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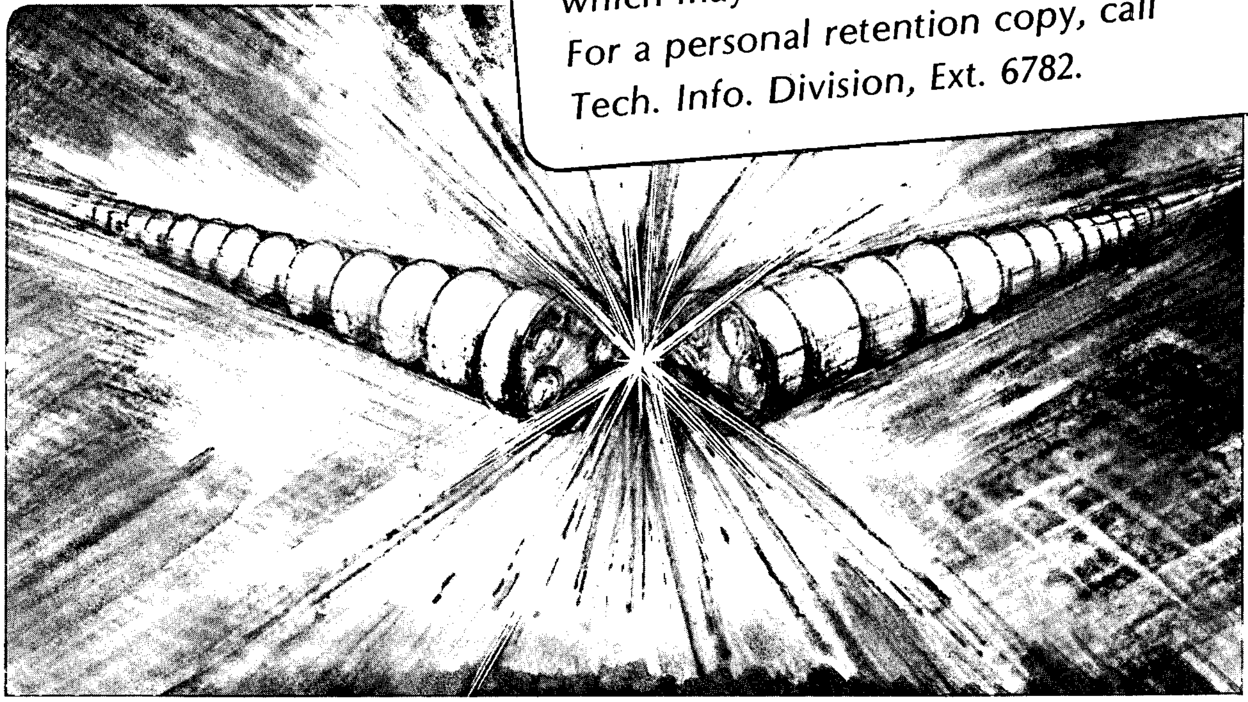

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ABSTRACT

Polarization transfer from an electron-spin-polarized alkali target to an incident ion beam is analyzed. For hydrogen ions incident on a thick 100 -electron-polarized alkali-vapor target at energies below a few keV/u, successive collisions pump the beam to a state that is entirely neutral, and entirely electron- and nuclear- spin polarized. A significant fraction of the resultant H^0 atoms can then be converted to nuclear-polarized H^- ions by electron attachment in a second alkali-vapor medium. This conversion is enhanced by spin-dependent electron attachment if the second medium is also electron-spin polarized, but in the opposite sense. Calculations and results are given for 400 eV/u H^+ and D^+ beams in an electron-spin-polarized cesium-vapor target.

