Fusion Reactor Plasmas with Polarized Nuclei

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Nuclear fusion rates can be enhanced or suppressed by polarization of the reacting nuclei. In a magnetic fusion reactor, the depolarization time is estimated to be longer than the reaction time.

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Recent technological developments[1,2] have made possible the generation of polarized gases in quantities of practical interest for the production of polarized fusion plasmas. The dependence of nuclear fusion reactions on nuclear spin[3] suggests that polarization of the reacting particles may be advantageous in providing control of the reaction rates and the angular distribution of the reaction products.

The large cross section for the reaction D(T, n)^{4}He at low energy arises primarily from a $J=\frac{3}{2}^+$ resonant level of ^{5}He at 107 keV above the energy of the free D and T nuclei.[4] At low energies, the reaction occurs only in the $l=0$ state, so that the angular momentum must be supplied by the spin of the D and T nuclei. Since D has spin 1 and T spin $\frac{1}{2}$, their possible combined spin states are $S=\frac{3}{2}$ and $\frac{1}{2}$. The reaction is due almost entirely to interacting pairs of D and T nuclei with $S=\frac{3}{2}$. The statistical weight of this state is 4 while that of the $S=\frac{1}{2}$ state is 2. Thus, for a plasma of unpolarized nuclei, effectively only $\frac{2}{3}$ of the interactions contribute to the reaction rate.

We consider now the case of a magnetic D-T reactor where the fractions of D nuclei polarized parallel, transverse, and antiparallel to $\vec{B}$ are d_+, d_0, and d_-, respectively, while the corresponding fractions of the T nuclei are t_+ and t_-. Then the total cross section is

$$\sigma=(a+\tfrac{2}{3}b+\tfrac{1}{3}c)f\sigma_0+(\tfrac{2}{3}b+\tfrac{4}{3}c)(1-f)\sigma_0, \qquad (1)$$

where $a=d_+t_++d_-t_-$, $b=d_0$, $c=d_+t_-+d_-t_+$, and $f\sigma_0$ is the cross section for the $\frac{3}{2}^+$ state. The magnitude of f has been estimated at about 0.95,[4] but may be greater than 0.99.[5] (The remainder of the cross section is ascribed to a $\frac{1}{2}^+$ state that lies 3 MeV about the $\frac{3}{2}^+$ state.) For an unpolarized plasma, $a=b=c=\frac{1}{3}$ so that $\sigma=\frac{2}{3}\sigma_0$. On the other hand, if all the nuclei are polarized along $\vec{B}$, then $a=1$, $b=c=0$, and $\sigma=f\sigma_0$, so that the enhancement of reactivity is $\frac{3}{2}f$.

The resultant angular distributions of the neutrons and α particles are

$$\frac{d\sigma}{d\Omega}=\frac{f\sigma_0}{2\pi}\left[\tfrac{3}{4}a\sin^2\theta+(\tfrac{2}{3}b+\tfrac{1}{3}c)\left(\frac{(4/f)-3+3\cos^2\theta}{4}\right)\right], \qquad (2)$$

where θ is the pitch angle relative to $\vec{B}$. If all the nuclei are polarized parallel to $\vec{B}$, the angular distribution of the neutrons and α particles is $\sin^2\theta$; if the D nuclei are polarized transverse to $\vec{B}$, then the distribution is $(4/f)-3+3\cos^2\theta$. The polarization of the neutrons also varies with θ. At $\theta=90°$, it is given by

$$n_+-n_-=\frac{\tfrac{3}{4}(d_-t_--d_+t_+)+\tfrac{1}{6}d_0(t_+-t_-)+\tfrac{1}{12}(d_+t_--d_-t_+)}{\tfrac{3}{4}a+\tfrac{1}{6}b+\tfrac{1}{12}c}, \qquad (3)$$

where n_+ and n_- are the fractions of neutrons polarized parallel and antiparallel to $\vec{B}$. (We have set $f=1$.) Since these results depend only on the vanishing of the orbital angular momentum prior to the reaction, they are roughly independent of energy within the range of fusion interest.

