightarrow 3$ and $3 \leftrightarrow 2$ RF transitions. Monte Carlo simulation of the process gives $\epsilon_{24} \approx 0.9$.

Based on previous experience, we estimate a $P_D = 0.7$ and AF $= 0.8$ to be achievable, leading to a $\mid p_{zz} \mid = 0.50$. A recently-acquired Ti-sapphire laser provides an increase of a factor of 4 in available photon flux ($1.2 \times 10^{19} s^{-1}$). Thus, deuterium atom fluxes of $\sim 1 \times 10^{18} s^{-1}$ should be achievable.

SUMMARY

Over the past two years, an increase of approximately a factor of 8 in figure of merit has been realized for the laser-driven source of polarized deuterium. The gains have been due to a change in the spin-exchange intermediate from potassium to sodium and increased laser power. In its present state, Ip_z^2 AF$^2 = 2.0 \times 10^{16} \overrightarrow{D}/s$, the laser-driven source is already comparable to classical atomic beam sources. Further improvements (a factor of ~ 12) are expected with increased laser power and a new scheme employing high-field optical-pumping spin-exchange followed by RF transitions.

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