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R.M. Kulsrud, H.P. Furth, E.J. Valeo, R.V. Buñny,

D.L. Jassby, B.J. Micklich, D.E. Post

Plasma Physics Laboratory

Princeton University

Princeton, New Jersey 08544 USA

M. Goldhaber

Brookhaven National Laboratory

Upton, New York USA

W. Happer

Princeton University

Princeton, New Jersey USA

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Fusion Reactor Plasmas with Polarized Nuclei

Abstract

New techniques of bulk polarization could be used to fuel a reactor with polarized hydrogenic atoms, so as to form a plasma of polarized nuclei. Theoretical calculations indicate that, once the nuclei of the plasma are polarized in some preferred state, they can maintain this state with a probability near 100% during their lifetime in the reactor, including possible recycling. There are a number of practical advantages to be gained from the use of polarized plasma in a fusion reactor. The nuclear reaction rates can be increased or decreased, and/or the direction of emission of the reaction products can be controlled. The D-T reaction rate can be enhanced by as much as 50%, with the reaction products emitted perpendicular to the magnetic field. Alternatively, it is possible to direct the reaction products primarily along the field, with no enhancement. In the case of the D-D reaction, the theoretical predictions are somewhat less certain. Enhancement of the reaction rate by a factor of 1.5-2.5 is to be expected. In a different polarization state, suppression of D-D reactions may be feasible -- a possibility that would be of interest for a "neutron-free" D-He³ reactor. A quantitative discussion of the relevant nuclear physics as well as of the various mechanisms producing depolarization is given.

Introduction

A recent note [1] proposed that the performance of thermonuclear reactors could be improved by injecting fuel atoms whose nuclear spins are polarized

relative to a plasma confining magnetic field. This injection may be accomplished by gas puffing or by energetic neutral beams. It was pointed out that the nuclei would remain polarized after ionization, even in the extreme environment of the thermonuclear plasma, and even after a number of recycling passes to the wall and back. A number of practical advantages were cited: Nuclear reaction rates could be increased or decreased and/or the direction of emission of the reaction products e.g., alpha particles and neutrons could be modified. If a practical technology of fuel injection can be developed, as now seems likely, the use of polarized fuel will provide fusion reactor engineers with a powerful tool.

In this paper we present theoretical substantiation of the conclusions of Ref. 1, along with some new results. We first review the modifications to be expected in the nuclear reactions D-T, D-D, and D-He³. We then discuss the degree of polarization actually to be expected in a reactor and show that it may be close enough to 100% to yield the desired practical benefits.

I. Nuclear Reactions

A. The DT Reaction

Assume we have a partially polarized plasma. Let m_s denote the component of nuclear spin along $\underline{B}$ and let t_+ and t_- denote the fraction of tritons with $m_s = 1/2$ and $-1/2$ respectively. Let the fraction of deuterons with $m_s = 1, 0, -1$ be d_+, d_0 and d_- . Let $a \equiv d_+t_+ + d_-t_-$, $b \equiv d_0$, $c \equiv d_+t_- + d_-t_+$. Let the probability that the D-T reaction goes through the resonant $3/2^+$ state of He⁵ be f where $f \gtrsim .95$. Then a simple application of quantum theory shows that the average total nuclear cross section is

$$\sigma = \left(a + \frac{2}{3}b + \frac{1}{3}c\right) f\sigma_0 + \left(\frac{2}{3}b + \frac{4}{3}c\right) (1-f)\sigma_0, \quad (1)$$

while the differential cross section for alpha particles to be emitted in solid angle $d\Omega$ (and neutrons in the opposite direction) is

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

where θ is the pitch angle of the velocity vector of the alpha particle. In terms of these equations it is easy to predict the dependence of the nuclear reaction rate on the state of polarization, as well as the angular distribution of the emitted alpha particles.

If the nuclei are unpolarized, then $a = b = c = 1/3$, $\sigma = 2/3 \sigma_0$, and the differential cross section is isotropic. If on the other hand the nuclei are nearly polarized along $\underline{B}$, then $d_+ = 1-\epsilon$, $d_0 = \epsilon$, $d_- = 0$, $t_+ = 1-\epsilon$, $t_- = \epsilon$, where $\epsilon \ll 1$ represents the lack of total polarization, $\sigma = \sigma_0 (f - \epsilon/3)$ and $d\sigma/d\Omega$ is proportional to $\sin^2\theta + (4\epsilon/9) (1 + \cos^2\theta)$ valid to first order in ϵ and $1-f$. Thus, the corresponding reaction rate is almost 50% faster and the emission of neutrons and alpha particles is nearly perpendicular to $\underline{B}$. An incidental advantage of this mode of polarization is that neutrons will pass through the surrounding walls more nearly perpendicularly than in the unpolarized case, with correspondingly reduced first-wall damage and heating. In the particular case of a mirror machine, the neutron flux to the end plugs can be reduced and the fraction of alpha particles trapped in the mirror field can be enhanced. In an alternate polarization mode $d_0 = 1-\epsilon$, where the deuterons are nearly transverse to $\underline{B}$, there is no enhancement in σ ,

but the angular distribution of alpha particles and neutrons is approximately $(9\epsilon/2) \sin^2 \theta + 4(1-f) + (1 + 3 \cos^2 \theta)$ so that they are emitted preferentially along β . This mode of polarization may be of particular usefulness in a tokamak reactor, where fusion energy multiplication is less critical than in a mirror machine, so that the enhancement in Q is less important. Parallel emitted alpha particles are easier to contain in a tokamak reactor and make a more favorable contribution to MHD stability. Reduction of the neutron flux striking the small-major-radius side simplifies tokamak blanket design. (A calculation for a tokamak of aspect ratio 3 and square minor cross section shows that the resulting flux of neutrons to the small radius side of the blanket is 70% of that for an unpolarized reactor.) Which mode of polarization is most advantageous is thus seen to depend on the specific practical considerations peculiar to each reactor design.