The D-D reaction is more complex than the D-T reaction and its properties are less well known; therefore, we can give only an indication of the potential effects of polarization. From the results of Ad'yasevich and Fomenko[6] it can be demonstrated that enhancements of order 2 can be obtained at low energy. For an ordinary thermal ion distribution, such enhancements can be obtained by polarizing the deuterons transverse to the magnetic field. Alternatively, if colliding-beam or beam-target methods are used, the two ion components should be polarized in opposite directions relative to the field. If, on the other hand, the ions are all polarized parallel to the field, one may conclude from these results that the reaction rate is suppressed by a substantial factor. While the results of Ad'yasevich and Fomenko provide a good fit to one class of data,[6] other recent measurements[7] lead to substantially different conclusions, indicating D-D enhancement factors smaller than 1.6.

There would be little pratical value in polarizing nuclei if the depolarization rates were rapid compared with the fusion reaction rate. At first sight, it would appear that, because of the small energy difference between the two polarization states ($\Delta E \approx 10^{-7}$–10^{-6} eV $\ll kT$), an unpolarized equilibrium would be rapidly established. However, as far as we can see, the *mechanisms* for depolarization of nuclei in a magnetic fusion reactor are suprisingly weak. We will consider four such mechanisms:

(1) *Inhomogeneous static magnetic fields.*—Let $\omega_2 = eB_0/2m_p c$ be the deuteron cyclotron frequency, and let $\Omega_2 \equiv \Delta E/\hbar = g_2 eB_0/2m_p c$ be the deuteron precession frequency, where ΔE is the Zeeman energy for a change of spin orientation $\Delta m = 1$, and g_2 is the magnetic moment of the deuteron in nuclear magnetons. Similarly, let Ω_3 and g_3 be the precession frequency and magnetic moment of the triton. Then $\Omega_2 = 0.86\omega_2$, and $\Omega_3 = 5.96\omega_2$. If a nucleus with velocity v passes through static magnetic-field inhomogeneities of scale s, it sees them at a frequency v/s. As in the case of the adiabaticity of the ordinary magnetic moment of the particle gyromotion, frequencies below the nuclear precession frequency —i.e., static inhomogenities on a scale that is large compared with the ion gyroradius ($s \gg \rho_i$) —cannot change the polarization.

(2) *Binary collisions.*—Simple electrostatic Coulomb scattering does not affect the nuclear spins, but there are many other potential depolarization mechanisms: The triton can interact with electrons, deuterons, and other tritons by spin-orbit and spin-spin interactions; the deuteron can also interact by means of its quadrupole moment. Fortunately, the associated depolarization rates turn out to be quite small.[8] During each collision, the change in polarization from state α to state β is small and of random sign. We have calculated the cross section σ_i for the rate of increase

$$d(\beta^2)/dt = n\sigma_i v_{\mathrm{rel}} \qquad (4)$$

by process i, where n is the particle density and v_{rel} is the relative velocity. The cross sections for interaction with electrons are found to be of the same order as for ions; because of the factor v_{rel} in Eq. (4), depolarization by electrons therefore predominates. For spin-orbit depolarization of T, we have

$$\sigma_i = (4\pi/3) g_3^2 r_p^2 \ln(c/\omega_p \lambda\!\!\!^{-}) = 1.7\times10^{-29}\ \mathrm{cm}^2,$$

where $r_p \equiv e^2/m_p c^2$, $\omega_p^2 = (4\pi n e^2)/m_e$ and $\lambda\!\!\!^{-} = \hbar/m_e v$. For spin-spin depolarization, $\sigma_i = \frac{11}{9}\pi g_3^2 r_p^2 = 8\times10^{-31}$ cm^2. For the d_0 state of D, σ_i is smaller by $(g_2/g_3)^2 = 0.083$ than for T; for the d_+ or d_- states, it is smaller by $\frac{1}{2}(g_2/g_3)^2 = 0.042$. Interaction with the quadrupole moment is negligible for electrons. Using typical reactor parameters, $n = 2\times10^{14}$ cm^{-3}, $T = 10^4$ eV, we find the rate of depolarization to be 2.1×10^{-5} s^{-1} for T, 1.75×10^{-6} s^{-1} for the d_0 state of D, and 0.9×10^{-6} s^{-1} for the d_+ or d_- state of D. These rates are small compared with the typical 1 s^{-1} rate for fusion energy multiplication or the 10^{-2} s^{-1} rate for complete fuel burnup. There is also a contribution from elastic nuclear scattering, which we estimate at $\Delta\beta^2 \lesssim 10^{-4}$ per fusion event.

