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STORAGE CELLS AS POLARIZED GAS TARGETS

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ABSTRACT

Storage cells for polarized atomic hydrogen or deuterium have been proposed for use as polarized internal gas targets in storage rings. The cells have openings for entry and exit of the charged particle beam, and an opening for injection of the polarized atoms produced by an atomic beam source. Typical experiments for storage rings of protons, antiprotons and electrons are used here to assess the required target thickness. For certain experiments, useful count rates are obtained with currently available techniques, but studies of depolarization of the target atoms in cells with different wall coatings and different wall temperatures are required.

1. Introduction

The review of operational polarized targets, which was presented to us earlier today, has illustrated the high degree of development of solid targets containing polarized protons or polarized deuterons. However, there is also interest in the development of polarized gaseous targets of hydrogen and deuterium, even if their density will be minimal compared to solid targets. Gaseous targets of low density would be useful as internal targets in storage rings, where reasonable luminosity may be achieved because of the large circulating current. Factors which make polarized gas targets interesting are: high chemical and isotopic purity; the possibility to reverse the target polarization within a fraction of a second; the absence of strong magnetic fields, free choice of polarization direction; large deuteron polarization and alignment; and insensitivity to radiation damage.

In the simplest arrangement (Fig. 1), the polarized atoms from an atomic beam source serve as a polarized target. Scattering of α-particles from such a target was demonstrated at Stanford [1]. The observed target thickness was 1.6×10^{11} atoms/cm^2, and the target polarization $P = 0.37 \pm 0.06$, compared to an ideal value for the arrangement used of $P = \frac{1}{2}$. This

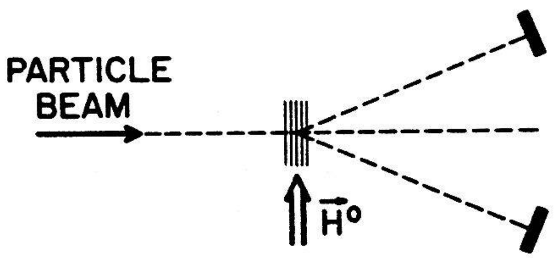


Fig. 1 Schematic diagram of the experiment at Stanford [1] where a beam of α-particles was scattered from a beam of thermal polarized H atoms.

target thickness corresponds to a 1 cm diameter atomic beam of 3×10^{16} atoms/sec with an average velocity of 2.5×10^5 cm/sec ($T \approx 300K$). With improved methods, a target thickness of 10^{12} atoms/cm^2 seems feasible [2], but the target densities required for some of the most interesting experiments are at least two orders of magnitude higher.

The arrangement of Fig. 1 makes inefficient use of the polarized atoms, since each atom passes through the beam but once. The efficiency can be improved by injecting the atoms into a storage cell (Fig. 2) so that they are reflected repeatedly by the wall and thus have several chances of passing through the beam before escaping through one of the openings. This principle was tested at Wisconsin [3], where 1×10^{16} atoms/sec were injected into a storage cell to produce a target density of 3.0×10^{11} atoms/cm^3 and a useful target thickness of 1.1×10^{12} atoms/cm^2. The polarization of the target protons, measured by scattering of α-particles, was found to be $P = 0.38 \pm 0.04$, compared to an ideal value of $P = \frac{1}{2}$. In the average, the atoms made $\approx 10^3$ collisions with the wall before escaping from the cell. The three

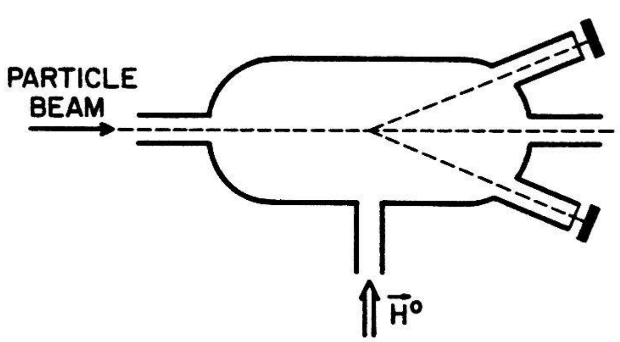


Fig. 2 Schematic diagram of the experiment at Wisconsin [3], where polarized atoms were injected into a storage cell to improve the target thickness compared to the arrangement in Fig. 1. The atoms made about 10^3 wall collisions without significant depolarization.

