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PROSPECTS FOR A DEUTERIUM INTERNAL TARGET, TENSOR POLARIZED BY OPTICAL PUMPING - SPIN EXCHANGE

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ABSTRACT

The prospects for a tensor polarized deuterium target ($\sim 10^{15}$ atoms/cm^2) appropriate for nuclear physics studies in medium and high energy particle storage rings are discussed. Using the technique of electron spin exchange with an optically pumped sodium (or potassium) vapor, we hope to polarize deuterium at a rate $\sim 10^{17}$ atoms/sec. Predictions for the deuterium polarization for a particular target cell design will be presented leading to the identification of the required optical pumping power and cell wall depolarization probability to attain optimum performance. The technical obstacles to be surmounted in such a target design will also be discussed.

INTRODUCTION

With the aim to carry out measurements of electron-deuteron elastic scattering at high momentum transfer with a tensor polarized deuterium target, we are currently attempting to develop a polarized deuterium gas (internal) target appropriate for use in an electron storage ring.[1-3] We hope to achieve a target thickness in the range of 10^{15} atoms/cm^3 with the deuterium tensor polarization, $t_{20} = 0.3$. Such an internal target should also be suitable for studies with the cooled hadronic beams planned for the IUCF cooling ring.

The deuterium gas density necessary for our target thickness goal is most easily attained by a containment cell placed in the circulating particle beam. Of course, such a cell must have entrance and exit apertures for the beam, through which the gas in the cell leaks out. We estimate that the rate at which gas leaks from such a cell with reasonably sized apertures is $\sim 10^{17}$ atoms/sec. In order to maintain the gas density in the cell, the source of polarized atoms must supply atoms at this rate. "Standard" polarized sources generally produce $\sim 10^{16}$ polarized atoms/sec.[4] Thus, we were lead to consider other techniques for polarizing atoms at the required rate.

As will be discussed in more detail in the following sections, the technique of optical pumping - spin exchange shows some promise of polarizing $\sim 10^{17}$ atoms/sec. While this technique has been used by atomic physicists to polarize a number of different atomic species,[5] the necessary polarization rates and a number of other requirements particular to our application have yet to be demonstrated.

PHYSICAL COMPONENTS AND PROCESSES

In this section the basic components of a system to produce a polarized deuterium target by optical pumping-spin exchange with a Na vapor are discussed; and the atomic and nuclear processes necessary for the production of nuclear polarization are reviewed.

The deuterium polarization process is best idealized as a somewhat ordered sequence of physical interactions at the atomic and nuclear level schematically represented in Fig. 1. The optically pumped Na vapor (electron polarized) transfers angular momentum to the deuterium atom ensemble (previously rf-dissociated) via atomic electron spin exchange. In the absence of a strong magnetic field, the hyperfine interaction transfers a portion of the deuterium electron polarization to the deuterium nuclei. Meanwhile, the Na vapor polarization is replenished and a second spin exchange collision re-polarizes the deuterium electron with hyperfine interactions polarizing the nucleus. After at least two spin exchange collisions, the deuterium nucleus ensemble has some degree of tensor (and vector) polarization. Repeated spin exchange/hyperfine interactions increase the tensor polarization of the ensemble to some limit determined by the degree of Na polarization. For the systems we will consider, spin-exchange collisions occur about once every 10^{-4} sec as compared to the hyperfine mixing time of 10^{-9} sec. Thus our assumption of complete hyperfine mixing between electron-spin exchanges is well justified.

Figure 2 shows the basic components of a spin-exchange polarization system with a dissociator bottle feeding atomic deuterium into a spin exchange cell used for development tests. A liquid Na pot is heated to maintain the desired Na density in the slightly hotter spin-exchange cell (to prevent Na condensation on the cell walls). A set of Helmholtz coils (not shown) provide a weak magnetic "guide" field (5 gauss) aligned along the polarization axis. Polarized deuterium (and some Na) flow out of the end spout. The spout and cell dimensions (discussed later) are chosen so as to contain the deuterium and Na for a time sufficient to allow for the desired number of spin-exchange collisions. This general design is based on the presumed limitation that the deuterium dissociation must take place outside of the polarizing region. We have also assumed that the deuterium emitted through the spout cannot be recycled back into the spin exchange cell because it would most likely be recombined into D_2 nor can it be dissociated again because of Na contamination.