(3) *Magnetic fluctuations.*—A polarized moving nucleus will tend to be depolarized by those harmonics of the fluctuating fields which are left-circularly polarized with respect to $\vec{B}$, if the Doppler-shifted frequency in the frame of the nucleus is equal to its precession frequency. Defining the intensity of magnetic fluctuations as I_ω, where $(\delta\tilde{B})^2 \equiv \int I_\omega d\omega$, then

$$\frac{d(\beta^2)}{dt} = \left(\frac{ge}{2m_p c}\right)^2 I_\omega(\Omega) = \frac{(geB/2m_p c)^2}{\Delta\omega}, \qquad (5)$$

where $\Delta\omega$ is the bandwidth around Ω over which $\tilde{B}^2$ extends in the frame of the nucleus.[9] The resonant frequency in the laboratory frame is $\omega = \Omega_i - k_z v_z - n\omega_i$, where k_z is the component along $\vec{B}$ of the wave number of the fluctuation. The cyclotron frequency term $n\omega_i$ in this equation ($n = 0$, ±1, ±2, etc.) is produced by the gyromotion of the nucleus, with the amplitude of the higher harmonics seen by the nucleus reduced by $J_n(k_\perp \rho_i)$. In thermal equilibrium, plasma fluctuations are very small: For a 10^4-eV Planck spectrum of electromagnetic waves, we find that $d(\beta^2)/dt \sim 10^{-14}$ s^{-1}. A depolarization rate sufficiently large so as to prevent reactor operation [i.e., $d(\beta^2)/dt \gtrsim 1\ s^{-1}$] would imply $\tilde{B} \gtrsim 3(\Delta\omega/\Omega)^{1/2}$ G in the case of either D or T. For a highly non-Maxwellian plasma velocity distribution, microinstabilities around the deuteron cyclotron frequency could indeed give rise to significant depolarization through direct interaction ($n = 0$) with the precession of the deuteron ($\Omega_2 = 0.86\omega_2$). In a roughly Maxwellian plasma, however, such waves are strongly damped, so that their amplitude should be small. Spatial gradients of plasma temperature and density tend to excite lower-frequency field perturbations with longer wavelengths, which could interact through higher-n resonances. For example, with $n = -1$, the Ω_2 resonance can occur for a transverse Alfvén wave at $\omega = 0.15\omega_2$, while the higher-frequency triton precession ($\Omega_3 = 5.96\omega_2$) could resonate with a whistler mode propagating at an angle to $\vec{B}$. Because of the complexity of the plasma wave spectrum, it is difficult to place detailed upper limits on "anomalous" depolarization in a magnetic fusion reactor, but for a moderately close approach to thermal equilibrium (i.e., avoidance of steep gradients, especially in velocity space), the desired degree of quiescence seems likely to be attainable.

(4) *Atomic effects.*—The polarized nucleus of a hydrogenic atom is not depolarized by ionization, but if recombination (or charge exchange) couples the nucleus to an electron of opposite spin, it can be depolarized with 50% probability. This process, however, is inhibited by an external magnetic field B sufficiently strong compared with the critical field B_c at which the Zeeman splitting equals the hyperfine splitting: The probability of spin exchange is then reduced[10] by the factor $(B_c/2B_0)^2$. Since B_c is only of order 3×10^2 G for D and 10^3 G for T, multiple processes of recombination into atomic hydrogen, followed by reionization, could take place in a 5×10^4 G field without significant depolarization. Recombination into molecular hydrogen could expose the nucleus to more rapid depolarization by spin-orbit coupling associated with the molecular tumbling; however, the boundary conditions at the edge of hot plasmas can be designed to discriminate against molecular recycling (e.g., in the case of tokamaks with divertors, or mirror machines with axial plasma outflow).

