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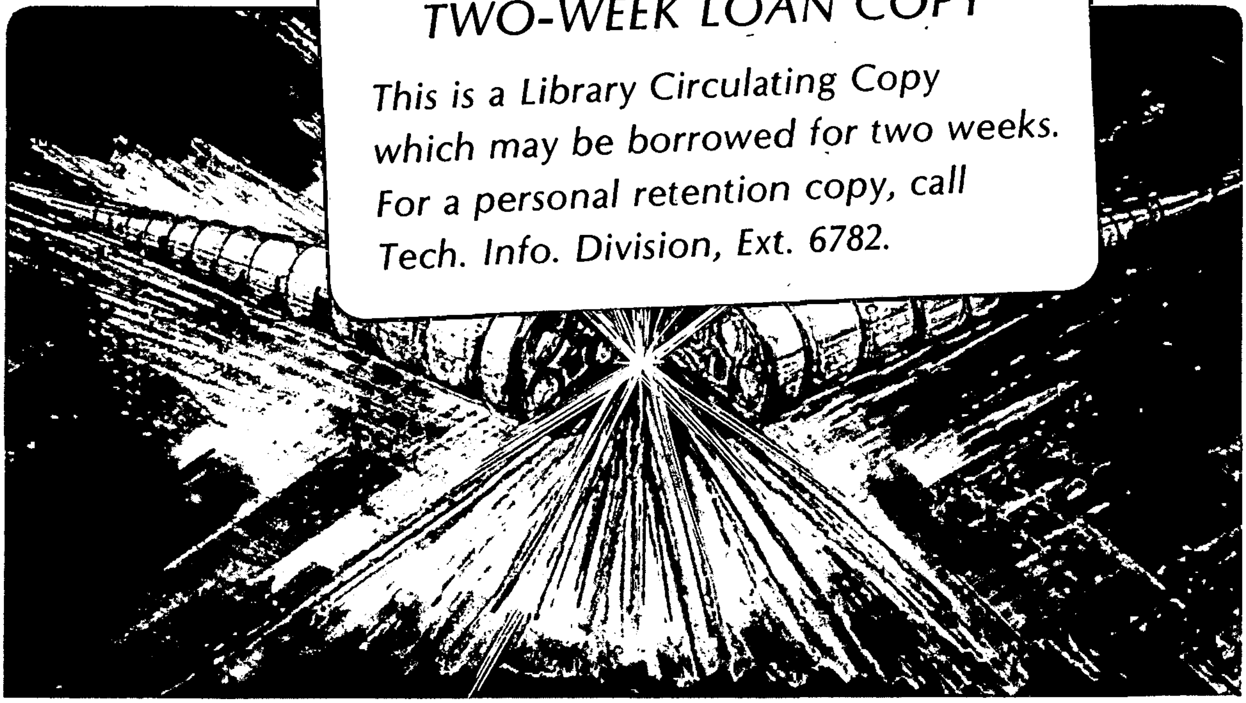

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Polarization of Fast Atomic Beams by "Collisional Pumping"

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The production of polarized ions by "collisional pumping" is described. Collisional pumping utilizes a succession of electron-transfer collisions between a fast ion beam and a thick electron-spin-polarized target to polarize the beam. High polarizations at ampere currents should be possible. Analysis is made and calculational results are given for 20 keV/amu hydrogen and deuterium beams passing through a polarized target in low and high magnetic fields.

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We describe a new means of producing polarized ions, in which polarization is built up by a succession of electron-transfer collisions in a thick electron-spin-polarized target. We call this process "collisional pumping." While it can be applied to many nuclear species, we describe 3 examples for hydrogen (or tritium) and deuterium ions, leading to a high degree of polarization and the prospect of intense beams.