access tubes to the cell had diameter 1.0 cm and length 10 cm. The walls of the cell and the openings for exit of scattered particles were covered with a film of teflon.

2. Required Thickness of Target

The primary application of polarized gas targets will be in storage rings, where the small available target thickness is compensated in part by the large circulating current. In order to be reasonably definite, we will consider specific examples of possible experiments for three different storage rings.

We first consider a proton ring for intermediate-energy physics (≤ 1 GeV), and will use parameters applicable to the Indiana Cooler Ring. As a typical example, we assume measurements of spin correlation parameters (e.g. $\vec{p} + \vec{d}$ elastic scattering), using a beam of circulating polarized protons. A reasonable design aim for the liminosity is

$$L = 10^{30}\ \mathrm{sec}^{-1}\mathrm{cm}^{-2}, \qquad \text{(proton ring)} \qquad (1)$$

since this would provide a detector rate of 50 events/sec, assuming a detector solid angle $\Delta\Omega = 50$ msr and a differential cross section $\sigma = 1$ mb/sr. This detector rate is reasonably generous, permitting measurements of spin correlation coefficients to ±0.01 in some 10 minutes. This estimate includes incomplete target and beam polarization, macroscopic duty cycle of the machine, and overhead. The above luminosity would be sufficient also to study processes with smaller cross sections, down to perhaps 10 μb/sr. Since the ring is expected to provide 10^{16} protons/sec incident on the target, the required target thickness ρx is

$$\rho x = 10^{14} \text{ atoms/cm}^2 \qquad \text{(proton ring).} \tag{2}$$

Next we consider the low energy antiproton ring at CERN. It has been proposed [4] to polarize the circulating $\bar{p}$ beam in LEAR by inserting a polarized hydrogen gas target in the ring. If the $\bar{p}p$ total cross section is significantly different when the spins of the collision partners is parallel ($\uparrow\uparrow$) than when they are antiparallel ($\downarrow\uparrow$), one $\bar{p}$ spin is depleted more than the other and the circulating beam will become increasingly polarized. The target thickness ρx needs to be large enough that the total thickness traversed during some reasonably short time T (e.g. T = 10 hours) equals one attenuation length, i.e. $\rho x \sigma f T = 1$, where $f = 10^6$ sec^{-1} is the circulation frequency of the beam. For a $\bar{p}$ beam of energy 30 MeV, the $\bar{p}p$ total cross section is $\sigma \approx 300$ mb, so that $\rho x = (\sigma f T)^{-1}$ becomes

$$\rho x = 10^{14} \text{ atoms/cm}^2, \qquad \text{(antiproton ring)} \tag{3}$$

where we assumed T = 10 hrs. The degree of polarization of the remaining $\bar{p}$ beam depends on the relative cross section difference between ($\uparrow\uparrow$) and ($\downarrow\uparrow$), which, unfortunately, is not known. If we assume that of the original $10^{10}\bar{p}$ in the ring, $10^9\bar{p}$ survive, the incident beam on the target will be 10^{15} sec^{-1}, and thus the luminosity

$$L = 10^{29} \text{ sec}^{-1}\text{cm}^{-2} \qquad \text{(antiproton ring).} \tag{4}$$

This luminosity is sufficiently large that significant polarization experiments in the $\bar{p}p$ system still would be possible, even if the relative cross difference were only of the order 0.1.