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Charge-state equilibration of a fast ion or atom beam in a gas or vapor target has been studied for more than 30 years, first in gas targets and later in metal-vapor targets. The charge-state fractions exiting a target vary as a function of target thickness, approaching charge-state equilibrium for a sufficiently thick target. Two or more charge states are present at charge-state equilibrium for all cases, except for the case of a very fast beam, which is almost completely ionized at sufficiently high energies ($\gtrsim$ 1 MeV/u). A beam of hydrogen (or deuterium or tritium) in charge-state equilibrium in a gas or vapor target at intermediate energies ($\gtrsim$ 25 keV/u) is primarily composed of H^0 and H^+. In alkali-vapor targets, at lower energies, the H^+ fraction becomes negligible, and the beam atoms undergo charge-transfer collisions between H^0 and H^- charge states.

We have recently shown that the collision processes leading to charge-state equilibrium for intermediate-energy hydrogen ions in an electron-spin-polarized target can be used to produce intense beams of nuclear-spin-polarized hydrogen atoms (Anderson et al 1983). In this paper we analyze the behavior of a *low-energy* beam in an electron-spin-polarized alkali-vapor target.

A positive hydrogen-ion beam passing through a polarized target acquires electron-spin polarization in its initial electron interaction. Spin-dependent charge-transfer effects then begin to play a role in subsequent interactions, causing significant modifications in the ultimate charge-state distribution of the beam. We show below that, at energies below a few keV/u, in a thick electron-spin-polarized cesium (or other alkali) target, charge-state and polarization equilibrium leads to *a beam which is entirely in the neutral charge state and entirely polarized*, with all of the atoms in the F = 1, m = 1 state (where F is the total angular momentum, and m is its z component). Calculations are presented for the case of 400 eV/u H^+ and D^+ passing through an electron-spin-polarized cesium-vapor target to demonstrate this effect. There are important potential applications of these results, not only for the production of intense polarized atom and ion beams for atomic and nuclear physics research, but also, with sufficiently intense beams, for enhancing reaction rates in nuclear-fusion reactors (Kulsrud et al 1982). By analogy with optical pumping, we call this process of polarization by multiple electron-transfer collisions in an electron-spin-polarized target "collisional pumping" (Anderson et al 1983).

The buildup of polarization and the elimination of the H^- component in the projectile beam occur because electron capture is inhibited when both projectile and target electrons are polarized in the same direction. Consider the case of 400 eV H^+ ions incident on a 100% electron-spin-polarized cesium-vapor target in a low magnetic field ($B \ll B_c$, where B_c is the critical field, and is equal to 507 G, 117 G, and 541 G for the ground states of H, D, and T respectively). For a thick target the H^+ fraction essentially vanishes because the cross-section ratio σ_{0+}/σ_{+0} is small (Schlachter et al 1980). The H^+ beam is neutralized by electron capture, primarily into the n = 2 level of the H atom. Atoms in the 2p level decay radiatively to the n = 1 level, and atoms in the 2s level are de-excited collisionally to the n = 1 level. Once an H atom is in the n = 1 level it can only form H^- ions in subsequent collisions. Thus for a target thickness, π, greater than about $3/\sigma_{+0}$, the beam consists almost entirely of H^0 and H^-. If the electron spin polarization of the Cs target is 1, then an electron captured by the H^+ ion will have $m_s = 1/2$, and the H^0 atoms will be formed with their initial spin orientation $|m_s = 1/2, m_n = 1/2 >$ or $|m_s = 1/2, m_n = -1/2>$, where m_s and m_n are the z components of the electron spin and nuclear spin respectively.