The polarization cell in Fig. 2 can be configured into an internal target cell with entrance and exit apertures for a circulating particle beam (instead of an end spout) with little change in performance characteristics. In the current design, the Na density is ~0.3% of the deuterium density which could be a source of background for some nuclear reaction studies. The reaction products of a nuclear interaction between the beam and target must necessarily pass through the polarization cell walls in such a design. Cell walls can be made thin; however, heat loss from the cell walls must be replenished, and the heat conductance of walls must be taken into consideration.

This technique of tensor polarizing deuterium is initially quite attractive because of its mechanical simplicity (no sextupole magnets or high-speed vacuum pumps) relative to conventional atomic beam sources. However, there are some forseeable technical obstacles in the development of such a target including high-power optical pumping

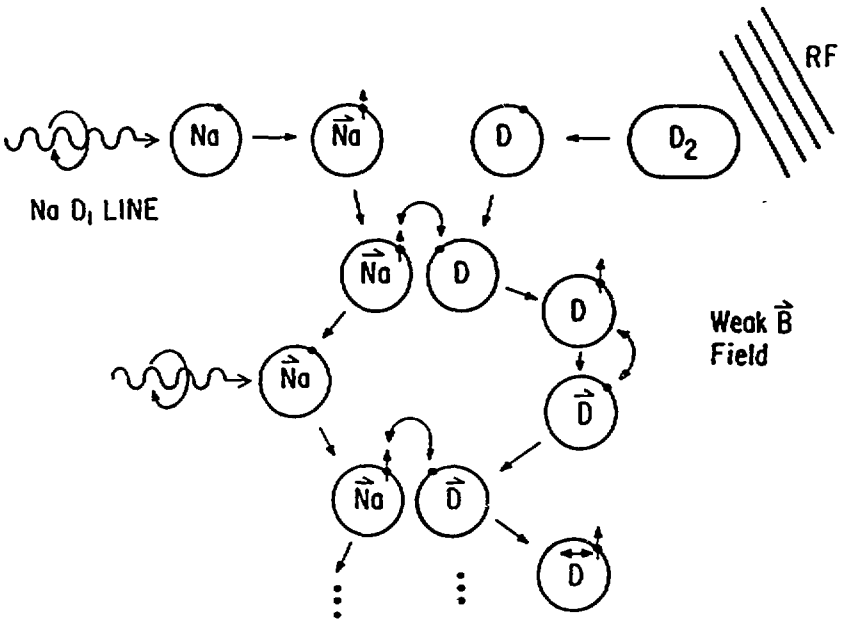

Figure 1. The deuterium tensor polarization process. Optically pumped Na and RF dissociated D_2 undergo repeated electron spin exchange/hyperfine interactions.

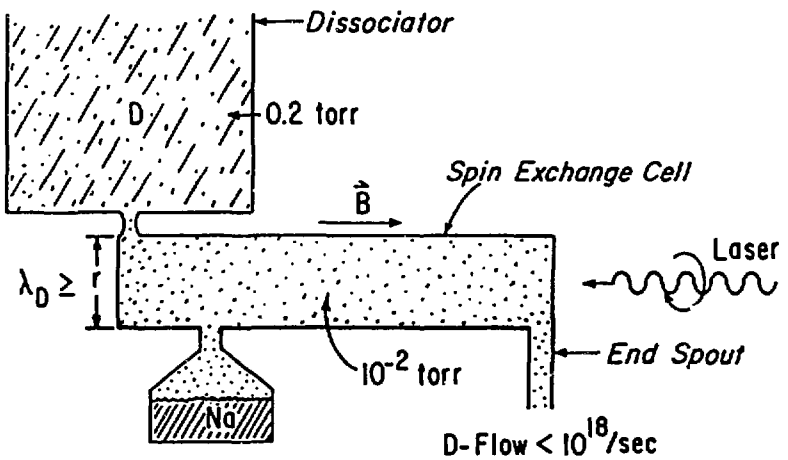

Figure 2. The basic components of a spin exchange polarization cell to produce tensor polarized deuterium.

of a relatively dense alkali vapor, high-efficiency dissociation, and cell wall coatings which sufficiently minimize both D recombination and depolarization.