Finally we consider experiments with polarized internal targets in electron storage rings. One fundamental problem of long standing is the separate determination of the charge form factor F_c and the quadrupole form factor F_q of the deuteron. It has long been known that separation of these form factors can be accomplished by electron scattering from a deuterium target which is aligned (i.e. tensor polarized). Figure 3 shows various predictions of the tensor analyzing power T_{20} as a function of momentum transfer, to illustrate that even measurements of moderate accuracy (e.g. ±0.05) above $q = 3$ fm^{-1} are interesting. The figure also emphasises the lack of experimental data. The count rate calculations by Holt [5], shown in Fig. 4, are based on an assumed target thickness of

$$\rho x = 10^{15} \text{ atoms/cm}^2 \qquad \text{(electron ring)} \tag{5}$$

and a beam aurrent of 100 mA at 14.5 GeV (25 mA at 5.0 GeV), which corresponds to a luminosity

$$L = 6 \times 10^{32} \text{ sec}^{-1}\text{cm}^{-2} \qquad \text{(electron ring).} \tag{6}$$

Depending on the kinematic region, the assumed detector solid angle is 3 to 15 msr. The above luminosity would be sufficient for measurements in the interesting region up to $q = 6$ fm^{-1}, but problems of beam life time have not been considered. Even target thicknesses a factor ten below the assumed value would yield useful results, particularly if it turned out that a detector system of larger acceptance angle can be designed.

The two points shown in Fig. 4 are the results of measurements with an unpolarized deuterium target [6], in which the alignment of the recoil

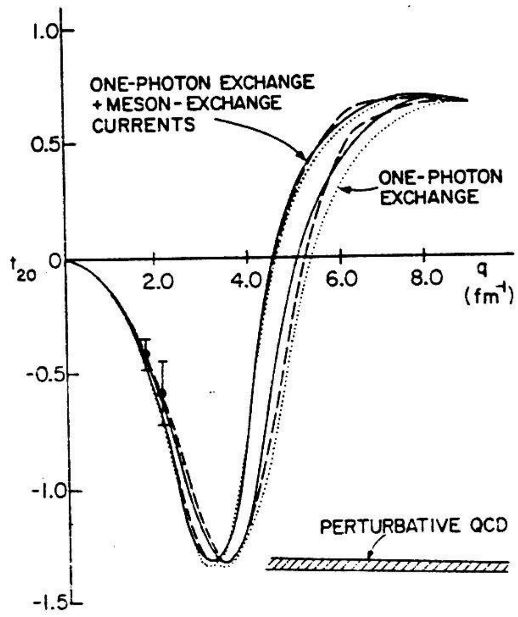


Fig. 3 Predicted tensor analyzing power vs. momentum transfer in electron scattering from deuterium. The figure is from ref. [5].

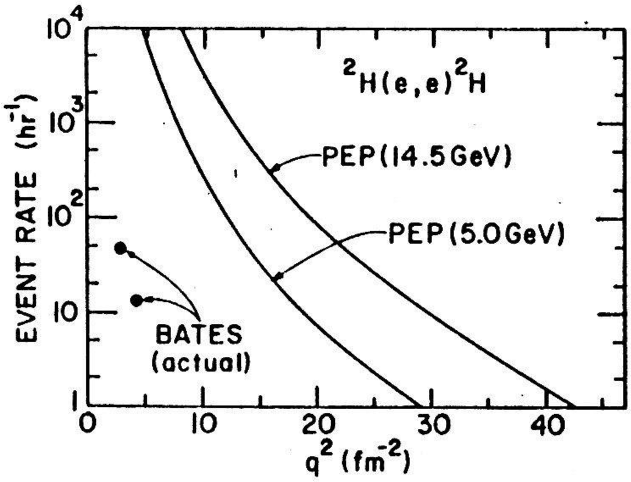


Fig. 4 Count rate in elastic scattering of electrons by deuterium. The assumptions are stated in the text. The figure is from ref. [5].

deuterons was detected by use of the $^3He(d,p)^4He$ reaction. For momentum transfer $q > 3\ fm^{-1}$ the cross section drops so drastically that this method becomes impractical.

