Concerning one possibility of obtaining beams of polarized ions

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The plasma produced when a laser beam acts on a polarized target is suggested as a source of polarized ions. It is shown that the time of the proton spin relaxation in a dense plasma with $T = 10^5$ K amounts to $\gtrsim 10^{-3}$ sec.

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The problem of obtaining a beam of accelerated polarized protons (nuclei) is of considerable interest for the physics of particle interaction at high energies. We propose a new method, in which the following are feasible in principle: 1) near-unity polarization in the beam, 2) intensity on the order of 10^{12} particles in the acceleration pulse.

To this end, the source of the protons injected into the accelerator should be a polarized proton target. A laser beam or an electron beam is used to produce from this target a plasma with initial density on the order of the density of the solid target and with a temperature $\sim 10^5$ K. This plasmoid expands in a vacuum, and to accelerate the polarized protons successfully it is necessary that the time that the protons stay in the dense hot plasma be much shorter than the proton spin relaxation time.

The plasma preparation time is $\sim 10^{-9}$ sec. It is easily shown that the time required for a plasmoid with $T \sim 10^5$ K to expand to a density $\sim 10^{-4}$ of the initial value is $\sim 10^{-8}$ sec. It will be shown below that at this density one can neglect any further spin depolarization.

Let us estimate the proton spin relaxation time in a plasma with electron density n_e and a temperature T_e. In this system, just as in normal metals, the relaxation rate is determined by the hyperfine interaction of the protons with the free electrons. For simplicity we take into account only the contact interaction:

$$\hat{V} = \frac{8\pi}{3} \gamma_e \gamma_n \hat{\mathbf{S}} \hat{\mathbf{I}} \, \delta(\mathbf{r}) , \tag{1}$$

where $\hat{\mathbf{S}}$ and $\hat{\mathbf{I}}$ are the spin operators and γ_e and γ_n are the gyromagnetic ratios of the electron and proton, respectively, while $\mathbf{r}$ is the electron coordinate relative to the proton. (We note that in metals it is precisely the contact interaction which makes the largest contribution to the nuclear spin relaxation[1] and at electron energies of approximately several eV the interaction of the proton spin with the orbital angular momentum of the electron does not exceed the spin-spin interaction).

The probability of proton spin flip can then be calculated in the first order of perturbation theory with respect to $\hat{V}$, while the electron-proton Coulomb scattering functions should be used as the zeroth-approximation wave functions. As a result we obtain

$$W = \frac{8\sqrt{2}\pi}{9} \gamma_e^2 \gamma_n^2 m_e^{3/2} n_e \int f(E) A^2(E)\sqrt{E}\, dE, \quad (2)$$

where $f(E)$ is a Maxwellian electron-energy distribution function, m_e is the electron mass, and $A(E)$ is the ratio of the probability densities of the Coulomb and free wave functions at $r=0$.[2] If the electron energy E is less than the hydrogen ionization potential Y we have $A(E) \approx 2\sqrt{2}(J/E)^{1/2}$. Ultimately, for a plasma with temperature T_e, we obtain

$$\frac{1}{\gamma} \equiv W = \frac{2^{15/2}\pi^{5/2}}{9} (\gamma_e \gamma_n)^2 m_e^{3/2} n_e \frac{J}{(kT_e)^{1/2}} \approx 10^{-17} \frac{n_e}{T_e^{1/2}} \text{ sec}^{-1}, \quad (3)$$

where T_e is in °K and n_e in cm^{-3}. Formula (3) is valid for a nondegenerate plasma, i.e., $T_e > (\hbar^2/m_e) n_e^{2/3}$. In the case of plasma degeneracy, W only decreases, inasmuch as a small fraction of the electrons participate in the relaxation.

For $n_e \approx 10^{22}$ cm^{-3} and $T_e \approx 10^5$K we obtain $\tau \approx 10^{-3}$ sec. Thus, within the working range of the plasma parameters, the proton spin relaxation time exceeds the lifetime of the dense plasma by several orders of magnitude.

The protons can also become depolarized by electron capture (production of the atom H), after which the hyperfine interaction upsets the coherence of the proton spins. The hyperfine field acting on the nuclear magnetic moment can be represented as a random field with a correlation time τ_1, where τ_1 is the lifetime of the neutral atom in the plasma:

$$\tau_1^{-1} = \sigma n v \exp\{-J/kT_e\}. \quad (4)$$

Here σ is the ionization cross section of the H atoms and v is the electron velocity. We recall that a polarized target and the produced plasma are situated in a strong magnetic field $\sim 2\times 10^4$ Oe. Then, according to[1]

$$\frac{1}{\tau} = \omega_p^2 \frac{\tau_1}{1+(\omega_e \tau_1)^2} c_0, \quad (5)$$

where $\omega_p \approx 10^{10}$ sec^{-1} is the Zeeman frequency of the proton in the hyperfine field, ω_e is the Zeeman frequency of the electron in the external magnetic field ($\omega_e \sim 10^{11}$ sec^{-1}), and c_0 is the concentration of the H atoms in the plasma:

$$c_0 \approx n_e \left(\frac{2\pi\hbar^2}{m T_e}\right)^{3/2} \exp\{J/kT_e\}. \quad (6)$$

It is easily seen from (4)—(6) that the dependences of τ on T_e and n_e are entirely different for $\tau_1 \ll \omega_e^{-1}$ (initial stage—dense plasma) and for $\tau_1 > \omega_e^{-1}$ (tenuous plasma). Under the conditions proposed by us, however, we have $\tau \gtrsim 10^{-4}$ sec, which is also larger by several orders of magnitude than the lifetime of the plasmoid.

The power needed to obtain 10^{13} ions per second amount to $J\times 10^{13}$ eV/sec $\approx 10^{-5}$ W. This laser power is much less than the microwave power fed to the sample to maintain the polarization ($\sim 10^{-2}$ W).

[1]A. Abragram, Principles of Nuclear Magnetism, Oxford, 1961, Chap. 9.
[2]L. D. Landau and E. M. Lifshitz, Kvantovaya mekhanika (Quantum Mechanics), Nauka, 1963, p. 604 [Addison-Wesley 1965].