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COLLISIONAL PUMPING IN POLARIZED SODIUM VAPOR*

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ABSTRACT

Collisional pumping has been proposed as a mechanism for efficient transfer of spin from an electron-spin-polarized target to the nuclei of a fast atom or ion beam. Collisional pumping takes place in low magnetic fields, can give polarization transfer approaching 100%, and offers the potential for producing polarized beams orders of magnitude more intense than presently achieved. Recently reported calculations of electronic spin-exchange cross sections at useful ion-source energies suggest significantly greater rates of pumping than first estimated, and give cause for increased optimism about sucessful implementation. Collisional pumping is described, and beam characteristics are given for prototype polarized source parameters.

1. Introduction

In 1984 we proposed a new method, which we called "collisional pumping," for producing intense, nuclear-spin polarized beams [1]. It would employ intense, fast atomic beams with fluxes up to those developed for injection into fusion reactors [2], and require polarized alkali-vapor targets similar to, but much thicker than, those presently used for polarized-beam production. Compared to present methods, this method has the advantage of neutralizing and polarizing fast (> 2 keV/u) ion beams in a low (< 30 G) magnetic field. A significant fraction of H^0 atoms can then be converted to nuclear-polarized H^- ions by electron attachment in a second alkali-vapor target. This conversion is enhanced by spin-dependent electron attachment if the second target is also electron-spin polarized, but in the opposite sense.

2. Description of the Process

A simplified schematic of the collisional-pumping process is shown in Fig. 1. In an electron-spin-polarized Na-vapor target, an H^+, after

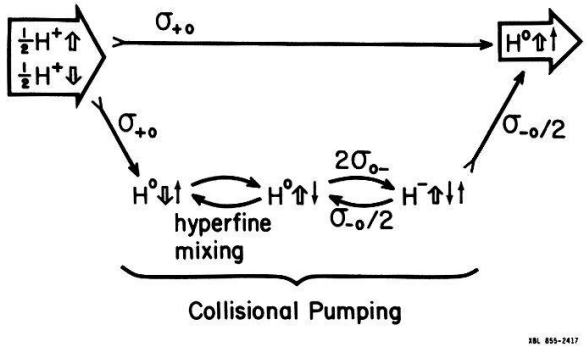

Fig. 1 Simplified schematic of collisional pumping, for a hydrogen-ion beam in a polarized alkali-vapor target in a low magnetic field. The thick arrow, ⇑, shows the nuclear-spin orientation, and the thin arrow, ↑, the electron-spin orientation of the beam ions. The spins of the target electrons are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

capturing a spin-aligned electron, will either have both atomic and nuclear spins aligned in the resultant H^0, or will enter the collisional-pumping cycle. In a low external magnetic field, hyperfine mixing transfers up to half of the electron polarization to the nucleus, and, in a beam-energy region where the electron-loss cross section, σ_{0+}, is negligible (below a few keV), a succession of electron attachment and detachment collisions pumps the beam until it is fully atomic- and nuclear-spin polarized. The fully polarized beam will also be a pure neutral atomic beam, because the polarized atoms cannot capture a second polarized electron. The process is qualitatively the same for the spin-one deuterium nucleus, except that an additional pumping stage is involved, and therefore a somewhat thicker target is required.

The simplified description above neglected two important processes: spin exchange, and partial depolarization following initial electron capture. The paths for these two processes have been included in Fig. 2, which shows the collisional-pumping cycle for a spin-one deuteron. These two processes were omitted from Fig. 1 for simplification of the discussion, although they apply equally to H and D. The added spin-exchange path, σ_{se}, corresponds to exchange of electron-spin orientation without net charge transfer. This path was previously assumed to make a negligible contribution to collisional pumping at the beam energies of interest. Also shown in this diagram is the effect of partial electronic depolarization that occurs in the radiative decay following electron capture by an H^+ or D^+ ion. At low B the retained electronic polarization is 41% [3], corresponding to a spin-retention factor f=0.70. Presently used polarized sources are based on a single-electron-attachment collision in an optically-pumped polarized alkali vapor, and must operate in magnetic fields high enough to decouple L and S in the n=2 level of H^0, in order to retain the atomic polarization. There is no counterpart to this depolarization effect in the charge-changing collisions, $H^0 \rightleftharpoons H^-$ or $D^0 \rightleftharpoons D^-$.

