ELECTRON-SPIN-POLARIZED TARGETS FOR A COLLISIONALLY-PUMPED POLARIZED-ION SOURCE*

S. N. Kaplan, C. F. Burrell,+ R. V. Pyle, L. Ruby, A. S. Schlachter, and J. W. Stearns

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

Collisional pumping has been proposed as a mechanism for producing polarized ion beams more intense by orders of magnitude than those from the best existing sources. One implementation of this method employs a very thick electron-spin-polarized alkali-vapor target in a low magnetic field, and is characterized by a predicted 100% spin-transfer efficiency from the target to the beam. Target characteristics and design constraints are discussed.

Introduction

The use of an electron-spin-polarized alkali-vapor target for the production of polarized H^- beams, an idea first proposed by Haeberli [1], and further developed by Anderson [2], is gaining wide acceptance in the particle-accelerator community. Polarized ion sources based on this method (identified by the acroynm OPPIS, for optically-pumped, polarized ion source) are in operation at KEK [3], at an advanced stage of development at TRIUMF [4,5], and about to be developed for LAMPF. Central to the development of such a source is the production of a highly polarized alkali-vapor target by optical pumping. As a result of the need for such a target much work is also curently under way to understand target relaxation mechanisms [6], and to improve the efficiency and yield from the optical pumping process [7].

The above authors, together with L.W. Anderson, have recently proposed a new method for the production of polarized ion beams which we called collisional pumping [8,9]. This method will require alkali-vapor targets two or three orders of magnitude thicker than presently produced, but offers the promise of producing intense highly polarized beams. At ampere intensities such beams could be used as enhanced-yield fuel for nuclear-fusion reactor [10,11].

Physical Principles

The physical principle behind collisional pumping as it applies in an alkali vapor target is illustrated in Fig. 1. An incident unpolarized H^+ captures a spin-aligned electron, with a fifty-percent probability that the nucleus will be aligned in the same direction. In this case, the H^0 formed would be fully polarized if the electron were captured to the ground state. The capture, however, occurs almost entirely to excited states, and only 41% of this alignment is retained after radiative decay to the ground state [2]. The polarization after the first electron capture, however, is irrelevant insofar as collisional pumping is concerned. Collisional pumping occurs during subsequent electron-capture collisions by the H^0 and electron-loss collisions by the product H^-. When the H^0 is produced with both atomic and nuclear spins aligned, then it is forbidden by the Pauli principle from capturing a second electron with the same alignment, and will pass through the target without any further charge-changing collisions. When the nucleus and the electron are oppositely aligned, and in a low magnetic field, the spins will precess with the hyperfine frequency, so that alternately one spin (electron or nuclear) will be aligned with the field, and the other antialigned. Subsequent capture of an aligned electron can occur only during that part of the cycle when the electron is antialigned (and therefore the nucleus aligned) with the field. Each successive pair of electron-capture and -loss collisions will polarize approximately half of the remaining unpolarized nuclei, and ultimately, the beam will become both electron- and nuclear-spin polarized to the same extent that the

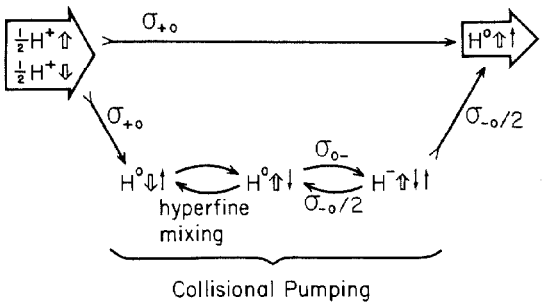

Fig. 1 Simplified schematic of collisional pumping of a hydrogen-ion beam in a polarized alkali-vapor target in a low magnetic field. The thick arrow, ⇑, shows the nuclear-spin orientation and the thin arrow, ↑, the electron-spin orientation of beam ions. The spins of the polarized target electrons are pointing up in the figure.

target is electron-spin polarized. For collisional pumping to occur it is crucial that the hyperfine interaction be large compared to the interaction with the external magnetic field, i.e. that the external field be low compared to the critical field, B_c (the field that produces an energy splitting equal to the hyperfine splitting).

For comparison, in the high-field method which employs an alkali-vapor target (OPPIS), a polarized electron is captured in a single collision. The orientation of the nuclear spin is unaffected because the atomic and nuclear spins are decoupled in the high magnetic field. For a spin 1/2 nucleus, 1/2 of the nuclei will be aligned with the electron (and with the external field), and 1/2 will be antialigned. Under a rapid (diabatic) reversal of magnetic field, the so-called Sona transition occurs, [12] where the oppositely aligned electron and nucleus exchange the sense of their spatial orientations, producing an atomic beam that is nuclear-spin polarized but unpolarized in electron spin. While in principle highly effective, and, as we shall see, requiring significantly

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thinner polarizing targets and less optical pumping power, this method has some defficiencies. Two of these are characteristic of the reaction physics. For atoms with nuclear spin greater than 1/2 (e.g. deuterium), the upper limit on achievable nuclear polarization will be much less than the initial atomic polarization. In addition, the atomic-polarization transfer from the target to the beam is less than 100%; as noted earlier, only 41% in the low-magnetic-field limit. This polarization loss can, however, be reduced significantly with a magnetic field which is much higher than would otherwise be required for implementation of the method [13].

