Polarization of Fast Atomic Beams by "Collisional Pumping": A Proposal for Production of Intense Polarized Beams

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(Received 13 September 1983)

Production of nuclear-spin–polarized atoms by "collisional pumping" is proposed. Collisional pumping utilizes a succession of charge-transfer collisions between a fast ion or atom beam and a thick electron-spin–polarized target to polarize the beam. Calculational results are presented for 20-keV/u H or D ions or atoms incident on a polarized target. The process appears to have unique capabilities for polarizing fast H, D, T, and perhaps other nuclei, with the possibility of producing ampere currents.

PACS numbers: 34.70.+e, 07.77.+p, 29.25.Cy

We analyze in this Letter the physics of multiple charge-changing collisions of a fast beam in a thick electron-spin–polarized target, and propose a new means for producing very intense beams of highly polarized hydrogen, deuterium, or tritium ions. At present the best polarized ion sources produce about 100 μA of polarized hydrogen or deuterium. One recent method[1,2] has produced polarized hydrogen atoms by capture of a spin-polarized electron by a proton passing through a thin electron-spin–polarized target. We show for *thick* targets that repeated charge-changing collisions combine with electron-nucleus spin mixing *between* collisions to pump the entire beam to a high state of nuclear polarization. For intense beams incident on thick electron-spin–polarized targets, "collisional pumping" (by analogy with optical pumping) offers the prospect of producing ampere beams of highly polarized hydrogen, deuterium, or tritium nuclei, creating new opportunities in atomic, nuclear, and plasma physics.

Intense beams of fast deuterium atoms obtained by multiple charge-changing collisions of deuterons in a thick gas target are used for heating and fueling fusion plasmas.[3] The use of polarized reacting particles in a fusion reactor to modify the reaction rates and the angular distribution of reaction products has recently been suggested by Kulsrud *et al.*[4] Fueling could be accomplished by injection of multiampere (equivalent) beams of nuclear-polarized atoms into the reactor. Collisional pumping could provide the means of producing such beams.

Considerable progress has recently been made in the development of dense electron-spin–polarized media which could be used as targets for production of intense polarized beams by collisional pumping. Kleppner and co-workers[5] and others[6] have demonstrated that it is possible to produce a cold, dense, highly polarized, atomic-hydrogen target in a strong magnetic field by cryogenic techniques. In addition, there are good prospects for producing a dense polarized hydrogen target in a low magnetic field.[5] Happer and co-workers[7] have proposed an alternative 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.[1,8,9]

Collisional pumping requires that the magnetic field be low so that electron spin $\vec{J}$ and nuclear spin $\vec{I}$ in the ground level of the hydrogen atom are coupled together by the hyperfine interaction to form total angular momentum $\vec{F}=\vec{J}+\vec{I}$. Therefore F and m_F (the eigenvalue of the projection of $\vec{F}$ along the magnetic field direction) are good quantum numbers. This requires a field B much less than the critical field B_c (hyperfine energy splitting divided by the Bohr magneton), which is 507 G for H, 117 G for D, and 541 G for T. Consider a beam of unpolarized protons incident on a thick polarized hydrogen target. Following capture of a polarized electron by a fast ion, the hyperfine interaction transfers some of the electron-spin polarization into nuclear-spin polarization. This occurs as follows: When the proton spin is parallel to the spin of the captured electron, the nuclear spin is unaffected; but when the proton spin is antiparallel to the spin of the captured electron, the hyperfine interaction causes both the electron and nuclear spins to oscillate while maintaining an m_F of zero. The combination of these effects leads to a net nuclear-spin polarization of 0.5, provided that the collision frequency is less than the hyperfine frequency. A subsequent electron-loss collision does not affect the nuclear spin. Subsequent capture of a polarized electron in the target further increases the nuclear polarization of the beam. Thus a succession of electron-capture and -loss collisions "pumps" both the electron-spin and the nuclear-spin polarization of the fast beam nearly up to the electron-spin polarization of the target. If the target electron-spin polarization is 1, and we ignore the small negative-ion fraction and possible depolarization mechanisms, we can describe the fast-hydrogen beam in a low magnetic field ($B \ll B_c$) with the following equations:

$$dH_{1/2}{}^{+}/d\pi = -\sigma_{+0}H_{1/2}{}^{+} + \sigma_{0+}(H_{11}{}^{0} + \tfrac{1}{2}H_{10}{}^{0} + \tfrac{1}{2}H_{00}{}^{0}),$$