Polarized ions have been used in nuclear-physics research for about 20 years; at present the best polarized positive hydrogen ion sources produce currents of about 100 μA. Kulsrud et al.[1] recently have suggested that polarized reacting particles in a fusion reactor can be used to modify the reaction rates and the angular distribution of reaction products. Fueling could be accomplished by injection of a multiampere (equivalent) beams of nuclear polarized atoms into the reactor. We show that the physics of atomic charge-transfer reactions permits, through collisional pumping, the efficient transfer of electron polarization from an electron-polarized medium to nuclear polarization of a fast, intense atomic beam of the sort currently used for heating and fueling fusion plasmas.[2]

There has been considerable recent progress in the development of electron-spin-polarized media. Kleppner and coworkers[3] and others[4] have demonstrated that it is possible to produce a cold, dense, highly-polarized, atomic-hydrogen target in a large magnetic field using cryogenic techniques. In addition, there are good prospects for producing a dense polarized hydrogen target in a low magnetic field by ejecting atoms from the low-temperature high-field target by use of rf transitions. Happer and coworkers[5] have proposed an alternate method to produce large numbers of polarized atoms using spin-exchange optical pumping with high-intensity dye lasers. It may also be possible to produce dense polarized alkali-vapor targets using laser optical pumping.[6-9]

The above-mentioned authors have proposed that these electron-spin-polarized media could be used to produce intense polarized atom or ion beams. This paper describes and analyzes a new method of polarizing fast (hundreds of eV to hundreds of keV) hydrogen ions or atoms by means of collisional pumping in such targets. Collisional pumping differs from previous methods in 2 significant ways: very fast ions or atoms are polarized and the polarization takes place in thick targets, so that equilibrium yields are obtained.

We first describe collisional pumping with a thick polarized hydrogen target in a <u>low magnetic field</u>, $B << B_c$ (where $B_c = 507$ G for the ground state of H, 117 G for D, and 541 G for T). A beam of unpolarized protons (or tritons) is incident on the polarized target. Following capture of a polarized electron by a fast ion, the hyperfine interaction transfers some of the electron polarization into nuclear polarization. A subsequent electron-loss collision does not affect the nuclear spin, so that a succession of electron-capture and -loss collisions "pumps" the nuclear polarization of the fast beam nearly up to the electron polarization of the target. It is only necessary that the collision frequency be much less than the hyperfine frequency (0.3-1.5 GHz). If we assume that the collision-frequency criterion is met, that the target is 100% electron-spin polarized, and we ignore the small negative-ion fraction and possible depolarization mechanisms, we can describe the fast-hydrogen beam with the following equations:

$$dH^+_{\frac{1}{2}}/d\tau = -\sigma_{+0}H^+_{\frac{1}{2}} + \sigma_{0+}(H^0_{11} + \tfrac{1}{2}H^0_{10} + \tfrac{1}{2}H^0_{00})$$

$$dH^+_{-\frac{1}{2}}/d\tau = -\sigma_{+0}H^+_{-\frac{1}{2}} + \sigma_{0+}(H^0_{1-1} + \tfrac{1}{2}H^0_{10} + \tfrac{1}{2}H^0_{00})$$

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

$$dH^0_{10}/d\tau = -\sigma_{0+}H^0_{10} + \tfrac{1}{2}\sigma_{+0}H^+_{-\frac{1}{2}}$$

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

$$dH^0_{00}/d\tau = -\sigma_{0+}H^0_{00} + \tfrac{1}{2}\sigma_{+0}H^+_{-\frac{1}{2}}$$

where σ_{+0} and σ_{0+} are the electron-capture and electron-loss cross sections; $H^+_{\frac{1}{2}}$ and $H^+_{-\frac{1}{2}}$ are the fractional populations of spin-up and spin-down protons; $H^0_{Fm_F}$ are the fractional populations of the atoms in the low-field atomic eigenstates of total angular momentum F and its projection in the magnetic field direction m_F; and τ is the integral of the target atomic density over the path length. The H^- fraction is negligible at 20 keV. For an unpolarized proton beam incident on the target (i.e., $H^+_{\frac{1}{2}} = H^+_{-\frac{1}{2}} = 1/2$ at $\tau = 0$), the neutral fraction of the beam leaving the target is

$$f = \sum H^0_{Fm_F} = f^\infty(1 - e^{-\tau})$$

where $f^{\infty} = \sigma_{+0}/(\sigma_{+0} + \sigma_{0+})$ and $T = (\sigma_{+0} + \sigma_{0+})\pi$. The nuclear polarization of the neutral beam is

$$P = (H^{0}_{11} - H^{0}_{1-1})/f = 1 - \tfrac{1}{2}f^{\infty}(e^{-\gamma_{-}T} - e^{-\gamma_{+}T})/[(\gamma_{+} - \gamma_{-})f]$$

where $\gamma_{\pm} = 1/2 \pm \sqrt{1-2f^{\infty}(1-f^{\infty})/2}$.