In the hydrogen ground level, the state $|m_s = 1/2, m_n = 1/2>$ is identical to the low-field eigenstate $|F = 1, m = 1>$, so that atoms formed in this state remain in this state. The state of spin orientation $|m_s = 1/2, m_n = -1/2>$ is, however, a linear superposition of the low-field atomic eigenstates $|F = 1, m = 0>$ and $|F = 0, m = 0>$. Atoms formed in these states oscillate at the hyperfine frequency between $m_s = 1/2, m_n = -1/2$, and $m_s = -1/2, m_n = 1/2$. Thus the hyperfine interaction transfers some of the electron-spin polarization into nuclear-spin polarization. The H^0 atoms in the $|F = 1, m = 1>$ state cannot capture a second electron from the polarized Cs target to form an H^- ion since the only bound state of H^- is $^1S_0$ (electron spins anti-parallel). However, the H^0 atoms that are in the $|F = 1, m = 0>$ and $|F = 0, m = 0>$ states can form H^- ions by electron attachment when $m_s = -1/2$ and $m_n = 1/2$. Since either electron may be detached in a subsequent collision, the repeated attachment of a polarized electron, followed by detachment results in the entire beam being collisionally pumped into the $|F = 1 \; m = 1>$ state.

This description neglects one effect: electron capture by H^+ in cesium vapor is predominantly into n = 2 levels. Radiative decay of the 2p level leads to some ground-state population in the |F = 1, m = -1> state. Atoms in this state also form negative ions which are collisionally pumped into other states, and, finally, into the |F = 1, m = 1> state.

The kinetics of the above processes are described by the following set of equations:

$$dH^+/d\pi = -\sigma_{+0}H^+$$

$$dH^0_{11}/d\pi = 1/2\sigma_{+0}H^+ + 1/2\sigma_{-0}H^-$$

$$dH^0_0/d\pi = 1/2\sigma_{+0}H^+ - \sigma_{0-}H^0_0 + 1/2\sigma_{-0}H^-$$

$$dH^-/d\pi = \sigma_{0-}H^0_0 - \sigma_{-0}H^-$$

where H^+ and H^- are the fractional H^+ and H^- populations, H^0_{11} is the beam fraction in the (1,1) state, and $H^0_0 = H^0_{10} + H^0_{00}$, where H^0_{10} and H^0_{00} are the fractional populations in the (1,0) and (0,0) states respectively. (We have ignored the small production of atoms in the |F = 1, m = -1> state due to radiative decay of the 2p level, since this state rapidly vanishes.) For these calculations we ignore σ_{0+} and σ_{-+} since they are much smaller than the other cross sections. The target thickness, π, is the integral of the target atomic density over the path length.

The above equations apply equally well to tritium, as the proton and triton both have spin 1/2. However, for deuterium, while qualitative results are similar, the detailed description is complicated by the deuteron spin, which is unity. The corresponding equations for deuterium are:

$$dD^+/d\pi = \sigma_{+0}D^+$$

$$dD^0_{3/2,3/2}/d\pi = 1/3\sigma_{+0}D^+ + 1/2\sigma_{-0}D^-_+$$

$$dD^0_{3/2,1/2}/d\pi = 2/3\sigma_{+0}D^0_{3/2,1/2} + 2/9\sigma_{+0}D^+ + 1/6\sigma_{-0}D^-_+ + 1/3\sigma_{-0}D^-_0$$

$$dD^0_{3/2,-1/2}/d\pi = -4/3\sigma_{0-}D^0_{3/2,-1/2} + 1/9\sigma_{+0}D^+ + 1/3\sigma_{-0}D^-_+$$

$$dD^0_{1/2,1/2}/d\pi = -4/3\sigma_{0-}D^0_{1/2,1/2} + 1/9\sigma_{+0}D^+ + 1/3\sigma_{-0}D^-_+ + 1/6\sigma_{-0}D^-_0$$

$$dD^0_{1/2,-1/2}/d\pi = -2/3\sigma_{0-}D^0_{1/2,-1/2} + 2/9\sigma_{+0}D^+ + 1/6\sigma_{-0}D^-_0$$

$$dD^-_+/d\pi = \sigma_{-0}D^-_+ + 2/3\sigma_{0-}D^0_{3/2,1/2} + 4/3\sigma_{0-}D^0_{1/2,1/2}$$

$$dD^-_0/d\pi = \sigma_{-0}D^-_0 + 4/3\sigma_{0-}D^0_{3/2,-1/2} + 2/3\sigma_{0-}D^0_{1/2,-1/2}$$