Another fundamental quantity that would become accessible with an internal polarized target is the electric form factor of the neutron. The interference term $G_E G_M$ between electric and magnetic form factor can be detected [7] by quasifree scattering $^2\vec{H}(\vec{e},e'n)^1H$ of polarized electrons from neutrons in a polarized deuterium target.

3. Target Configurations and Attainable Target Thickness

3.1 General Considerations

Assume a target cell, such as the one shown in Fig. 2, into which polarized atoms are injected at the rate of N atoms/sec. The density of atoms in the cell, ρ, will build up to the point where the number of atoms escaping per second through the openings, ρC, equals N, or:

$$\rho = N/C. \tag{7}$$

The gas conductance C depends on temperature T and mass number M of the gas. For openings consisting of tubes with diameter d_i and length ℓ_i:

$$C = 3.8 \times 10^3 \sqrt{T/M}\ \Sigma d_i^3(\ell_i + \tfrac{4}{3}d_i)\ cm^3/sec. \tag{8}$$

The average dwell time τ of atoms in the cell is roughly $\tau = V/C$, where V is the volume of the cell. The number of wall collisions ν, which an atom undergoes before escape, is approximately

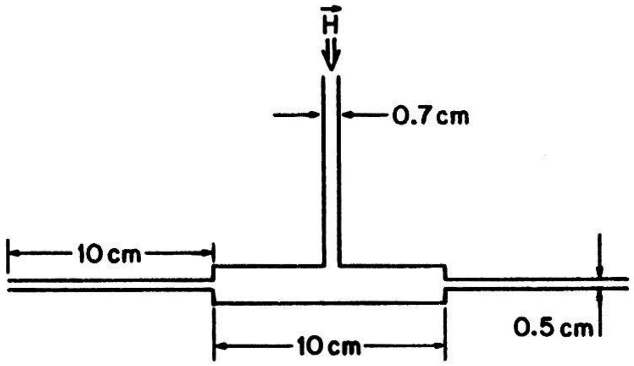
$$\nu = v\tau/\lambda, \tag{9}$$

where λ characterizes the mean distance between collisions with the wall, and $v = 1.45 \times 10^4\sqrt{T/M}$ cm/sec is the average speed of the atoms in the cell.

The maximum injected intensity N is determined by the limitations of atomic-beam sources of polarized atoms, unless some other method can be developed (see below). The most effective way to increase the target density ρ is to reduce C by limiting the diameters d_i of the access tubes. However, since the diameter of the atomic beam is at best about 7 mm, there is little gain in reducing openings much below this value.

3.2 Required Feed Rate of Cells

The cell shown in Fig. 5a has access openings sufficient for the circulating beam in a proton ring (Indiana Cooler Ring), while the circulating $\bar{p}$ beam in LEAR requires a cell of considerably larger acceptance (rectangular openings of the size shown in Fig. 5b). For the electron ring we assume the cell in Fig. 5a although this choice is speculative since it is not based on design parameters of an actual machine.



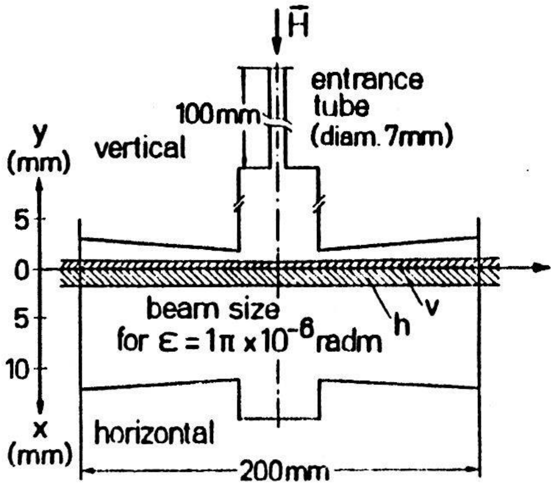


Fig. 5 The cell shown on the left has sufficient acceptance for the proton beam in the Indiana Cooler Ring. During loading, the cell aperture would need to be opened (clam shell cell). The cell on the right accepts the $\bar{p}$ beam in LEAR.