The Na vapor in the spin exchange cell is spin polarized by a "standard" optical pumping technique. The cell is illuminated by circularly polarized Na D_1 light (5896 Å) (from a dye laser) which excites the $S_{1/2}$-$P_{1/2}$ electron transition in the Na atoms. In effect, the circularly polarized light pumps angular momentum into the Na atom vapor by repeated excitation and spontaneous emission which eventually spin polarizes the outer unpaired electron of the Na atoms as well as their nuclei via the hyperfine interaction. Although optical pumping of Na and other alkali vapors has been studied for many years,[5-8] the efficient pumping of a relatively thick vapor with a high angular momentum transfer rate due to electron spin exchange (without a buffer gas) required for our application, has been mostly unexplored.[9-10]

The initial preparation of the deuterium is to break apart or dissociate the natural diatomic configuration of deuterium. Since all atoms which come out of the dissociator also pass through the spin-exchange cell and eventually contribute to the target thickness, a high dissociation fraction is a prerequisite to obtaining a high target polarization. We are currently pursuing the "standard" technique[11] of radio-frequency (rf) dissociation in an appropriately tuned cavity. While this technique is well known, the dissociators of standard atomic beam sources are operated so as to give a high flux of atoms with the undissociated gas being pumped away after magnetic separation. However, it has been demonstrated that dissociation fractions of 95% are obtainable using rf dissociation.[12]

TARGET PERFORMANCE

In modeling the performance of our cell, we have used the Pauli master equation[13] to describe the coupled rates of interaction between the deuterium and Na spin populations.[14] This approach assumes that there is no quantum mechanical phase coherence between consecutive spin exchange/hyperfine interactions. (For systems of gases having completely random interactions, this assumption seems well justified.) Also, the deuterium flow through the cell has been modelled as simply a depolarization process wherein the spin exchange cell can be viewed as a closed system (see Fig. 3). The average deuterium tensor polarization inside the cell is then given by the equilibrium spin population of this system.

The result of this modeling is shown in Fig. 4 which, for various Na vapor electron polarizations P_{Na}, shows the anticipated tensor polarization of the deuterium t_{20}, versus X_{eff}, the average number of effective Na-D spin-exchange collisions a deuterium atom undergoes before escaping from the cell. Letting X be the average number of Na-D spin-exchange collisions a D atom makes before escape, then

$$X_{eff} = X/(1 + D_p W), \qquad (1)$$

where D_p is the probability that a D atom is completely depolarized by

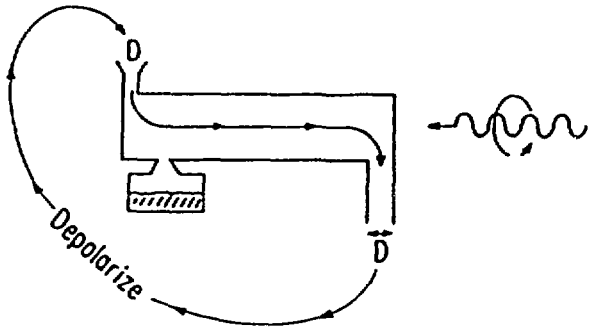

Figure 3. Spin exchange cell viewed as a closed system with D flow as a depolarization process.

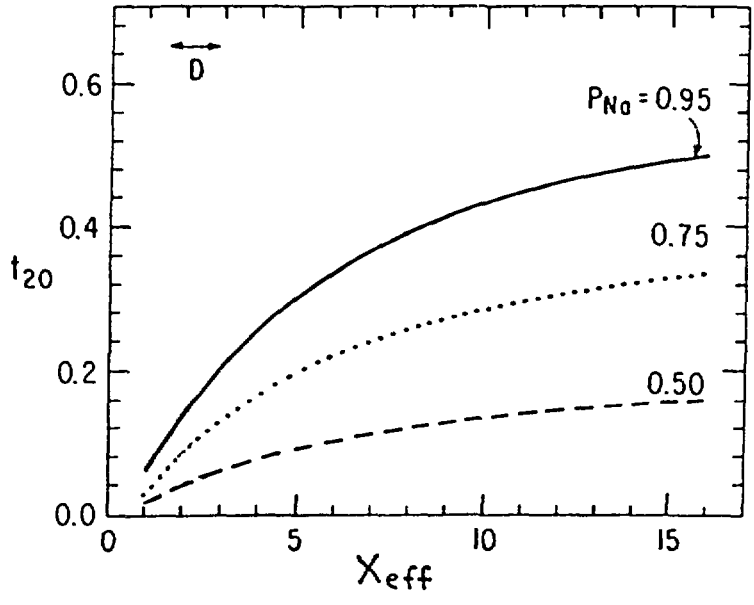

Figure 4. The deuterium tensor polarization, t_{20} versus X_{eff}, the effective number of Na-D spin exchange collisions/D atom, for various Na polarizations.

a wall collision and W is the number of wall collisions a D atom makes before escaping from the cell. Thus, X_{eff} can be viewed as X corrected for wall depolarization processes. From Fig. 4, we see that even with near perfect Na polarization an $X_{eff} = 5$ yields a tensor polarization $t_{20} = 0.3$.