A calculation which considers a target that is not 100% electron-spin polarized and which includes some depolarization in the electron-capture process gives the following expression for the beam polarization

$$P = P_{t}\frac{1-\varepsilon}{1+\varepsilon}\left[1-f^{\infty}\frac{1-\varepsilon}{2}(e^{-\gamma_{-}T} - e^{-\gamma_{+}T})/[(\gamma_{+} - \gamma_{-})f]\right]$$

where ε is the fraction of electron-capture collisions that lead to nuclear depolarization, and P_t is the target polarization. For small ε the thick-target polarization $P^{\infty} \approx P_{t}(1- 2\varepsilon)$.

Electron, and therefore nuclear, depolarization, occurs via radiation from decay of $n = 2$ or higher atomic levels produced in the electron capture. We estimate that no more than 10% of the fast neutral atoms are produced in the $n = 2$ levels[10] for 20 keV protons. Most of the capture is into the 2s level, which ordinarily undergoes collisional detachment before decay. (The 2s level can also be quenched in an electric field, by Stark mixing with the 2p level). Calculations show[11] that the electron spin polarization of atoms in the 2p level is reduced from 1.0 to 0.41 in decaying to the 1s level, if [illegible] atoms decay [illegible] a low magnetic field. Capture into higher n levels decreases as n[illegible] and can be neglected. Based on these considerations, we estimate that $\varepsilon \leq 0.04$.

Atomic charge-transfer cross sections[12] are the same for unpolarized hydrogen and deuterium at the same velocity. However, because the deuteron has a spin of 1, a comparable description requires nine, instead of six, differential equations, and nuclear polarization must be described by two parameters, a vector polarization, $P_z = N_+ - N_-$, and a tensor polarization, $P_{zz} = 1 - 3\,N_0$, where N_+, N_0, and N_- are the relative populations of the three nuclear-spin substates.

Figure 1 shows both the calculated neutral fraction and nuclear polarization of the fast hydrogen atoms as a function of target thickness, for 20-keV/amu unpolarized protons and deuterons incident on a target with polarization $P_t = 0.95$, depolarization factor $\varepsilon = 0.04$, and neutral atom eigenstates appropriate to an external magnetic field B = 10 G.

As a second case we consider an unpolarized beam of hydrogen (tritium) or deuterium atoms incident on a thick electron-spin-polarized hydrogen target in a <u>high</u> <u>magnetic</u> <u>field</u>. Because of the large magnetic field, the electron and nuclear angular momenta are decoupled in both the polarized target H atoms and in the fast H or D atoms. Hence the nuclear spin plays no role. The fast H or D atoms will repeatedly lose and capture electrons during their passage through the target. The H or D atoms emerging from the target will have a high electron-spin polarization parallel to the target polarization. The rate equations governing this process are

$$dH^0_\alpha/d\tau = -\sigma_{0+}H^0_\alpha + P_t(1-\varepsilon)\sigma_{+0}H^+ + \frac{1}{2}\varepsilon\sigma_{+0}H^+ + \frac{1}{2}Q_t(1-\varepsilon)\sigma_{+0}H^+$$

$$dH^0_\beta/d\tau = -\sigma_{0+}H^0_\beta + \frac{1}{2}\varepsilon\sigma_{+0}H^+ + \frac{1}{2}Q_t(1-\varepsilon)\sigma_{+0}H^+$$

$$dH^+/d\tau = -\sigma_{+0}H^+ + \sigma_{0+}(H^0_\alpha + H^0_\beta)$$

where H^0_α and H^0_β are the atomic fractions of the fast H^0 or D^0 beam with electron spins parallel and antiparallel to the magnetic field; H^+ is the fraction of protons or deuterons in the beam; P_t is the target electron-spin polarization; and $Q_t = 1-P_t$. The other parameters are as defined previously. Negative ions can be neglected for a beam energy of 20 keV/amu. For the initial condition $H^0_\alpha = H^0_\beta = 1/2$, the neutral fraction is