Table 1 summarizes the parameters of the cells. The effective length is assumed to be ≈ 10 cm in all cases. The conductance C is calculated for H-atoms at room temperature. We note that the dwell time is short enough that the target polarization can be reversed several times per second by reversing the polarization of the injected atoms (RF transitions on atomic beam source). The large number of wall collisions raises concern about depolarization and recombination. However, wall coatings that permit 10^4 collisions have been developed in connection with the hydrogen maser [8]. Whether these coatings are compatible with the target environment in a storage ring remains to be seen.

Table I
Summary of Storage Cell Characteristics

	Proton Ring	Antiproton Ring	Electron Ring
Target thickness ρx (atoms/cm²)	10^{14}	10^{14}	10^{15}
Effective target length (cm)	10	11	10
Ave. target density ρ (atoms/cm²)	10^{13}	10^{13}	10^{14}
Conductance C for H-atoms (room temp.) (ℓ/sec)	3.5	2.4	3.5
Ave. dwell time τ (msec)	15	2.5	15
Number of wall collisions	≈4000	≈500	≈4000
Required feed rate N (room temp. cell) (atoms/sec)	3.5×10^{16}	2.4×10^{17}	3.5×10^{17}
For comparison: Atomic beam target requirement (atoms/sec) (assuming beam temperature 50K, beam diameter 1 cm, Θ=15° with respect to circulating beam)	2×10^{18}	2×10^{18}	2×10^{19}

The rate of injected atoms, N, required to meet the design value of target thickness, is significantly higher than currently available from atomic beam sources. Detailed measurements of atomic beam density, velocity distribution and beam intensity distribution for a modern atomic beam source have recently been published by the group at Bonn [9]. From these data one calculates $N = 2.5 \times 10^{16}$ atoms/sec over a 7 mm diameter if two hyperfine states are populated, or $N = 1.5 \times 10^{16}$ atoms/sec when the equipment is changed to select a single hyperfine state. The first case leads to lower polarization (ideally $P = \frac{1}{2}$ instead of $P = 1$) unless one can tolerate a sufficiently strong magnetic field over the cell (≈ 100 mT for H, 20 mT for D). Thus, presently available beam intensities are nearly sufficient to inject into a target for a proton ring, while the other targets require improved techniques.

3.3 Possible Improvements

The total output of the new atomic beam sources at ETH and SIN is estimated to be near 10^{17} atoms/sec [10]. The beam from these sources, however, has a relatively large beam diameter and beam divergence. Thus the access tube of the cell would need to be increased, causing a corresponding increase in conductance. A net gain may result if the cell already has a large gas conductance (i.e. cell for antiproton ring).

The gas conductance decreases as $T^{1/2}$, so that cooling the cell will increase the target density. The atomic beam itself does not need to be cooled, since the atoms will attain cell temperature after the first few collisions. Studies are needed to find suitable walls or wall coatings. Problems arising with wall coatings of solid hydrogen have recently been discussed [2]. A wall coating of superfluid helium is attractive because of the large gain in target density and the known low depolarization and recombination probability. However, the possibility of accidental film burning and considerable technical difficulties raise serious questions about the practicality of this solution.

For some of the applications considered above, it may well be possible to reduce the demands on target density by optimizing the geometry of the experiments, e.g. use of larger target length and increased detector solid angles.

Alternate methods of feeding a storage cell should be considered, such as the application of spin exchange between atomic hydrogen and optically pumped Na, proposed by Holt [5].

