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Test of Storage Cells for Polarized Atomic Hydrogen

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Work is in progress to test improved storage cells for polarized atomic hydrogen and deuterium. The target density and target polarization will be determined by passing a low energy beam of D^+ through the cell and determining the alignment of the resulting D° atoms by the T(d,n) reaction.

1. Introduction

In principle, a beam of polarized atoms from an atomic beam source can be used as a polarized target. Such a target has many advantages (high polarization, chemical and isotopic purity, absence of strong magnetic fields, easy polarization reversal etc.), but practical applications are limited because, with present techniques, the target thickness is limited to about 10^{12}cm^{-2} (see ref.1). Nevertheless, a pilot experiment at Stanford[2] has detected nuclear scattering from an atomic-beam target of thickness $1.6 \times 10^{11}\text{cm}^{-2}$. It has been claimed[3] that a target thickness of $\sim 10^{14}\text{cm}^{-2}$ can be produced, but no experimental evidence has been forthcoming.

The group at Wisconsin has proposed[4] to increase the density of polarized gas targets by storage of atoms in a cell, and has demonstrated the use of this method by scattering a beam of α-particles from polarized hydrogen and deuterium contained in a storage cell[5]. The principle has been described as dynamic storage, since the cell is leaky because of the required openings for injection of the atomic beam and openings for entry and exit of the beam from the accelerator. While high target polarization is assured for a free atomic beam, this is not the case for a storage cell where there is opportunity for depolarization in wall collisions. The above tests[5] showed that (75 ± 8)% of the ideal polarization values are achieved for atomic hydrogen and deuterium. The measured target thickness (1.1×10^{12} cm^{-2}) was rather modest, since the leak rate of the cell was large because of the rather large access openings (1 cm diameter). In the average, the atoms were stored for about 10 msec, during which time they made roughly 1000 collisions with the wall.

Here we will consider storage cells which might be useful as internal polarized gas targets for storage rings. In order to illustrate what can be achieved with present methods, we assume an atomic beam apparatus of the type described by Mathews et al.[6], which is typical of the best atomic beam sources now in operation. Besides achievable target density, the crucial question is whether the polarization survives in cells with relatively long storage times. Below, we describe a method to test the target polarization under realistic conditions without tying up an expensive accelerator.

2. Storage Cells

We assume that N atoms per second are injected into a storage cell. An example of a cell is shown in Fig.1. The cell dimensions chosen in this example are compatible with the circulating beam in a storage ring such as the Indiana cooler ring. To allow for beam excursions during loading of the ring (i.e. prior to cooling), the cell may need to be split lengthwise so that it can be opened (clam-shell cell).

The density of atoms in the cell, n, will build up to the point where the net flow out per unit time equals N. The flow out, in turn, is determined by the pumping conductance C of the openings. The number of atoms per unit volume in the cell, can thus be expressed as

$$n = N/C. \tag{1}$$

If the openings are tubes of diameter d_i and length ℓ_i, the conductance in cm³/sec is (ref.1)

$$C(\mathrm{cm^3/sec}) = 3.81\mathrm{x}10^3 (T/M)^{1/2} \sum_i d_i^3/(\ell_i + 1.33\ d_i) \tag{2}$$

where the sum extends over all openings. Here, T is the absolute temperature of the gas, and M the molecular weight. Eq. (2) requires corrections if the diameter of the vessel is not large compared to the diameter of the tubes, but these can be neglected for present purposes.

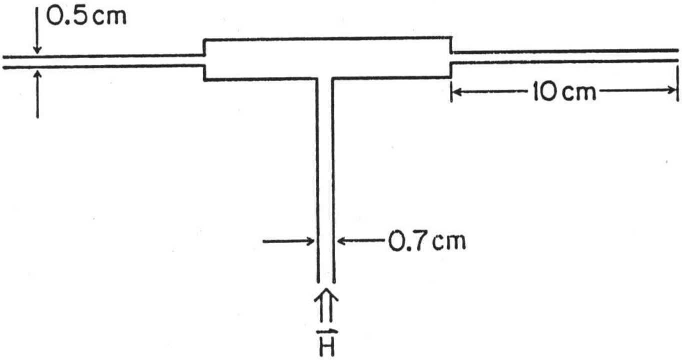

Fig. 1. Schematic of storage cell.