$$f = H^0_\alpha + H^0_\beta = f^\infty + (1-f^\infty)e^{-\tau}$$

where f^∞ and τ have been defined previously. The electron-spin polarization of the fast neutral atoms in the beam is

$$P_e = (H^0_\alpha - H^0_\beta)f = P_t(1-\varepsilon)[f^\infty + (1-f^\infty)e^{-\tau} - e^{-(1-f^\infty)\tau}]/f \ .$$

The depolarization parameter, ε, is expected to be much smaller than in the low-field case, because, in a 100 kG magnetic field, not only are I and J decoupled, but also L and S, in all n levels for atomic hydrogen. There is little depolarization as H atoms radiatively decay from n = 2 and higher levels to the n = 1 level, so $\varepsilon \simeq 0$. The electron spin polarization of the fast atoms can then be converted into nuclear polarization by a Sona diabatic transition.[13] Figure 2 shows both the neutral fraction and the nuclear polarization after a Sona transition, as a function of target thickness, for 20-keV/amu H^o or D^o atoms incident on a target with polarization $P_t = 1.0$. (The electron polarization prior to the Sona transition for both H^o and D^o is the same as $P(H^o)$).

The emittance of the fast beam is expected to increase only slightly as the beam passes through the target, because the particles entering and exiting the high magnetic field of the target are neutral and because the particle energy is high.

The nuclear-polarized fast neutral beam produced in either the low- or high-magnetic-field target can be partially converted into a polarized ion beam in a cell containing gas which need not be polarized. This cell should, however, be in a magnetic field that is large compared to the critical field. The equilibrium positive fraction is about 33% for 20 keV/amu H in Ar.[14] In addition, each particle makes from 10-30 charge-changing collisions as it passes through either polarized hydrogen target. The production rate of electron-polarized target atoms must therefore be comparable.

We mention a third case: if one can produce a thick polarized alkali target with electron-spin polarization $P_t = 1$, for a low-energy H^+ beam (~400 eV) entering the target, an analogous type of collisional pumping occurs, producing at equilibrium an exiting beam that is primarily H^o atoms in the $F = 1$, $m_F = 1$ level. This result comes about because, at such low energies, the neutral atoms can only form negative ions, and, if a neutral H atom is in the 1,1 state, it cannot capture another electron from an electron-polarized target atom to form H^-. (The H^- ion exists only in a $1s^2$ state, where the electrons have oppositely directed spins.) In the limit of a thick target with an electron polarization of 1, the entire beam emerging from the target is in the 1,1 state.

The production of very intense highly polarized fast ion or atom beams should be possible by use of collisional pumping with dense polarized targets. Polarized hydrogen-atom gas with density greater than 10^{17} atoms/cm^3 and electron-spin polarization greater than 99% has been produced.[3,4] It is also possible at the present time to produce multiampere H^0 beams at 20 keV/amu and higher energies, at particle current densities greater than 50 mA/cm^2.[2] Thus, with modest target dimensions, it should be possible to have H^0 beams equivalent to several amperes incident on a polarized target. If thick electron-polarized H^0 or alkali targets can be produced at a rate of 10^{20} -10^{21} atoms per second, we anticipate that fast polarized beams of 1 A or more can be made.

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Figure Captions

Fig. 1. Nuclear polarization and neutral fraction of fast H^0 and D^0 atoms from a polarized H target in a low magnetic field ($B = 10G$) for incident unpolarized 20 keV/amu H^+ and D^+. Target polarization $P_t = 0.95$, depolarization factor $\varepsilon = 0.04$. $P(H^0)$ is proton polarization, $P_z(D^0)$ and $P_{zz}(D^0)$ are deuteron vector and tensor polarization, f is neutral fraction.

