Nuclear Spin-Polarized Fuel in Inertial Fusion

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This Letter examines the possibility of using spin-polarized DT fuel for inertial-confinement fusion. Analytic models and estimates are developed to determine whether an initial spin-polarized state would survive target irradiation and implosion. It is found that collisional depolarization cross sections are not large enough to give significant depolarization, and that the short duration of inertial-fusion implosions precludes spin resonance for magnetic fields that can be reasonably expected in the target fuel.

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Kulsrud *et al.*[1] recently proposed the use of spin-polarized DT fuel in magnetic-confinement fusion. They reported potential increases in the effective fusion cross section of up to 50%. In this Letter, I report a preliminary study of the possibilities of this idea for inertial-confinement fusion.

The increased average thermonuclear reaction cross section of spin-polarized fuel would improve target performance and reduce the temperature required for target ignition. For example, a simple energy-scaling model developed by Brueckner and Jorna[2] predicts that the driver energy is proportional to $\langle \sigma \nu \rangle^{-3}$ for constant target gain. With this scaling, even a 25% increase in the fusion cross section would yield a 50% reduction in the size of the required laser driver. A weaker dependence ($\langle \sigma \nu \rangle^{-1}$) results from a more elaborate analysis which assumes central ignition of the fuel. The specific numbers may be debated, but they indicate that spin-polarized fuel offers significant advantages.

The anisotropy of reaction-product alpha particles[1] is an additional benefit because it spatially concentrates the plasma self-heating, thereby assisting the process of fuel ignition.

One crucial practical question is how to achieve nuclear spin polarization in a target suitable for laser irradiation. It is equally important to ask whether the target modifications required for achieving spin polarization would themselves reduce target performance. I will not address these essentially technological questions; in this Letter I consider the more fundamental question of whether an (assumed) initial spin polarization would survive target irradiation and implosion.

The spin moment $\vec{S}_j$ of an individual nucleus precesses under the influence of the local magnetic field, according to $d\vec{S}_j/dt = \gamma \vec{S}_j \times \vec{B}$, where[3] $\gamma \simeq g \times 4800/\mathrm{G \cdot sec}$, and $g = 0.86$ (deuterons) and 5.9 (tritons). $\vec{B} = \vec{B}[\vec{R}_j(t), t]$ is the magnetic field at the position $\vec{R}_j(t)$ of the nucleus. For order-of-magnitude estimates, I replace the vector equation by a scalar equation for the rotational phase accumulation $\Delta\varphi$:

$$\Delta\varphi = \gamma \int B\,dt. \tag{1}$$

If the magnetic field occurs as a pulse which obeys $\Delta\varphi \ll 1$, it is unable to depolarize the spins. In general, there are fields on three size scales: atomic fields arising in collisions, microscopic fields associated with surface instabilities, and macroscopic fields which extend throughout the target.

Collisional depolarization during thermonuclear burn is discussed by Kulsrud *et al.*[1] A plasma particle (ion or electron) produces a large magnetic field either by its magnetic dipole moment ($B \cong \mu/r^3$) or by Lorentz transform of its electric field ($B \cong ve/cr^2$). This field acts over the collision duration $\Delta t \cong r/v$, where r is the classical or quantum distance of closest approach for ions or electrons, respectively. The phase shifts $\Delta\varphi$ resulting from these collisions are small ($\sim 10^{-6}$) and random in sign; they cause the target nuclear spin direction to perform a random walk. Following Kulsrud *et al.*, we estimate the effective depolarization cross section as $\sigma \cong (\Delta\varphi)^2 \sigma_c$, where $\sigma_c = \pi r^2 \ln\Lambda$ is the Coulomb cross section.[4-6] The Coulomb logarithm $\ln\Lambda$, usually taken as $\ln(mv\lambda_d/h)$, serves to cut off the contribution of small-angle collisions and, while it reaches values ~ 20 at low plasma densities ($n_I \sim 10^{14}\ \mathrm{cm}^{-3}$), it is significantly smaller in dense plasmas of inertial-fusion interest ($n_I > 10^{24}\ \mathrm{cm}^{-3}$).[6]

These simple classical estimates are plotted for tritium in Fig. 1, along with a similar estimate of the cross section for quadrupolar depolarization of deuterons. Because high-density inertial-fusion plasmas have small Coulomb logarithms,[6,7] the spin-orbit cross section is somewhat smaller than that given by Kulsrud *et al.*

The probability of depolarization due to collisions may be estimated by forming the integral