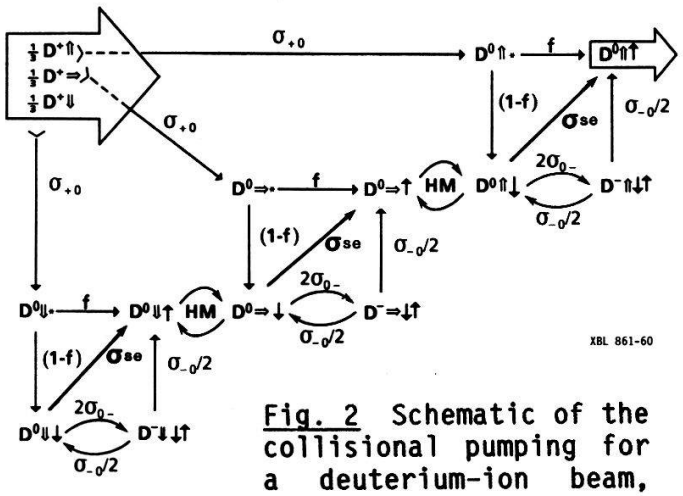

Fig. 2 Schematic of the collisional pumping for a deuterium-ion beam, showing the additional pumping stages for D, the partial depolarization following initial electron capture (see text), and the parallel pumping channel introduced by spin-exchange, with cross section σ_{se}.

3. Target Requirements and Magnetic-Field Limits

Based on data from a compilation of charge-transfer cross sections [4], a beam energy of 2.5 keV/u was determined to be suitable for design purposes [5] for a Na-vapor target. For a completely polarized sodium-vapor target in the low-magnetic-field limit, calculations were made of beam polarization as a function of target thickness (Fig. 3a), and estimates were made of laser power required, and of beam scattering [5].

Figures 3(a) and 3(b) show the polarization of H and D beams, after passage through a polarized target, as a function of target thickness, both without spin exchange (3a) and including the results of new calculations [6] of spin exchange (3b). Spin exchange is the predominant path for collisional

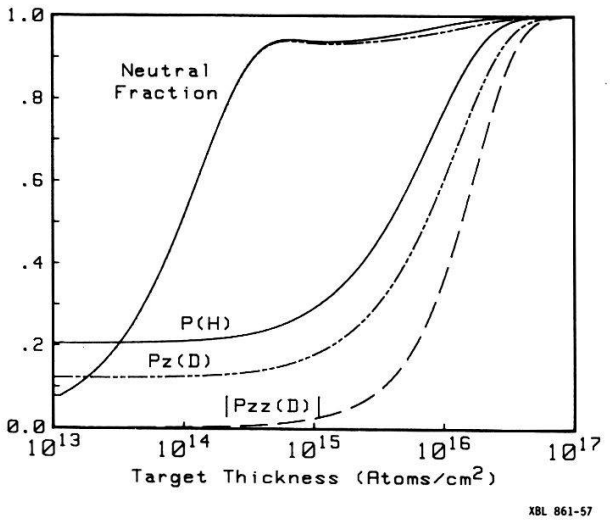

Fig. 3a

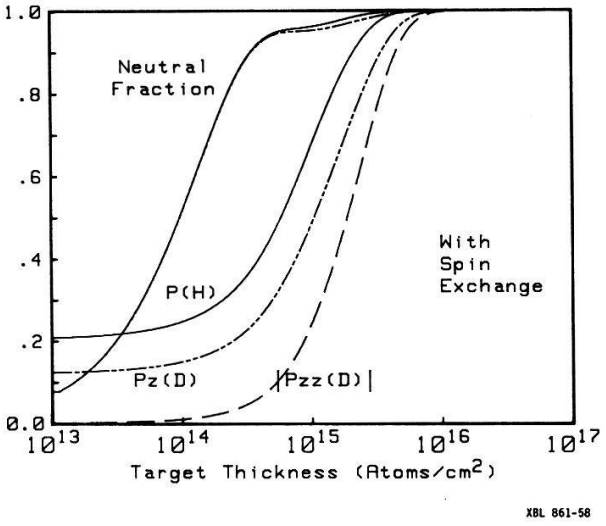

Fig. 3b

Fig. 3 Polarization and neutral fraction for 2.5 keV/u H^+ (solid lines) and D^+ (broken lines) as a function of sodium-vapor target thickness. P is the proton polarization, and P_z and P_{zz} are, respectively, the deuteron vector and tensor polarizations. 3a) Spin exchange not included. 3b) Spin exchange included.

pumping: polarization of an H or D beam is achieved for a considerably thinner target when spin exchange is included in the calculation. With the spin-exchange cross section included, the target thickness required for 95% polarization transfer (target electrons to beam nuclei) is shown in Fig. 4 as a function of external magnetic field, B. For fields up to 30 gauss, achieving 95% target polarization will require target thicknesses of less than 3×10^{15} cm^{-2} for H, and less than 5×10^{15} cm^{-2} for D.