Fig. 2. Nuclear polarization after a Sona transition and neutral fraction of fast H^0 and D^0 atoms from a polarized H target in a high magnetic field ($B = 100$ kG) for incident unpolarized 20 keV/amu H^0 and D^0. $P_t = 1.0$, $\varepsilon = 0$. $P(H^0)$ and $P_z(D^0)$ are the polarizations of the protons and deuterons in the neutral beam in a high magnetic field ($B \gg B_c$). $P_{zz}(D^0)$ is 0.

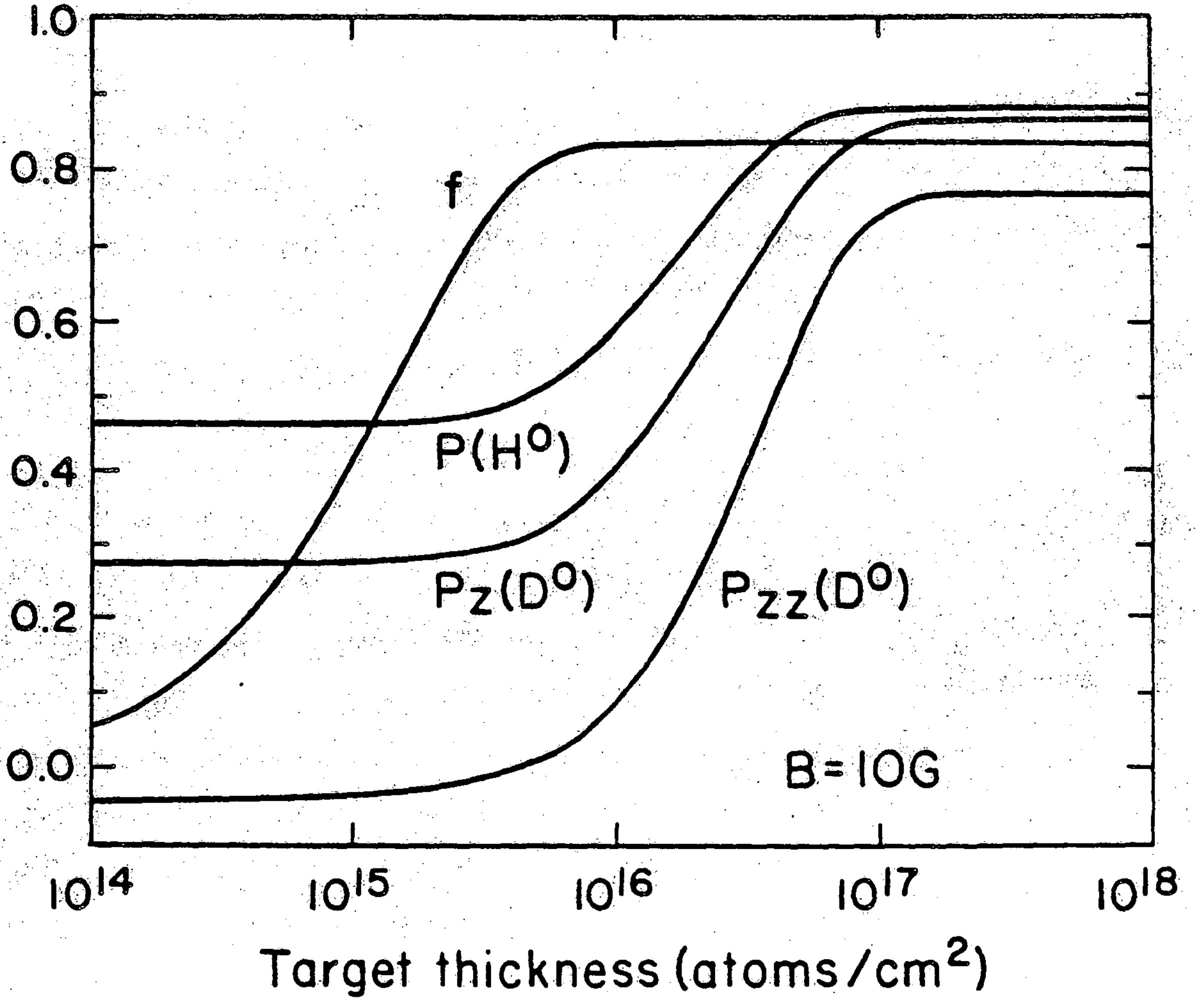

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FIGURE 1

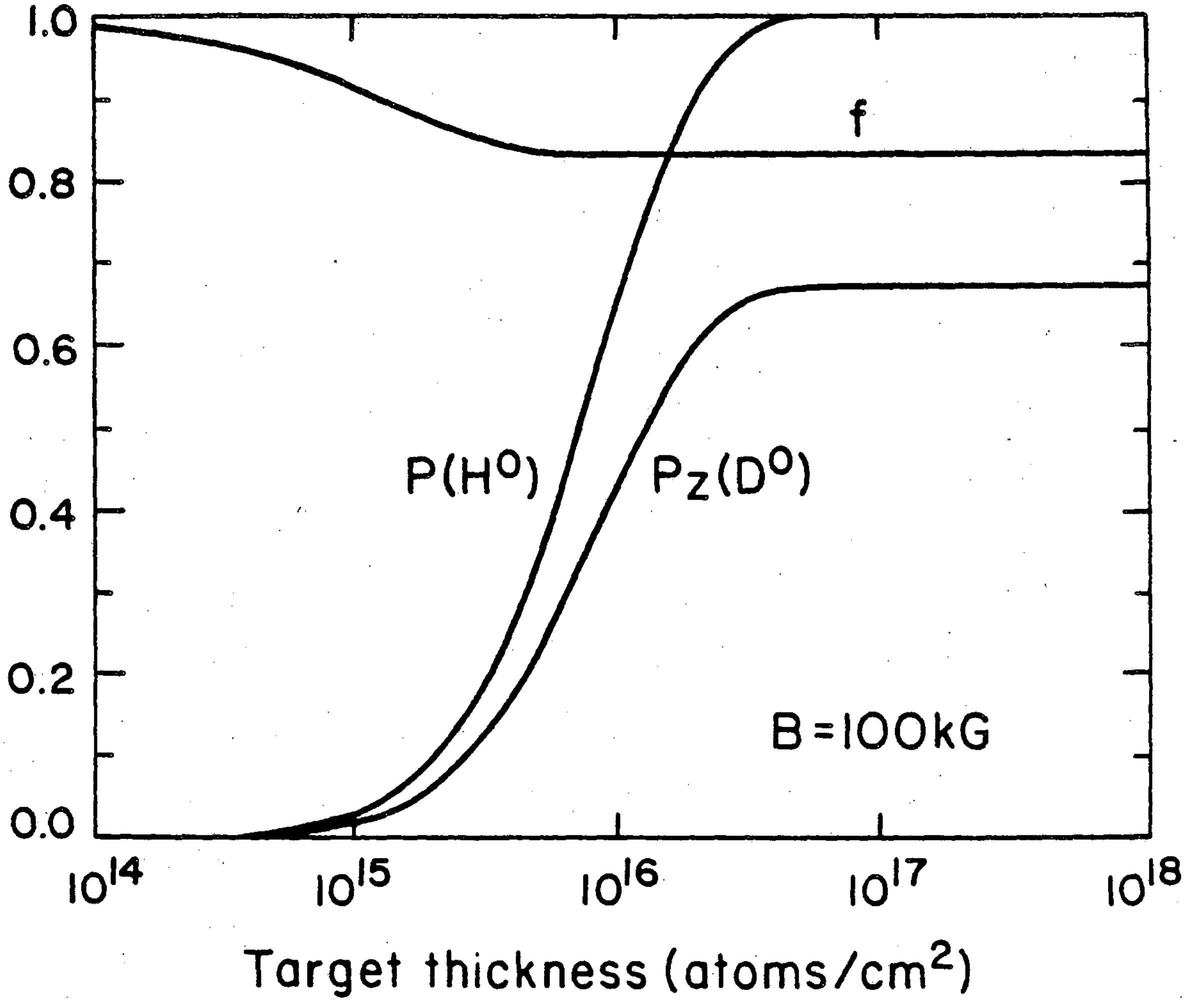

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FIGURE 2

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