$$dH_{-1/2}{}^{+}/d\pi = -\sigma_{+0}H_{-1/2}{}^{+} + \sigma_{0+}(H_{1-1}{}^{0} + \tfrac{1}{2}H_{10}{}^{0} + \tfrac{1}{2}H_{00}{}^{0}),$$

$$dH_{11}{}^{0}/d\pi = -\sigma_{0+}H_{11}{}^{0} + \sigma_{+0}H_{1/2}{}^{+},$$

$$dH_{10}{}^{0}/d\pi = -\sigma_{0+}H_{10}{}^{0} + \tfrac{1}{2}\sigma_{+0}H_{-1/2}{}^{+},$$

$$dH_{1-1}{}^{0}/d\pi = -\sigma_{0+}H_{1-1}{}^{0},$$

$$dH_{00}{}^{0}/d\pi = -\sigma_{0+}H_{00}{}^{0} + \tfrac{1}{2}\sigma_{+0}H_{-1/2}{}^{+},$$

where σ_{+0} and σ_{0+} are electron-capture and electron-loss cross sections; $H_{1/2}{}^{+}$ and $H_{-1/2}{}^{+}$ are fractional populations of spin-up and spin-down protons; $H_{Fm_F}{}^{0}$ are fractional populations of the atoms in low-field Fm_F atomic eigenstates; and π is target thickness.

Atomic charge-transfer cross sections are the same for H, D, or T at the same velocity. Tritium is described by the same equations as hydrogen since it also has a nuclear spin of $\frac{1}{2}$. However, because D has a nuclear spin of 1, a comparable description requires nine differential equations, and nuclear polarization is described by two parameters: vector polarization $P_z = N_+ - N_-$, and tensor polarization $P_{zz} = 1 - 3N_0$, where N_+, N_0, and N_- are the relative populations of the three nuclear-spin states. Electron and therefore nuclear depolarization occurs via radiation from the decay of $n = 2$ or higher atomic levels produced in the electron capture.[1,10] Using measured electron-capture cross sections into $n = 2$ and higher levels, we estimate an atomic depolarization of about 4%, which causes a reduction in nuclear polarization of about 8% for H (or T) and 12% for D.

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/u unpolarized H$^+$ (T$^+$) or D$^+$ incident on a polarized target in a low magnetic field. Target polarization P_t is taken as 1; if P_t is less than 1, the final nuclear polarization of the fast beam is reduced by the factor P_t.

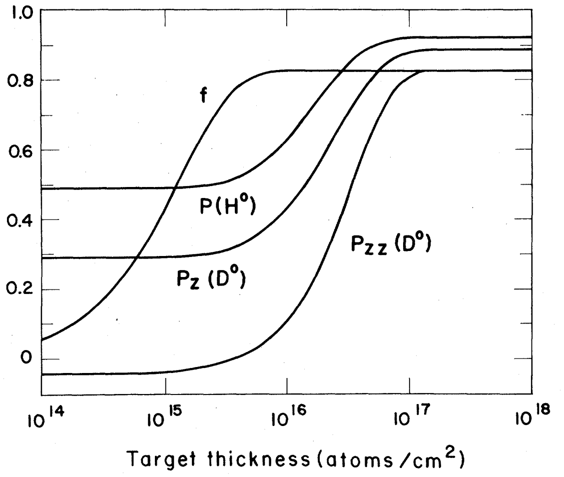

FIG. 1. Nuclear polarization and neutral fraction of fast H^0 and D^0 atoms from a polarized H target in a *low magnetic field* ($B = 10$ G) for incident unpolarized 20-keV/u H$^+$ and D$^+$. Target polarization is taken as 1. $P(\mathrm{H}^0)$ is proton polarization, $P_z(\mathrm{D}^0)$ and $P_{zz}(\mathrm{D}^0)$ are deuteron vector and tensor polarization, f is neutral fraction.