where neutral-fraction components corresponding to the F eigenstates, $|F,m\rangle$, are written in the form D^0_{Fm}, and the negative fraction components, D^-_+, and D^-_0, correspond respectively to $m_n = 1$, and $m_n = 0$. Negative ions with $m_n = -1$ cannot be produced in a 100% electron-polarized target. A plot of polarization and neutralization of 400 eV/u H^+ and D^+ are shown in Fig. 1 as a function of cesium-vapor target thickness. Two remarkable features are to be noted: both the neutral fraction of the beam and its polarization are nearly 100% for large target thickness. The initial maximum of the neutral fraction, at a target thickness of ~2×10^{14} atoms/cm^2, arises from the large ratio, $\sigma_{+0}/(\sigma_{0-} + \sigma_{0+})$ and is observed even with unpolarized targets (Schlachter et al 1980). The subsequent increase of the neutral fraction and its approach to unity for high target thicknesses, however, is due to the polarized target and spin-dependent collisions. Similar behavior will occur with a sodium-vapor target, but because of the smaller cross sections, (Ebel 1983, Howald et al 1983, Schlachter et al 1980), a factor of 10 thicker target would be required.

Conversion of the polarized H^0 beam to H^- with nuclear polarization is of interest for applications in which subsequent acceleration is desired. This can be accomplished by passing the beam through a non-polarized cesium vapor target, which will give an equilibrium yield of 30% H^- (Schlachter et al 1980). A higher yield of polarized H^- can be obtained, however, by passage of the polarized H^0 beam through a <u>second</u> polarized cesium-vapor target, where the polarization is directed oppositely to that in the first target, or by inverting the spin direction of the H^0 between two targets polarized in the same direction. The H^- production is enhanced because the electron-attachement cross section is double that of the unpolarized reaction when the H^0 and Cs electron spins are oppositely directed. This result is shown in Fig. 2 for a 100% polarized 400 eV/u H^0 or D^0 beam incident on a 100% polarized cesium-vapor target in a magnetic field with $B \gg B_c$. A maximum of 40% H^- (with 100% nuclear polarization) can be obtained for a target thickness of about 8×10^{14}

atoms/cm^2; the H^- fraction will of course, approach zero for large target thickness, as it does in the first polarized target. The H^- fraction in an unpolarized target is shown for comparison.

Electron-spin-polarized alkali-vapor targets can be produced by laser optical pumping. To date, cesium has not been used as an optically pumped target; however optically pumped sodium-vapor targets have been used for production of polarized H^- ions (Anderson 1983, Cornelius et al 1982, and Mori et al 1983). The thickest targets that have been produced at the present time have $\pi \simeq 10^{14}$ atoms/cm^2. It is not known how difficult it will be to produce targets with a thickness of $\pi \simeq 10^{16}$ atoms/cm^2 and in a low magnetic field. Targets with $\pi \simeq 10^{16}$ atoms/cm^2 might require the development of wall coatings with long relaxation times and methods for overcoming problems associated with radiation trapping. If thick polarized alkali targets can be produced, then intense beams of H^0 atoms almost entirely in the $|F = 1, m = 1\rangle$ state can also be produced.

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FIGURE CAPTIONS

1. Polarization and neutral fraction for 400 eV/u H^+ (solid lines) and D^+ (dashed lines) as a function of polarized cesium-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 deuteron polarizations in the neutral beam. The cross sections used in the calculations are from Schlachter et al 1980 and Miethe et al 1983.

2. Negative-ion fraction, f_-, as a function of target thickness, for a 400 eV/u neutral hydrogen beam incident on a cesium-vapor target. The curve for polarized cesium vapor assumes a 100%-nuclear-spin-polarized neutral beam incident on a 100%-electron-spin-polarized target, with the two polarizations oppositely directed.