For the above dimensions, the pumping conductance for hydrogen atoms is

$$C = 3.5\mathrm{x}10^3\ \mathrm{cm^3/sec}. \tag{3}$$

If we assume that $3\mathrm{x}10^{16}$ atoms/sec enter the 0.7 cm diameter feed tube of the cell, we obtain

$$n = 0.9\mathrm{x}10^{13}\ \mathrm{cm^{-3}}. \tag{4}$$

For comparison, the maximum density of atoms in the free atomic beam is 6×10^{11} cm^{-3}, or a factor 15 less. To convert n to a target thickness requires an assumption about the acceptable maximum length of the effective target. If we assume a target of 10 cm length, the target thickness for the cell becomes roughly

$$t = 10^{14}\mathrm{cm^{-2}}. \tag{5}$$

This is an improvement by a factor of about 30 compared to the same beam without storage cell even if an oblique angle is assumed between atomic beam and circulating beam.

A cell of this type has a volume $V \approx 50$ cm³, thus the average dwell time is

$$\tau = V/C \approx 15\ \mathrm{msec}. \tag{6}$$

This dwell time is short enough that it is possible to reverse the polarization of the sample several times a second.

The most important and also the most difficult questions to consider are recombination and depolarization of the atoms in wall collisions. If the average speed of the atoms is v, the number of wall collisions during time τ is roughly

$$\nu = v\cdot\tau/\lambda \approx 7\mathrm{x}10^3 \tag{7}$$

where $\lambda \approx 1$ cm characterizes the average distance the atoms travel between wall collisions. In connection with hydrogen masers, Kleppner et al.[7] have developed wall coatings which permit some 10^4 collisions before depolarization or recombination. Thus there is hope that for the cell considered here wall problems can be handled. However, it must be made clear that there are a number of open questions. In particular it must be ascertained that the wall coating survives in an accelerator environment in the presence of scattered particles and ions in the cell.

Use of storage cells for nuclear reaction experiments may require thin windows for exit of charged reaction products from the cell. The use of thin Teflon windows suggests itself, since wall coatings of the same material are known to be advantageous. Such windows were used successfully in a first experiment with a dynamically stored target of hydrogen.[5]

Since the gas conductance is proportional to $T^{1/2}$, the target density is expected to increase like $T^{-1/2}$ if the temperature of the cell is lowered. Use of a cold cell does not necessarily require that the injected beam be cold, since the atoms will be cooled to cell temperature in the first few collisions, and the heat load from the injected hot atoms is small.

The design of storage cells at various low temperatures requires suitable wall properties to avoid depolarization and recombination. At very low temperatures (<0.3K) wall coatings of superfluid helium offer a unique solution, but here we only consider cells at temperatures easily reached with liquid He. On the basis of conductance alone one predicts for 5 K a gain in density by a factor eight, but one needs to consider the effect of atomic hydrogen interaction with a frozen H_2 wall and also the fact that the vapor pressure of H_2 presents a background of unpolarized atoms in the cell. At a temperature of 4.5 K, the vapor pressure of H_2 contributes an unpolarized background gas density of roughly 10^{13} cm^{-3} which corresponds, for the atomic beam intensities assumed here, to 20% of all atoms in the cell. Since at 4.2 K the sticking time of H atoms on frozen H_2 is already 40 nsec, the use of wall temperatures below 4 K is precluded. It is not clear whether a temperature exists where depolarization on the wall and contamination from background are both tolerable. Wall coatings of Ne offer some hope of a partial solution, but it is questionable whether the coating can be reestablished under the severe vacuum limitations of a storage ring. Initially, we plan to study wall coatings such as Al_2O_3 near 100 K where the recombination rate has a minimum.

3. Test Method

The test method is shown in Fig. 2. A 30-50 keV D^+ beam is used as a probe. Pickup of polarized electrons in the storage cell produces fast $\vec{D}^0$ atoms which are polarized in electron spin. In a field free region, the hyperfine interaction transfers the electron polarization in part to the nucleus, which acquires a tensor polarization P_{zz}. The tensor polarization finally is detected as an anisotropy in the $T(\vec{d},n)$ reaction. The primary advantage of this test arrangement is that studies can be performed without the need for an accelerator. While the method used here measures only the electron polarization of the hydrogen atoms in the storage cell, and not the nuclear polarization, depolarization in wall collisions will certainly proceed via depolarization of the electrons.

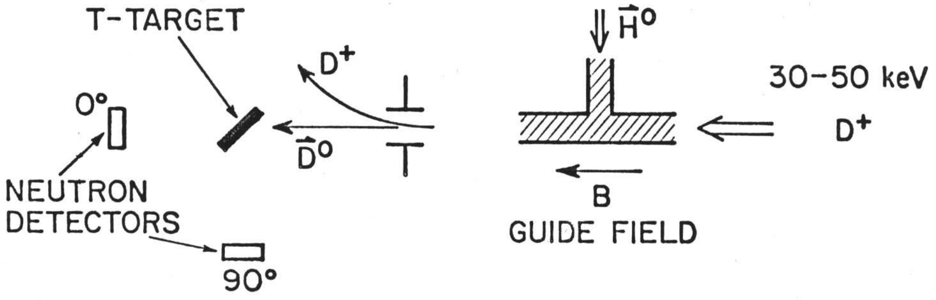

Fig. 2. Test arrangement for storage cells (schematic).