4. Tests of Storage Cells

It is essential to test depolarization mechanisms in storage cells prior to installation in a ring. The tests should include possible depolarization through excitation and ionization of the target atoms by the incident beam, as well as adverse effects on the wall coating by scattered particles, ions, and electrons. One possibility to test the alignment of a deuterium target is to detect the anisotrophy in the $^2\vec{H}(^3He,d)^4He$ reaction at a few hundred keV ^3He energy. A test method which does not require the use of an expensive accelerator has been described in ref. [11]. A 30-50 keV D^+ beam is used as a probe. Pickup of polarized electrons in the storage cell produces fast $\vec{D}^\circ$ 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}. Finally, the tensor polarization is detected as an anisotropy in the $^3H(\vec{d},n)^4He$ reaction. While this method 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.

In order to ascertain that this test method works as expected, a free atomic beam has been used as a target. Pickup of electrons took place in a weak-field region ($B \approx 0.2$ mT), while the tritiated titanium target was in a "strong" magnetic field ($B = 31$ mT). Under those conditions, the ideally expected electron polarization in the atomic beam is $P_e = \frac{1}{2}$, and the expected alignment of the deuteron is $P_{zz} = -\frac{1}{6}$. The alignment deduced from the relative count rates in two neutron detectors 90° apart, was $P_{zz} = -0.174 \pm 0.011$, in agreement with the expected value. The stated result contains a number of corrections (finite magnetic field, finite detector solid angle, etc.) of which the largest arises from a D_2^+ component in the incident deuteron beam. The assumption was made that pickup of polarized electrons by D_2^+ leads to unpolarized deuterons. It would be preferable to momentum analyze the incident beam to avoid any uncertainty associated with the D_2^+ beam.

5. Conclusions

Polarized gas targets with a thickness of 10^{14} atoms/cm^2 or more would permit interesting new experiments in storage rings for protons, antiprotons and electrons. The required target thickness can be approached by injecting atoms from an atomic beam source into a storage cell through which the charged particle beam passes. The attainable target density depends critically on the diameter of the access tubes fo the cell. For some applications (Indiana Cooler Ring) openings for the circulating beam of 0.5 cm diameter are sufficient, provided the cell aperture is increased during loading of the beam. For application to an antiproton ring, large apertures and a correspondingly larger rate of injected atoms are required. The economy of the cell may be improved by lowering the temperature of the walls.

No matter whether the cell is cooled or not, tests are required to determine whether the target polarization can be maintained in an accelerator environment during the several thousand wall collisions the atoms may undergo before escaping the cell. These tests can be carried out without the need for an expensive accelerator.

The present discussion was limited to targets of polarized hydrogen and deuterium atoms. The situation with regards to polarized ^3He targets is much more favorable, because in this case the density in the cell can be increased by cooling the walls without fear of relaxation. Recent papers [12] describe the use of laser optical pumping to polarize ^3He at the rate of 10^{16} atoms/sec, and reports long relaxation times for walls between 1.2 K and 4.2 K. Thus the number of atoms per unit volume, ρ, for a cold ^3He storage cell is at least an order of magnitude larger than for a room temperature hydrogen cell of the same dimension.

We see as the highest priority in the development of storage cells for hydrogen and deuterium the study of wall depolarization and wall coatings for different temperature regions, and the study of other possible depolarization mechanisms. At the same time, it would be desirable to proceed in the design of target and detector configurations for existing or planned storage rings, so that the target requirements can be more sharply defined.

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Secretary's report, Session (C), T.B. Clegg:

S. Jaccard : What is wrong with having several input beams into your cell?

Answer: You can do that, but you do not gain as much as you would expect because much of the gas is lost through the tubes through which the beam enters.

D. Kleppner : Does your cell load exceed the vacuum requirements of a ring like LEAR?

Answer: It certainly would without differential pumping and cell cooling.

D. Kleppner : There is another open cell geometry - the cooled hydrogen cell inside a superconducting coil of which we have spoken at previous meetings. It will attain the densities of the size which you need and the beam can pass through the cell along the magnetic field direction without being badly disturbed.

Answer: But this cell requires a longitudinally polarized beam, a feat which is definitely not easy to attain.