The curves in Fig. 4 also give the tensor polarization of the deuterium emitted out of the cell spout to the extent that polarization gradients can be ignored. We expect these gradients to be negligible as long as the cell is operated under conditions of molecular flow;[15] i.e., such that the mean free path for atomic collisions is greater than the diameter of the cell, and the motion of the D atoms is dominated by collisions with the cell walls.

Assuming molecular flow conditions, X (in Eq. 1) can be expressed in terms of cell geometry, the Na-D electron spin exchange cross section (σ_{ex}), and the Na density (n_{Na}) at the chosen operating temperature (T in degrees K); i.e.,

$$X = 4(1 + 2/23)^{1/2} V_c n_{Na} \sigma_{ex} W/A_c \ , \qquad (2)$$

where A_c and V_c is the cell wall area and volume, respectively. W (given only by cell geometry) is the number wall collisions an atom makes before exiting the cell. A conservative estimate of σ_{ex} is 5×10^{-15} cm^2 which comes from measurements of similar atomic reactions.[16] [Notice σ_{ex} (≈ 50 A^2) is an order of magnitude larger than the Na-D molecular collision cross section.]

We have chosen a set of cell dimensions and Na density (temperature) attempting to minimize depolarizing wall collisions while containing the D atoms for a sufficient number of spin exchange collisions at a moderate Na density.[14] These dimensions are the cell length (2.06 cm) and diameter (0.75 cm), the spout length (1.00 cm) and diameter (0.2 cm). These dimensions imply that an atom makes ~1000 wall collisions before exiting the cell. For a temperature of 232° C (T = 505° K) resulting in a Na density $n_{Na} = 3.2 \times 10^{12}$ atoms/cm^3, Eq. 2 yields X = 10. If the cell walls have a depolarization probability for deuterium of $D_p = 10^{-3}$, then $X_{eff} = 5$ according to Eq. 1.

Thus, independent of the deuterium flow and density, the tensor polarization of the target is limited to 0.3 for a near perfect Na vapor polarization (and $D_p = 10^{-3}$). Of course, the extent of the Na polarization in an operational cell is determined by the rate at which depolarizing spin-exchange collisions (and other losses) can be counteracted by the laser optical pumping process.

Using "low power" optical pumping rate equations in a model framework analogous to those used for the Na-D spin-exchange system, we have estimated that a target thickness of 2.3×10^{15} D atoms/cm^2 and a flow of 4×10^{17} atoms/sec are attainable. For this deuterium flow and thickness with complete frequency coverage of the Doppler broadened optical transition, a Na wall depolarization probability of 10^{-3}, and the previously discussed design parameters; our estimates of t_{20} versus the incident laser power are shown in Fig 5. We see that the limiting tensor polarization for this cell design is achieved for an incident laser power of ~2 W.

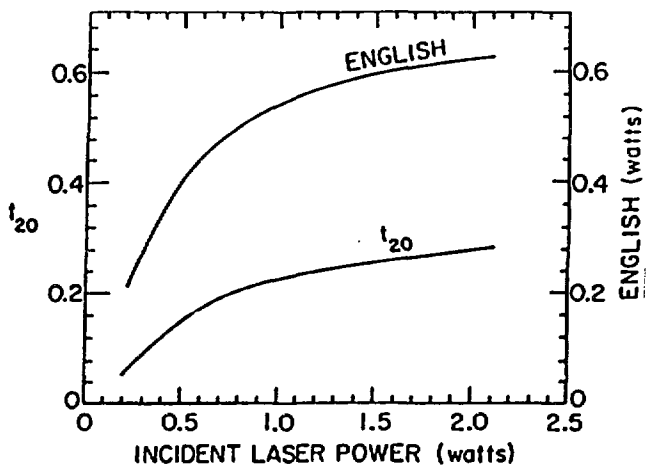

Fig. 5. The expected target tensor polarization (scale on the left) and absorbed English (scale on the right) for the proposed cell dimensions, operating temperature, and other design parameters (giving a target thickness $\sim 10^{15}$ atoms/cm^2) versus incident laser power (see text).