The engineering constraints imposed by the high magnetic field requirement extend to the ion source, which must produce the ion beam in the same high magnetic field to avoid significant degradation in beam emittance [14]. Finally, a relatively high vacuum must be maintained between the ion source and the polarized target, because any neutralization upstream of the polarized target will reduce the final polarization proportionately.

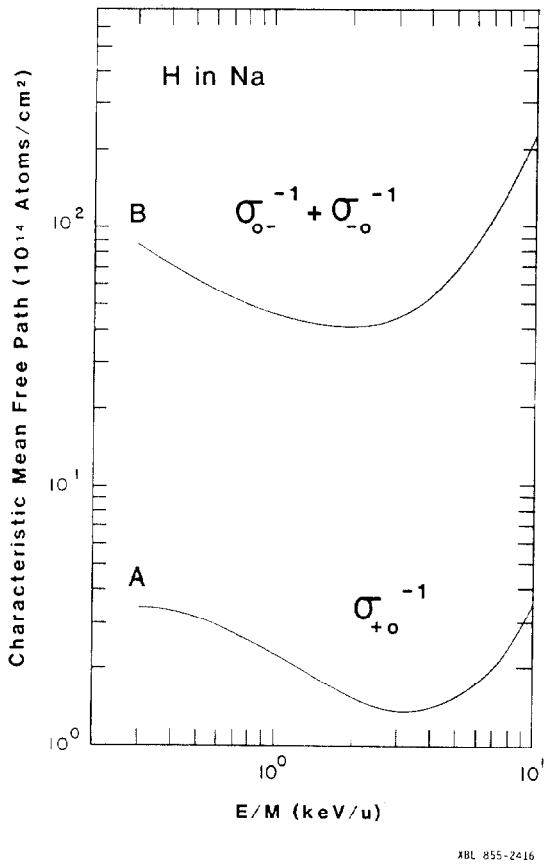

Fig. 2 Characteristic mean-free paths for 2.5 keV H ions in sodium vapor, A), for the reaction used by OPPIS sources, and B), for a single collision cycle that produces optical pumping.

Target Thickness and Density

In the high-field method, where a single electron-capture interaction by an H^+ leads to the design polarization, target thickness is determined by the σ_{+0} cross section, giving an interaction mean free path of $1/\sigma_{+0}$. In contrast, the characteristic interactions for collisional pumping are both $H^0 \rightarrow H^-$ and $H^- \rightarrow H^0$, and it can be shown that the interaction-cycle mean free path is $1/\sigma_{0-} + 1/\sigma_{-0}$. Mean free paths for the two processes in sodium, as functions of H kinetic energy, are shown in Fig. 2 [15].

An average of two interaction cycles for hydrogen are required to pump the nuclear polarization up to the electron polarization of the target. Deuterium, with a nulear spin of 1, requires an average of three cycles. Because of the sequential nature of the process, however, an asymptotic approach to the maximum polarization requires a target thickness of about 10 mean free paths. As can be seen in Fig. 2, the optimum beam energy in sodium is about 2.5 keV/u. The achievable polarization for this beam energy as a function of target thickness is shown in Fig. 3.

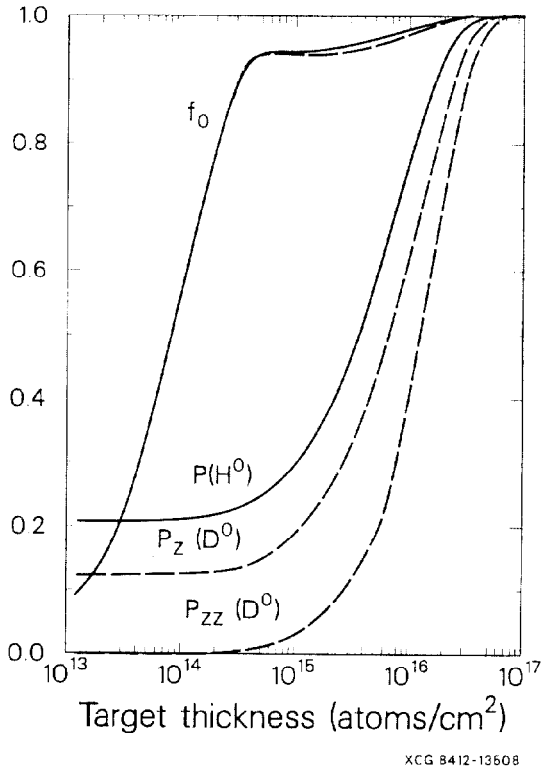

Fig. 3 Polarization and neutral fraction for 2.5 keV/u H^+ (solid lines), and D^+ (broken lines) as a function of polarized sodium-vapor target thickness. The lines labeled f_0 show the neutral fraction; P, the proton polarization; and P_z and P_{zz}, respectively, the vector and tensor polarizations of the neutral beam. It was assumed that 41% of the electron-spin polarization is retained after capture by the H^+ or D^+ (see text).