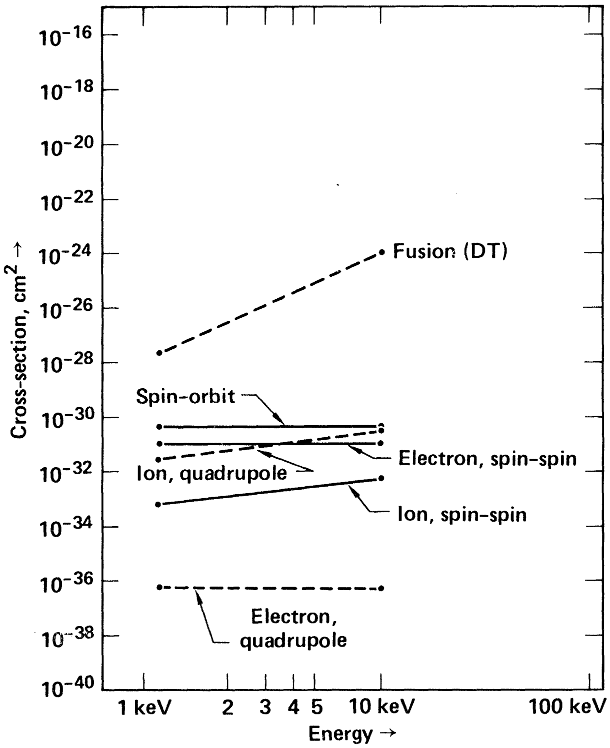

FIG. 1. Approximate cross sections for spin depolarization are compared with the DT thermonuclear cross section. The spin-orbit cross section is the same for incident electrons or ions. It and the spin-spin cross sections are evaluated for tritium nuclei (equivalent cross sections for deuterium are smaller). The quadrupole depolarization cross sections refer to deuterium (tritium has no quadrupole moment). The cross sections are calculated under the assumption of a Coulomb logarithm of unity, appropriate to very dense DT plasma (Ref. 10).

$D_{jk} = \int n_j \sigma_{kj} v_j dt$, where σ_{kj} is the depolarization cross section for species j impacting species k, and $n_j(r,t)$, $v_j(r,t)$ are number density and thermal velocity of species j. The integral is taken along the flow line $r = R(t)$ followed by the target ion during the implosion. D_{jk} may be explicitly calculated for the idealized implosion model introduced by Kidder.[8] For reasonable input parameters (e.g., 1–10-nsec implosion reaching $n_I \sim 10^{26}$ cm^{-3}, $kT_e \sim 10$ keV) D_{jk} is much less than unity and collisional depolarization may be neglected.

Next, we consider micron-scale inhomogeneities in $B(r,t)$. One question is whether two reacting nuclei might experience sufficiently different $B(R(t),t)$ histories to acquire different spin directions. Using the ion-ion Coulomb cross section, I estimate the distance of ion diffusion in a time t to be $d \simeq (6 l v_I t)^{1/2}$, where v_I is the ion thermal velocity, t is time, and $l = 1/n_I \sigma_c$ is the ion mean free path. This gives

$$d \cong (1.5\ \mu\text{m})(kT)^{5/4}(t/\rho)^{1/2},$$

where kT is in kiloelectronvolts, t in nanoseconds, and ρ in grams/centimeter^3. d is $< 0.1\ \mu$m for most plausible target plasma conditions. A field inhomogeneity of scale length L would have to be extremely strong to produce significant dephasing by this mechanism. With use of the Spitzer plasma conductivity σ, the damping time $\tau = 4\pi\sigma(L/c)^2$ for a 1-μm field gradient in a kilovolt plasma is ~20 psec. Therefore it would be difficult to sustain field inhomogeneities long enough to depolarize reacting nuclei, except possibly close to an unstable interface.

Estimates of fields generated in Rayleigh-Taylor instability range up to several megagauss[9]; such fields would be strong enough to depolarize spins of nuclei close to an unstable fuel-pusher interface. However, this fuel region is not likely to burn in any case because of contamination by pusher material.

It appears desirable to subject the target to an initial uniform magnetic field $B_0 \sim 10$ kG in order to inhibit hyperfine coupling which might otherwise occur on atomic hydrogen produced by fast electrons ("preheat") resulting from the laser-plasma interaction.

The next question concerns nuclear spin resonance as a depolarization mechanism. To address this issue, we consider a target subject to an initially uniform field B_0. (It is assumed that the spins are initially polarized along B_0.) During implosion, the field is compressed. To estimate $B(t)$ I employ the idealized model of homogeneous, isentropic compression,[8] which predicts a time-dependent uniform field $B(t) = A(t)B_0$. The area compression factor $A(t) = 1/h(t)^2$ is also the fractional increase in fuel ρR. [The parameter ρR, defined as an integral $\int \rho(r,t)dr$ over the fuel mass, is a conventional measure of target compression.[2]] For the Kidder model,

$$h(t) = (1 - t^2/t_0^2)^{+1/2}, \tag{2}$$

where t_0 is the total time until complete spherical collapse. This form applies only up to a final time t_f ($t_f < t_0$) determined by the symmetry of the implosion. The final field, and its time integral, are

$$B(t_f) = B_0 t_0^2/(t_0^2 - t_f^2), \tag{3a}$$

$$\int_0^{t_f} B(t)dt = \tfrac{1}{2}B_0 t_0 \ln[(t_0 + t_f)/(t_0 - t_f)]. \tag{3b}$$