Also plotted in Fig. 5 is the parameter we call "English" which we define as the rate at which angular momentum is transferred through an intermediary, the Na atoms in the cell, to the D and Na flow and the cell walls (analogous to the manner in which the term is used in the game of billiards or pool). This rate is directly related to the power absorbed by the Na vapor in an operating cell, which makes the natural choice of units for "English," power. We see that an incident power of 2 W corresponds to an English of 650 mW for the design parameters discussed earlier. If the Na atoms lose their polarizaion on every wall bounce (instead of 1 out of 1000 bounces), we have computed that the limiting polarization is achieved for an incident laser power of 3 W with an English of 1 W.

As long as molecular flow conditions are maintained (corresponding to deuterium thicknesses $< 8 \times 10^{15}$ atoms/cm^2), the deuterium flow, target thickness, and required incident laser power scale linearly together in our model.

TECHNICAL OBSTACLES TO A WORKING TARGET

In order to produce a tensor polarized deuterium target with $t_{20} = 0.3$ and a thickness 2.3×10^{15} atoms/cm^2, we require a laser with sufficient power and frequency coverage to optically pump a Na vapor at 232° C to 95% while putting 650 mW of English through this vapor. Also, the cell wall must have a wall depolarization probability $<10^{-3}$ and a recombination probability $<10^{-4}$ at 232° C with the deuterium entering the cell being >90% dissociated.

As for the laser requirements, we estimate that a 4.5 watts/cm^2 (2 W total power) with a 4 GHz bandwidth would do the job with one pass through the spin exchange cell. The current record for power from a dye laser at this wavelength is 40 W with no mention of bandwidth.[15] Commercially available dye laser/argon-ion laser systems are able to provide as much as 5 W in a 10-GHz or <1 GHz bandwidth. We are currently acquiring a 10-GHz system which we hope to adapt to our needs. Our estimates of laser power do not include stimulated

emission effects which we believe can only serve to increase the vapor polarization.

The recent work of Weber et al.[10] have shown that a 2×10^{13} atoms/cm^2 thick Na vapor can be optically pumped to a high polarization with 400 mW of laser power. We estimate that if the Na atoms in their cell were completely depolarized on each bounce, their vapor should have absorbed ~130 mW of English. Even though their vapor was twice as thick as in our design, we see that our English requirements (650 mW) due to Na-D spin exchange have yet to be demonstrated. It should be noted that the Na density of 5×10^{12} atoms/cm^3 is near the region for the Weber cell geometry where some[18] predict that "radiation trapping" starts to limit the vapor polarization.

Nearly independent of the necessary optical pumping technology is the requirement of low depolarization and recombination probabilities for the cell wall for deuterium. The relatively high operating temperature of 235° C is most likely a handicap in attaining both of these goals. Barker et al.[19] have reported depolarization probabilities in the 10^{-3} range, while Kleppner et al.[20] have reported recombination probabilities in the 10^{-4} to 10^{-5} range. Both these measurements were done at room temperature with teflon coated cells. Bouchait and Brossel[21] have observed depolarization probabilities for optically pumped rubidium in the 10^{-4} range for some wax based wall coatings at 100° C. As evident from our modeling, a higher wall depolarization of the optically pumped vapor can "in principle" be overcome by increased laser power whereas wall depolarization of the deuterium cannot.

Our choice of Na as the optical pumping vapor was motivated by its low Z to prevent excessive bremsstrahlung losses ($\propto Z^2$) in a stored electron beam.[3] In a hadron ring, a high Z "background gas" may in fact be desirable for efficient cooling of high beam currents;[22] in which case, one could operate with an optically pumped rubidium (or potassium) vapor. For a cell design similar to the Na system, a rubidium (potassium) based spin-exchange system should attain a $t_{20} = 0.3$ at a much lower operating temperature of 125° C (150° C). However, both rubidium and potassium systems require optical pumping wavelengths in the near infrared where recently developed laser dyes have produced less than 1 W of power, thus reducing the target thickness (effectively polarized) to ~10^{15} atoms/cm^2.

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