The target density for this process is also constrained by the physics of the collisional pumping process. For collisional pumping to occur, the average time between an electron-loss and an electron-capture collision must be on the order of, or greater than the hyperfine period, the reciprocal of the hyperfine frequency. (The time for spin reversal is half of the hyperfine period.) Table 1 shows the relevant hyperfine frequencies and sodium-target densities corresponding to a collision frequency equal to twice the hyperfine frequency. For all hydrogen isotopes, at 2.5 keV/u, target densities up to almost 4 x 10^{16}/cm^2 would satisfy the collision-frequency criterion. For a vapor target this is not a significant constraint.

Table 1

Target-dimension constraints imposed by collisional pumping, and related parameters (for 2.5 keV/u H and D beams):

		H	D
ν_{HFS}	Hyperfine frequency (Mhz)	1420.4	327.4
B_c	Critical field (gauss)	507	117
t_M [a]	$(2\ \nu_{HFS})^{-1}$ (ns)	0.35	1.53
d_M	beam velocity x t_M (cm)	0.024	0.106
ρ_{MAX} [b]	$(\sigma_0 \cdot d_M)^{-1}$ (10^{16}cm^{-3})	16	3.6
$X_{95}(B)$ [c]	@ B = 0 gauss (10^{16}cm^{-2})	2.3	3.5
	10	2.3	3.6
	20	2.3	3.7
	50	2.3	4.1
	100	2.4	5.8
	200	2.5	12.4
	500	3.9	52.9
	1000	9.1	

a) Minimum mean time to allow complete hyperfine mixing.
b) Hyperfine-frequency-limited target density.
c) Target thickness for 95% polarization (see text).

Magnetic Field

The target magnetic field must be sufficiently large to establish the magnetic axis, but small enough that the low-field hyperfine eigenstates that give the spin mixing necessary for collisional pumping are not significantly perturbed. Table 1 shows the target thickness required to pump the nuclear-spin polarization up to 95% of the electron-spin polarization of the target. This thickness, $X_{95}(B)$, is tabulated as a function of the external magnetic field, B. As can be seen from the tabulated data, the required target thickness does not change very rapidly at low B, but increases dramatically, when B exceeds B_c.

Laser Power

As a consequence of the low magnetic field, there will also be mixing between the atomic and nuclear spins of the sodium-vapor target. The optical pumping will therefore also pump the nuclear spin, and produce a target with both nuclear and atomic spins aligned. There is no benefit derived from aligned sodium nuclei, but the cost is a factor of three increase in laser intensity over that needed for high-field pumping. Each target atom pumped requires, on the average, angular-momentum transfer from two polarized photons. Assuming a target of thickness 3 x 10^{16} cm^{-2} and 100% efficiency for absorption of the laser light, then only 20 mJ/cm^2 of laser power at the sodium-D-line wavelength would be required for pumping the target. This light energy must, however, be delivered in a time short compared to the spin relaxation time of the target. At the target densities contemplated here, the principal mechanism for target depolarization is expected to be angular-momentum transfer in wall collisions [5]. The TRIUMF group using wall coatings recommended by Anderson [6], has been able to achieve relaxation times as long as 200 μs, corresponding to the preservation of target-atom polarization though more than 10 wall collisions. Assuming this relaxation time, a laser power density of at least 300 W/cm^2 will be required to maintain the target at 95% polarization. Losses associated with radiation trapping and saturation effects in a thick target have yet to be investigated. CW dye lasers are not yet available at this power level. However a 10-kW, 500-μs pulsed laser is available from Candella Corp., and would allow testing of the collisional pumping mechanism.

Beam Scattering

For a target of the thickness contemplated, some consideration must be given to problems of beam divergence caused by scattering. There is not a great deal of relevant data available here; however measurements, mostly with 1-2 keV deuterons incident on Na or Cs vapors of thicknesses 10^{15} cm^{-2}, have been analyzed by Hooper, Poulsen, and Pincosy [16], and fitted to an expression for the average scattering angle, θ_s (deg.),

$$\theta_s \sim 0.15(nl)^{0.7}/E,$$

for an H beam in a sodium-vapor target, where nl is the target thickness in units of 10^{15} atoms/cm^2 and E is the beam energy in keV. This gives, for a 2.5 keV beam passing through a target of thickness 3 x 10^{16} atoms/cm^2, an average scattering angle of 0.65 degrees. This would be suitable for fusion, and probably for most accelerator applications.

Conclusions

The calculated design limits show no insurmountable problems, or technical impediments to an early experimental test of collisional pumping as an alternative, and possibly very promising, technique for producing intense polarized beams. While the presently available CW lasers cannot meet the power requirements, there are no intrinsic reasons to doubt that such laser power is achievable. In the mean time pulsed lasers are currently available, which will permit a full test of the design principle.

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