One obvious economic advantage of polarizing the nuclear fuel of a reactor is the enhancement of fusion power (1.5 for D-T, $\gtrsim 1.6$ for D-D). This enhancement would be particularly helpful for small-sized reactors with intrinsically low power multiplication.[11] The ability to *suppress* reactions is also of practical value: For example, if the nuclei of a D-He^3 fuel mixture are all polarized parallel to $\vec{B}$, the D-D reaction rate will tend to be suppressed, while the D-He^3 rate is enhanced by 1.5 (similar to D-T). In this way, it may be possible to approximate a neutron-free fusion reactor without resorting to high-temperature, low-power processes such as p-Li.

In the case of the D-T reaction, the ability to control the anisotropy of the emitted α particles allows enhancement of the fraction trapped into well-confined orbits (d_+t_+ being favorable for mirror machines and d_0 for tori) and improvement of magnetohydrodynamic stability properties (d_0 being favorable for tori). Control of α-driven plasma currents and microinstabilities may also be possible. Reactor shielding and blanket design would benefit: e.g., in tori, tangential emission (the d_0 case) could minimize the neutron load on the constricted small–major-radius side of the vessel. The polarization of the neutrons should prove useful in research.

A fusion reactor could be fueled with polarized atomic hydrogen gas, using the optical pumping method described in Ref. 1. The incremental energy requirement per nucleus is very small (a few electronvolts) compared with the mean energy of fusion plasma particles. Polarized atomic hydrogen (or deuterium/tritium) could also be used as a plasma source for multiaperture ion acceleration in a conventional neutral beam line.[12] A moderate magnetic field ($\lesssim 1$ kG) along the direction of acceleration is needed to maintain polarization; following charge-exchange neutralization, the field direction can be rotated from longitudinal to transverse and matched smoothly into the main confining field. Injection of polarized frozen hydrogen pellets would be attractive, but appears problematical—as does the use of polarized targets for inertial fusion.

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Charge State and Slowing of Fast Ions in a Plasma

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The charge state of a projectile ion traveling through a plasma target under conditions relevant to ion-beam fusion is calculated. It is found that, at the projectile energies and target parameters considered, the projectile ionization is significantly higher than that of the same projectile species in a cold target. The resulting strong effects on the range and on the shape of the energy deposition profile are shown in several examples of full dynamic calculations.

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The processes involved in the slowing of fast ions in high-temperature plasmas are of prime interest in the study of inertial-confinement fusion systems using intense ion beams.[1] The case of proton beams was studied by Mosher[2] and Nardi, Peleg, and Zinamon.[3] In particular, the latter authors applied the theory of the plasma dielectric function to calculate the contribution of the free electrons to the stopping power, and constructed a model of the ions in order to extend Bethe's theory to treat the stopping power due to electrons bound in the plasma ions. Only proton slowing was considered in Ref. 3, because with heavier ions the charge state of the projectile has to be known. The problem of the charge state of projectiles moving in cold matter has been studied over a long period of time.[4,5] In that case the charge state of the projectile is determined by the competition between electron loss by collisions and capture from bound states in the target atoms. As was pointed out by Bell,[5] it is much more difficult for the projectile to capture a free electron than a bound electron. The reason is that for a free-electron capture to take place the excess binding energy has to be gotten rid of by one of the following processes: (a) radiative recombination, (b) three-body recombination, or (c) dielectronic recombination. Also, loss processes by collisions with the highly stripped plasma ions could be more efficient than those due to collisions with cold target atoms. It is to be expected, therefore, that the charge state of a projectile moving in a plasma will be quite different from that in a cold target. The effect is expected to become less important at high projectile energies, when capture from bound states is also hindered by the large relative kinetic energy. Work on this subject was first reported by Bailey, Lee, and More.[6] An estimate was made by Mehlhorn[7] without specifically considering recombination processes. In this work we present a simplified model for the calculation of charge state of ions moving in various ionized targets.

Electron loss due to collisions of the projectile with the background ions is calculated by the binary encounter approximation (BEA).[8] This approximate model agrees with the semiclassical description,[8] and with the plane-wave Born approximation.[9] For accurate agreement with experiment the Coulomb deflection effect and the