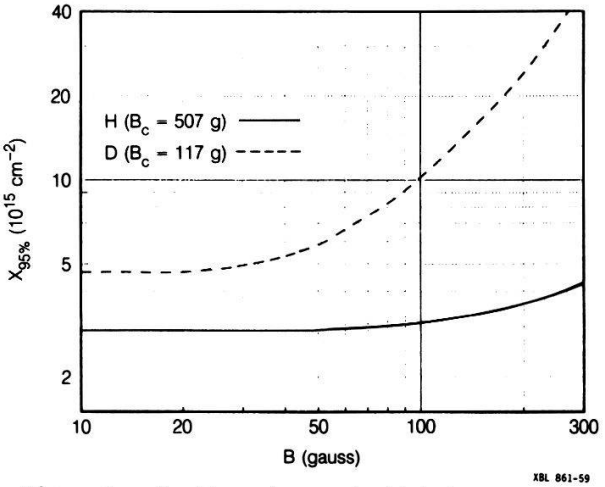

Fig. 4 Sodium-target thickness for 95% polarization transfer as a function of magnetic field, B. The required target thickness increases with B, but only very slowly below ~$B_c/3$ (where B_c is the critical field).

4. Laser-Power Requirements

In a low magnetic field there will also be mixing between the atomic and nuclear spins of the sodium-vapor target, and the nuclear spin (I=3/2) will be pumped along with the atomic spin. This pumping will require a factor of four increase in laser intensity over that

needed for high-field pumping. Each Na atom requires, on the average, angular-momentum transfer from two polarized photons. Assuming a target of thickness 3×10^{15} cm^{-2} and 100% efficiency for absorption of the laser light, only 2 mJ/cm^2 of laser power at the sodium-D-line wavelength could fully polarize the target. However, with a target spin-relaxation time of 200 μs, a laser-power density greater than 30 W/cm^{-2} would be required to maintain the target at 95% polarization. At high Na densities, radiation trapping might limit the target polarization obtainable. Although sufficient power is not presently available with cw dye lasers, it could easily be obtained with long-pulse pulsed lasers.

5. Beam Scattering

Beam divergence due to scattering can be estimated by use of a relationship [7] obtained by analyzing measurements, mostly with 1-2 keV deuterons incident on Na or Cs vapors of thicknesses $\leq 10^{15}$ cm^{-2}, for the average scattering angle, θ_S (in degrees). For an H beam passing through a sodium-vapor target,

$$\theta_S \approx 0.15(nl)^{0.7}/E,$$

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 3×10^{15} $atoms/cm^2$, an average scattering angle of 0.13 degrees.

6. Conclusion

Collisional pumping might be used to produce highly polarized beams of hydrogen and deuterium ions at intensities comparable to those presently obtained by unpolarized ion sources. The concept could be tested by use of pulsed dye lasers presently available.

7. References

[1] L. W. Anderson, S. N. Kaplan, R. V. Pyle, L. Ruby, A. S. Schlachter, and J. W. Stearns, J. Phys. B.: At. Mol. Phys. 17 (1984) L229.

[2] D. Post and R. V. Pyle, in Atomic and Molecular Processes in Controlled Nuclear Fusion, edited by C. J. Joachain and D. E. Post (Plenum, New York, 1983).

[3] L. W. Anderson, Nucl. Instr. Meth. 167 (1979) 363.
E. A. Hinds, W. D. Cornelius and R. L. York, Nucl. Instr. and Meth. 189 (1981) 599.

[4] T. J. Morgan, R. E. Olson, A. S. Schlachter. and J. W. Gallagher, to be published in Journal of Physical and Chemical Reference Data; JILA Information Center Report No. 29 (1985).

[5] S. N. Kaplan, C. F. Burrell, R. V. Pyle, L. Ruby, A. S. Schlachter, J. W. Stearns, IEEE Trans. Nucl. Sci. NS-32 (Oct. 1985) 1739.

[6] D. R. Swensen, D. Tupa, and L. W. Anderson, J. Phys. B.: At. Mol. Phys. 18 (1985) 4433.

[7] E. B. Hooper, P. Poulsen, and P. A. Pincosy, J. Appl. Phys. 52, (1981) 7027.

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