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Laser-Driven Polarized Targets of Hydrogen and Deuterium

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Abstract

An optical pumping technique used in a laser-driven source of polarized hydrogen or deuterium is described and measurements of the achievable polarization as a function of flow for both hydrogen and deuterium are presented. Ongoing tests of the feasibility of using a laser-driven polarized deuterium source coupled to a storage cell as a polarized internal target, including direct measurements of the nuclear polarization, are discussed.

I. Introduction

In the past few years the study of the spin properties of nucleons and nuclei has become a major focus of intermediate energy physics, with emphasis on studies requiring polarized targets of the few body nuclei ^1H , ^2H and ^3He . Although polarized ^3He targets with polarization and density sufficiently high to achieve practical luminosities in these experiments have been realized, the development of polarized ^1H and ^2H targets of equally high density and polarization has proven to be more difficult. While major breakthroughs have been made in increasing the thickness of conventional polarized gas targets [1, 2], significant further improvements to the atomic beam source technique will be difficult to achieve.

An alternative technique that could yield significant improvement in the figures-of-merit of hydrogen and deuterium polarized sources is the laser-driven polarized source, which uses optical pumping spin exchange as the polarization mechanism. Here we describe the laser-driven source developed at Argonne National Laboratory, present data on the achieved polarization vs. flow, and discuss direct measurements of the nuclear polarization of deuterium from the source.

II. Experimental Technique

The laser-driven source (LDS), shown in Figure 1, is a flow-through system consisting of a dissociator region where the H_2 (D_2) molecules are separated into atoms, an optical pumping cell containing H (D) and potassium, and a transport tube leading from the optical pumping cell. The optical pumping cell operates in a relatively high magnetic field ($\sim 1 - 4$ kG) to minimize depolarization from radiation trapping [3]. The K atoms in the optical pumping cell are polarized through absorption of circularly polarized light at $\lambda \sim 770$ nm from a Ti-sapphire laser that is pumped by an argon-ion laser. An electrooptical modulator is used to match the frequency profile to the Doppler width

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Figure 1: Schematic drawing of the laser-driven source.

of the atoms in the pumping cell. Polarization is transferred to the H (D) through K-H (K-D) spin exchange collisions. The polarized atoms exit the spin exchange cell through the transport tube. The vacuum system is separated into three regions: the flow from the transport tube goes into the first stage which would contain the storage cell when used as an internal target, the second stage contains a permanent sextupole magnet used to separate spin up atomic states from spin down states, and the third stage contains a quadrupole mass analyzer (QMA) located at the focus of the sextupole. The atomic polarization is determined by monitoring the mass 1 (H) or 2 (D) pressure at the QMA with and without optical pumping. The atomic fraction, or dissociation fraction, is determined by measuring the molecular flow from the source with and without the dissociator RF power on. The potassium polarization is determined by measuring with a photodiode the transmission through the optical pumping cell of a weak beam of circularly polarized light from a diode laser.

III. Results For The Laser-Driven Source

The most important issues relating to the use of the laser-driven source for nuclear physics experiments are the achievable polarization as a function of flow and the elimination of K from the target region where it would be a source of background in scat-

Figure 2: Measured atomic polarization of hydrogen and deuterium atoms from the laser-driven source as a function of flow rate. Three different data sets are shown for deuterium. The flow, in nuclei/s, accounts for H or D in both atomic and molecular form.

tering experiments. Recently, we have demonstrated that inserting a section of heated ($\sim 150^\circ\text{C}$) Teflon tubing in the transport tube reduces the percentage of K exiting the source to $\text{K/D} < 0.001$. Significant progress has also been made in demonstrating high polarizations and flows from the laser-driven source. The source has been tested to flow rates exceeding $1 \times 10^{18}/\text{s}$ for both H and D. Figure 2 shows the atomic polarization of hydrogen and deuterium as a function of flow achieved with the laser-driven source.

For comparison of the atomic beam source (ABS) with the laser-driven source, the fraction of nuclei in atomic vs. molecular form must be included to account for dilution from unpolarized nuclei. The molecules are present because of inefficiencies in the dissociation and recombination in collisions throughout the source. The atomic fraction is close to unity for flow from an atomic beam source, while for the laser-driven source, $f_{\text{atom}} = 0.75$ under typical operating conditions for all flows tested.

The figure-of-merit of a polarized source or target is $F = (P * f_{\text{atom}})^2 t$, where P is the polarization and t is the flow from the source or the target thickness of the internal target. The polarized hydrogen internal target thickness achieved with an ABS at Heidelberg is $5.6 \times 10^{13}/\text{cm}^2$ with nuclear polarization 83% [1]. Comparable data from the same ABS for deuterium has not yet been taken, although similar densities and polarizations are expected.

Recently, a polarimeter to directly measure the nuclear polarization has been added to the LDS at Argonne. Deuterium is ionized, extracted from a storage cell fed by the laser-driven source, and accelerated to 40 keV. The tensor polarization is determined by measuring the neutron anisotropy in the $^3\text{H}(^2\text{H},n)^4\text{He}$ reaction. The measurement has been made under operating conditions where D-D spin exchange collisions should drive the population to spin temperature equilibrium [4]. In this case, polarization is transferred from the atoms to the nucleus even in the presence of external magnetic fields

in excess of the critical field for deuterium (117 G), although the time for the system to reach equilibrium is longer at higher fields. Two signatures for this process are: 1) nonzero nuclear polarization of hydrogen or deuterium from the source without the use of induced RF transitions, and 2) deuterium tensor polarization greater than zero (physical limits are -2 to $+1$) when the K is optically pumped with either right or left circularly polarized light. Initial measurements of the tensor polarization of deuterium in a storage cell with target thickness of $4 \times 10^{14}/\text{cm}^2$, with the source operating at a flow of $1.1 \times 10^{18}/\text{s}$ and a field of 1.2 kG in the region of the optical pumping cell, yield a value of $+0.056 \pm 0.008$ for the tensor polarization. The tensor polarization remains roughly constant when the helicity of the optical pumping light is reversed. This measurement provides a clear signature that D-D spin exchange collisions mix the nuclear and atomic polarization at the densities obtained in the LDS. For the measured value of the tensor polarization, the inferred nuclear vector polarization is 0.27 ± 0.02 , assuming spin temperature equilibrium. Work is currently underway to increase the polarization in the storage cell.

The observation of spin temperature equilibrium in deuterium from the LDS has significant implications. Because hydrogen reaches spin temperature equilibrium much quicker ($\times 10 - 20$) than deuterium at the densities and fields in which the LDS operates, the observation of spin temperature equilibrium in deuterium means that the hydrogen is also nuclear polarized without the need to induce RF transitions. In spin temperature equilibrium, the polarization of hydrogen is shared equally between the nucleus and the atomic electron, so that the measured values of the atomic polarization shown in Figure 1 also reflect the nuclear polarization, at least for the higher flows. This means that hydrogen nuclear polarizations of $\gtrsim 50\%$ have been achieved at flows up to $\sim 2 \times 10^{18}/\text{s}$. For deuterium, one can potentially achieve very high vector polarizations from the LDS; measurements to map out the onset of spin temperature equilibrium in deuterium are underway at Argonne. One limitation of spin temperature equilibrium is that large tensor polarizations are difficult to achieve. However, it may still be possible to use RF transitions to achieve high tensor polarizations while operating the source at low flow or high magnetic field where spin temperature equilibrium is not attained.

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