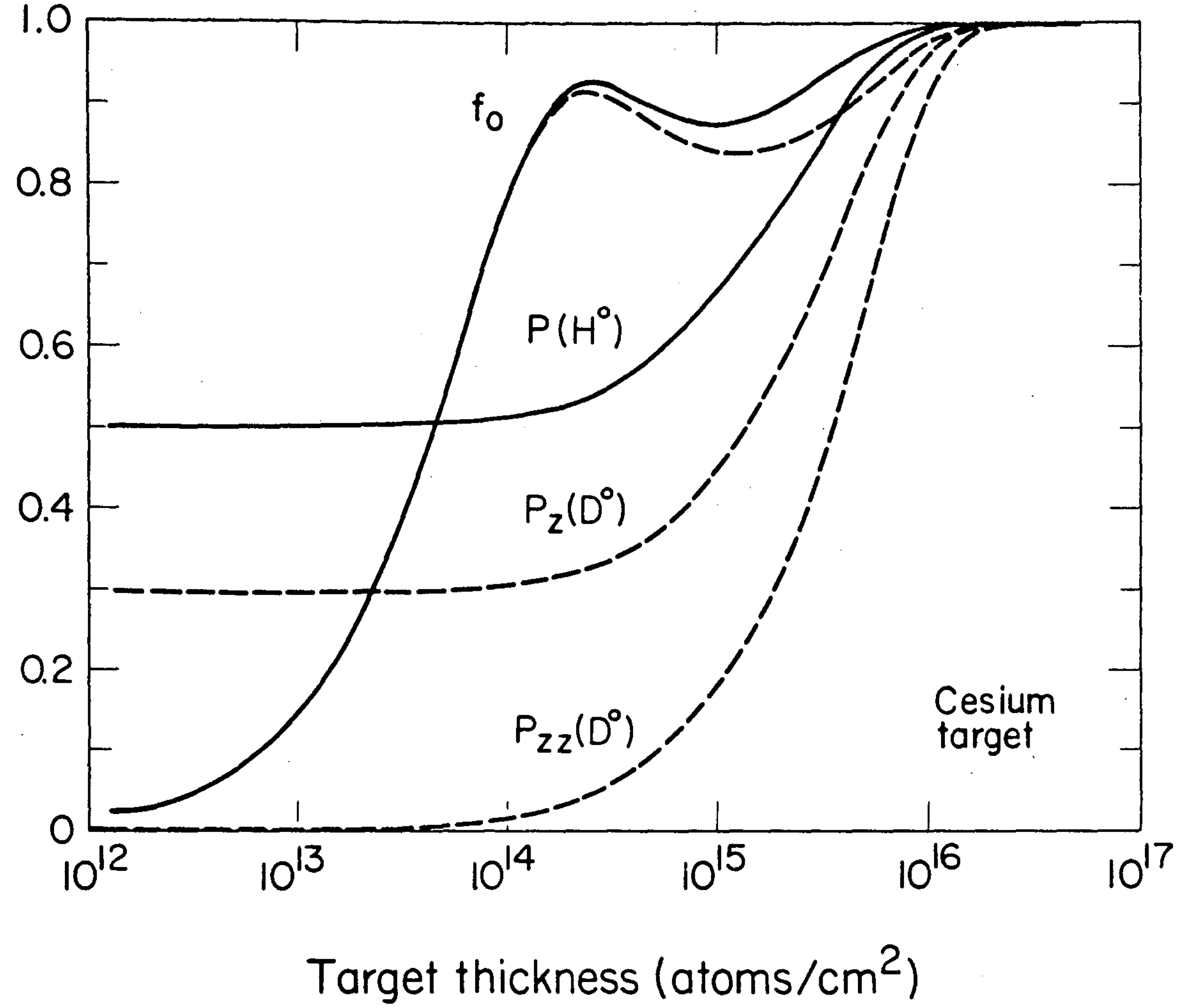

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Figure 1

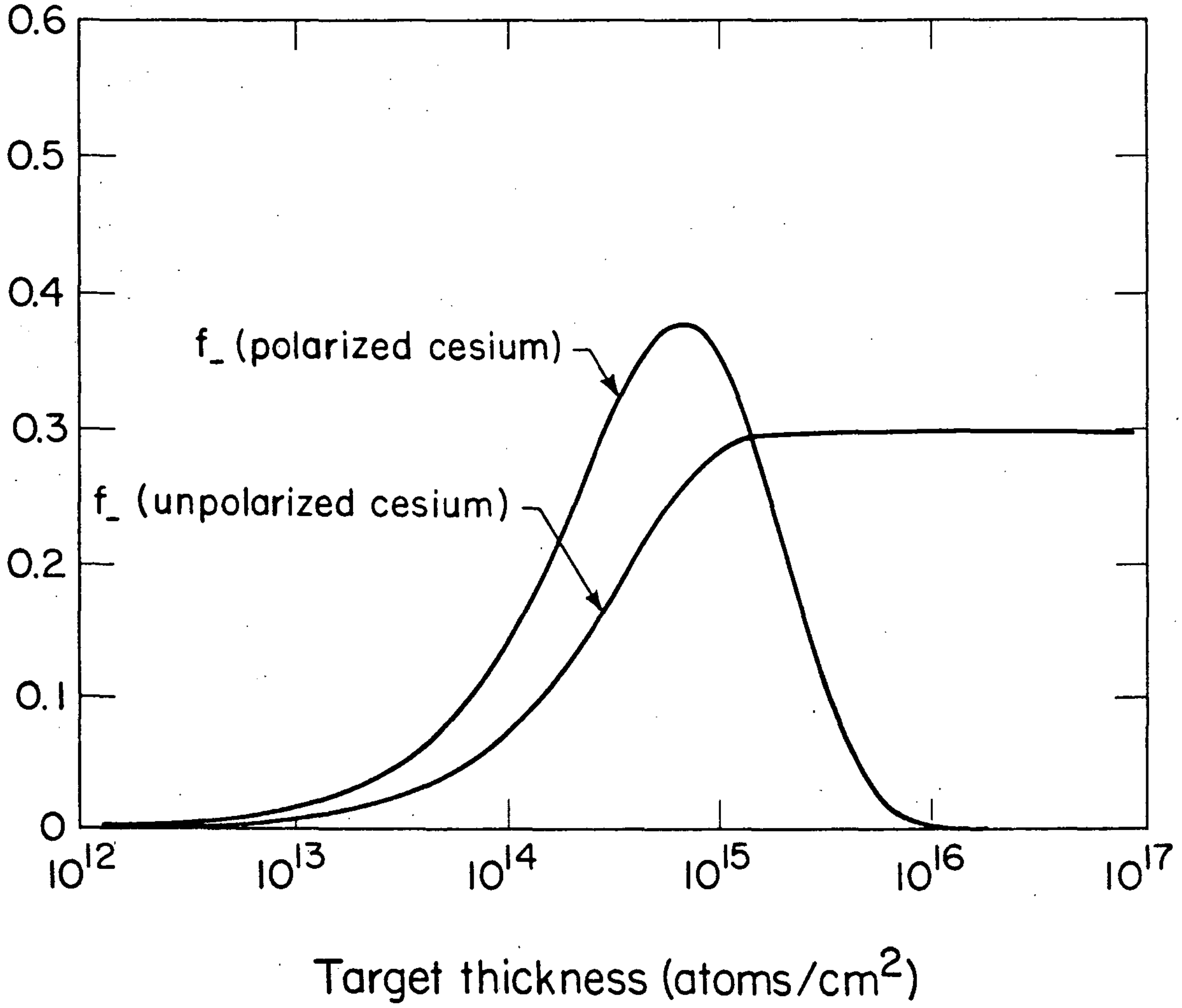

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Figure 2

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