For implosion which raises the density by a factor of 1000, with $t_0=1$ nsec and $t_f=0.995t_0$, we find that an initial field $B_0=10^4$ G gives a large final field $[B(t_f)\simeq 10^6\ \text{G}]$, but that the phase integral $\Delta\varphi$ remains small enough so that the spins do not precess through even one cycle. Given the assumption that this field is not exceeded by some other spontaneously generated field, *there is no spin resonance.*

We must ask whether larger fields would be generated during the implosion itself. There is no doubt that the plasma energy density is large enough to support enormous magnetic fields. However, a target implosion with good spherical symmetry will have no mechanism for generating a large magnetic field.

I estimate the field generated in a slightly unsymmetric implosion by integrating the rate of field generation[2]:

$$\partial\vec{B}/\partial t=(c/en)\nabla(kT)\times\nabla n, \tag{4}$$

where $n(r,t)$ is the electron density.

The density-temperature gradients of the idealized isentropic implosion model are purely radial so that the vector product is zero. An unsymmetric implosion may be modeled by using gradients from the isentropic flow solution and taking the vector product to be a constant fraction $a\sim\frac{1}{10}$ of the product of absolute values $(|\nabla n||\nabla kT|)$. The field generated is time integrated along a particle track (Lagrangian trajectory). Substituting ∇n and ∇T from the Kidder implosion model, I find $\partial B/\partial t$ proportional to $h^{-4}(t)$. Its integral is approximately (for $t\simeq t_0$)

$$B(r,t)\cong aF(C_a t/R_0^2)(kT_c/e), \tag{5}$$

where the shape factor

$$F(r,t)=3\beta\frac{\beta r^2}{\beta r^2+h^2R_0^2}\leq 3\beta \tag{6}$$

is constant along a Lagrangian track $r(t)=h(t)r(0)$. In these formulas, R_0 is the initial target radius, c_a is the initial sound speed, T_c is the current temperature at target center, and $\beta=\frac{1}{3}(R_0/c_a t_0)^2$ describes the nature of the implosion; $\beta\ll 1$ is a slow implosion, appropriate to a gas-filled target, while $\beta=1$ is a fast (sonic) or hollow-shell implosion.[7,10] Equation (5) predicts fields ~ 50 kG, too small to have any significant effect.

Another field-generation mechanism[11] applies in the outer pellet corona where ∇n is parallel to ∇T; this exterior instability field, like the laser-generated field, would have to penetrate diffusively a thick (50–100 μm) conducting ablator in order to affect the fuel. Assuming normal plasma conductivities, we find that the field would not penetrate in the time of interest. A recent experiment indicates that magnetic field penetration times are significantly longer than heat-front penetration times.[12]

These estimates indicate that an initial spin polarization would have a reasonable likelihood of surviving implosion and fuel burn. The analysis assumes that two essential conditions can be met: first, that the spins are initially polarized without adversely perturbing the target design; second, that large magnetic fields produced directly by the laser can be kept out of the fuel with a conducting pusher or by adopting a favorable target-irradiation geometry.

In summary, at inertial-fusion conditions, the collisional depolarization cross sections are reduced because of the smaller Coulomb logarithm. We do not encounter possible resonance depolarization mechanisms (e.g., Doppler-shifted static-field inhomogeneities) for two reasons: the ions move diffusively, and there is not enough time for spin resonance. In these respects, the inertial-confinement fusion situation appears favorable for exploitation of the idea of fusion with spin-polarized DT fuel.

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[2]K. A. Brueckner and S. Jorna, Rev. Mod. Phys. 46, 325 (1974).

[3]See, for example, C. Kittel, *Introduction to Solid-State Physics* (Wiley, New York, 1967).

[4]This method of obtaining spin-flip cross sections is a classical equivalent of the Coulomb-Born approximation. In dense plasmas, $\ln\Lambda\simeq 1$ and it does not matter whether it is included in the cross section. In the expression for $\ln\Lambda$, λ_d is the Debye length.

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[6]The description of spin-flip collisions given here is simply an estimate of the actual cross sections, similar to estimates in Refs. 1 and 5. It may be worth comment-

ing that only the spin-orbit cross section actually requires a cutoff at large impact parameters, and that Ref. 1 gives a slightly different choice of the Coulomb logarithm. In any case, the collision cross sections would have to be several orders of magnitude larger than the estimates in order to constitute an important depolarization mechanism.

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[9]K. Mima, T. Tajima, and J. Leboeuf, Phys. Rev. Lett. 41, 1715 (1978).

[10]In Eqs. (5) and (6), c_a is the initial sound speed in the fuel. The notation β conforms to Ref. 8. The current particle radius is r and $h = h(t)$.

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