For our initial test the storage cell consists of a 20 cm long tube of 0.7 cm inner diameter. The feed tube for the atomic beam is of the same diameter and of 5 cm length. The gas conductance of this cell for atomic hydrogen at room temperature is C = 8 l/sec, so that the expected $\vec{H}^\circ$ density at the center of the cell is $\rho \approx 10^{12}cm^{-3}$ if 1.0×10^{16} atoms/sec are injected into the cell. The corresponding target thickness for the D^+ beam passing through the cell is 10^{13} atoms/cm². Since the cross section for neutralization of D^+ in H° is $\sigma = 4x10^{-16}$ cm² for a D^+ energy of 50 keV, roughly 0.4 particle-μA of $\vec{D}^\circ$ will be produced for 100 μA of D^+. Past experience indicates that the count rate in the neutron detectors is such that the electron polarization of the hydrogen atoms in the storage cell can be measured to 2% in about 10 minutes. Thus the method is useful even for quite modest target thickness.

The electron polarization of the $\vec{D}^\circ$ atoms is expected to be equal to the electron polarization in the target gas provided the charge exchange reaction proceeds directly to the ground state of the D° atoms. For pickup into excited states, part of the polarization will be lost in the subsequent decay. The net effect is to underestimate the target polarization. The expected effect is small, since electron capture to the ground state is strongly favored (>90%). Nevertheless, we plan a direct calibration by using the free atomic beam as a target. Comparison of results with the free beam and with the storage cell will provide a measurement of depolarization in wall collisions which is free of assumptions about depolarization in the charge exchange process.

The scheme now under construction will be used to study the density and polarization of storage cells in the temperature range 300 K to 4 K.

4. Conclusions

The two most important characteristics of a storage cell for polarized hydrogen or deuterium are target thickness and target polarization. Both aspects can be tested by the method described above.

The goal of the present investigation is to answer the question whether the target densities available from present atomic-beam and storage cell technology is sufficient to proceed with the construction of an internal polarized gas target for a storage ring. If tests show that high polarization can be obtained with a target thickness of some 10^{14} cm^{-2} (density 10^{13} cm^{-3}, length 10 cm), preparation of a target for the Indiana cooler ring would be interesting. In this machine the circulating polarized beam is expected to provide 10^{16} protons/sec incident on the target, so that the luminosity becomes $L \approx 10^{30}$ sec^{-1}cm^{-2}, or roughly 10^8 events/day•mb. A cell of this type also would provide useful event rates e.g. for electron scattering from aligned deuterons, a problem which is of considerable current interest since it promises interesting new information about the form factors of the deuteron. Other applications, such as the possiblity to polarize circulating antiprotons in LEAR by spin-selective attenuation in an internal polarized hydrogen gas target, must await further technical developments, since the rather large access openings of the cell[8)] require either higher feed rates or lower cell temperatures than presently available.

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DISCUSSION

NISIMURA: How are you monitoring the target polarization during a scattering experiments?

HAEBERLI: One would use a reaction of known analyzing power and measure the change in count rate associated with polarization reversal of the target. For a proton storage ring, the analyzing powers for elastic pp and pd scattering are known. For an aligned deuterium target in an electron ring, one can make use of the model-independent prediction that the analyzing power T_{20} reaches the value $-\sqrt{2}$ at some momentum transfer between 3 and 4 fm^{-1}.

DICK:
1. Geometrical acceptance 0.5 cm for the cell is too small for a high energy storage ring.
2. For a low energy storage ring we must take into account a factor 100 for its multitraversal rate compared to a high energy collider (SPS) and gives its limitation for the density in the cells.
3. For low energy storage ring cooling is necessary to prevent the degradation of the beam by multiple scattering.

HAEBERLI: The problems you are pointing out are dependent on the particular accelerator. The target design I considered is compatible with the requirements of the Indiana Cooler Ring.

STEFFENS: In our proposal about using such a storage bottle in a low energy storage ring like LEAR/CERN we have assumed a low β insertion. In this case the openings of the bottle have roughly to be 5×20 mm^2, which conserves the full acceptance of the machine (vacuum chamber limit).