Recent progress in production of dense polarized gas[5,6] in high magnetic fields (100 kG) and excellent prospects for producing thick polarized H targets[5] lead us to analyze collisions of fast atoms or ions incident on a thick polarized target in a high magnetic field. Electron and nuclear angular momenta ($\vec{I}$ and $\vec{J}$) are decoupled at high fields, so that no nuclear polarization can be directly obtained, and collisional pumping as we have defined it does not occur. Electron-spin polarization can, however, be obtained with subsequent conversion to nuclear polarization. Fast H or D atoms will repeatedly lose and capture electrons during their passage through a target; those emerging from a thick polarized target will have a high electron-spin polarization parallel to the target polarization. The electron-spin polarization of the fast atoms can be converted into nuclear polarization by adiabatic transition to low magnetic field followed by a sudden field reversal. This technique, called a Sona transition,[11] is commonly used in Lamb-shift and optically pumped polarized-ion sources; experience with Lamb-shift ion sources[12] indicates that, for H, electron-spin polarization can be almost completely converted into nuclear polarization. A Sona transition with D leads to a vector polarization which is $\frac{2}{3}$ of the electron-spin polarization of the fast beam. Depolarization in electron capture is expected to be very small because $\vec{L}$ and $\vec{S}$ in all n levels of atomic hydrogen are also decoupled. Figure 2 shows both the neutral fraction and the nuclear polarization after a Sona transition, as a function of target thickness, for 20-keV/u H^0, T^0 or D^0 atoms incident on a polarized target. [The electron polarization prior to the Sona transition for both H^0 and D^0 is the same as $P(H^0)$]. The emittance of the fast beam is expected to increase only slightly as the beam passes through the target, because the particles entering and leaving the high magnetic field of the target are neutral and because the particle energy is high. This would be particularly useful with cryogenic polarized H targets with "open" geometry.[5]

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 second target, which need not be polarized. This second target should, however, be in a magnetic field that is large compared to the critical field, in order that $\vec{J}$ and $\vec{I}$ in the ground level of H are decoupled, so that there is no nuclear depolarization due to the hyperfine interaction as the beam passes through the target.

We have only discussed charge-transfer collisions, and have ignored spin exchange. Spin-exchange cross sections for H^0-H^0 at high energies (20 keV) are not known, but are expected to be smaller than charge-transfer cross sections. To the extent that spin exchange occurs, however, it increases the polarization rate and hence decreases the target thickness required for equilibrium polarization.

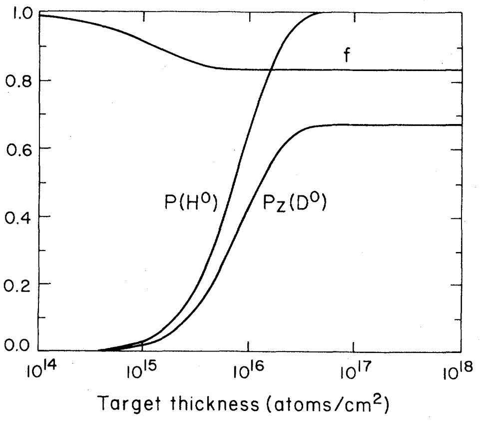

FIG. 2. Nuclear polarization after a Sona transition and neutral fraction of fast H^0 and D^0 atoms from a polarized H target in a *high magnetic field* ($B = 100$ kG) for incident unpolarized 20-keV/u H^0 and D^0. Target polarization is taken as 1. $P(H^0)$ and $P_z(D^0)$ are the polarizations of the protons and deuterons in the neutral beam in a high magnetic field ($B \gg B_c$). $P_{zz}(D^0)$ is 0.

Spin-polarized *target thickness* required for production of a fast polarized H beam by collisional pumping is about $10^{17}/cm^2$. The *rate* at which target particles must be produced depends on the incident beam current. Each projectile in the beam being polarized makes ten to thirty charge-changing collisions as it passes through the polarized hydrogen target; the production rate of electron-spin–polarized target atoms must be comparable, i.e., 10 to 30 times the number of beams particles per second. This implies a production rate of $10^{20}-10^{21}$ polarized target atoms per second to produce a 1-A polarized beam. The largest existing ^{3}He dilution refrigerator can cool about 0.3 W at 0.3 K; this corresponds to $10^{21}-10^{22}$ particles per second cooled from 4 to 0.3 K.

There is another interesting case of collisional pumping: a low-energy H^+ beam (~400 eV) in a thick electron-spin–polarized alkali target. Neutral atoms can only form negative ions at low energies in an alkali target; 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^- because the H^- ion exists only in a $1s^2$ state, where the electrons have oppositely directed spins. Collisional pumping produces, at equilibrium, a beam that is primarily H^0 atoms in the $F = 1$, $m_F = 1$ level. This case will be analyzed in another publication.

The production of 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.[5,6] It is also possible at the present time to produce multiampere H^0 beams at 20 keV/u and higher energies, at particle current densities greater than 50 mA/cm^2.[3] 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.

This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Applied Plasma Physics Division, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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