B. D-D Reactions

The results to be expected for the D-D reaction are more controversial. For the neutron reaction $D(d,p)He^3$ the various matrix elements for the different spin states have been evaluated by Ad'yasevich and Fomenko [2] from analysis of data based on a polarized beam of deuterons incident on an unpolarized target.

They found that the most important matrix elements for the reaction $D(d,p) He^3$ were from the $S=0, l=0, J=0$ initial state, α_0 , and from the $S=1, l=1, J=1$ state, α_1 . The matrix elements from all the $S=2$ states which we denote by δ were much smaller. Consider the interaction of two D populations, as for the case of a beam and a target plasma of deuterons, and let A_{ij} be the fraction of deuterons pairs with $m_{s1} = i, m_{s2} = j$. Then keeping only these matrix elements, we have for the total average cross section,

$$\begin{aligned}
\frac{2\sigma}{\pi\lambda^2} = & 2(A_{11} + A_{-1-1})\delta^2 + A_{00}\left(\frac{4}{3}\delta^2 + \frac{2}{3}|\alpha_0|^2\right) \\
& + (A_{10} + A_{01} + A_{-10} + A_{0-1})\left(\delta^2 + \frac{3}{2}|\alpha_1|^2\left[\cos^2\theta_0 + \frac{1}{2}\sin^2\theta_0\right]\right) \\
& + (A_{1,-1} + A_{-1,1})\left(\frac{\delta^2}{3} + \frac{2}{3}|\alpha_0|^2 + \frac{3}{2}|\alpha_1|^2\sin^2\theta_0\right),
\end{aligned}
\tag{3}$$

where θ_0 is the direction of relative motion before the reaction and $|\delta|^2 \approx .01$ represents the contribution of the quintuplet state $S=2$.

In terms of this we may derive the enhancements of the reaction rate E_{ij} for $A_{ij} = 1$ and all other A 's zero, relative to the unpolarized case $A_{ij} = 1/9$.

$$E_{11} = \frac{9\delta^2}{\Delta}, \quad E_{10} = [4.5\delta^2 + 6.75|\alpha_1|^2\left(\frac{1}{2}\sin^2\theta_0\right)]/\Delta$$

$$E_{1,-1} = (3|\alpha_0|^2 + 6.75|\alpha_1|^2\sin^2\theta_0 + 4.5\delta^2)/\Delta,$$

$$E_{00} = \frac{3|\alpha_0|^2 + 6\delta^2}{\Delta}, \quad \Delta = |\alpha_0|^2 + 3|\alpha_1|^2 + 5|\delta|^2.$$

(4)

Ad'yasevich and Fomenko estimate $|\alpha_1|^2/|\alpha_0|^2 = .5$, $\delta^2/|\alpha_0|^2 = .01$ at 290 keV bombarding energy. They extrapolate to other energies by letting $|\alpha_0|^2$ and $|\delta|^2$ vary as the penetrability of an S wave through the Coulomb barrier, and, $|\alpha_1|^2$ as the penetrability of a P wave. Table I gives these enhancements at

various bombarding energies. It is seen that enhancements in excess of 2 are obtained for E_{00} and $E_{1,-1}$ at low energies. Suppressions of order 5 to 10 are obtained for E_{11} . The cases (1,1) and (0,0) apply to reactions in thermal plasma while (10) and (1,-1) apply only to beam-plasma reactions. For the (1,1) case the large suppression would provide an easy test of the polarization concept.

Unfortunately, the relative size of the matrix elements is not at all certain. Hale and Dodder [3] on analyzing other data, found that $\delta^2/|\alpha_0|^2 \sim 1$, which vitiates the results of Table 1. Suppression is small and the maximum enhancement is only 1.7. However, the discrepancy may be due to the fact that the data they analyze is from a thick target. Such data overemphasizes δ^2 .

C. D-He³ Reactions

The D-He³ reaction is identical to the D-T reaction with different values of σ_0 and f . It also can be enhanced by 50%. However, if the D are all polarized with $m_s = 1$, the D-D reaction is suppressed, according to Table I, so a D-He³ reactor would be free of neutrons. (This conclusion may not be valid if the Hale-Dodder³ results are the correct ones.)

II. The Polarization of the Plasma

We now summarize the four processes that could depolarize the nuclei once they are polarized. These processes can operate on the nuclei while they are in the reactor, or during the injection phase, or in a tokamak during the recycling phase. These four are (a) inhomogeneous fields, (b) collisions, (c) magnetic fluctuations, and (d) the atomic processes: recombination,

charge-exchange, and ionization. It will appear that the depolarization rates of all these processes are very small.

A. Inhomogeneous Fields

As a nucleus moves through a static magnetic field whose direction is changing in space, it can be depolarized if the rate of change of direction is too fast. If the nucleus is nearly polarized in a single spin state (say $m_s = 1$ for the deuteron), then the change of amplitude of the adjacent state β is given up to a phase factor by

$$\Delta\beta = - e^{i\phi} \left(\frac{1}{2}\right)^{1/2} \int_0^\phi e^{-i\phi'} \frac{d\theta}{d\phi'} d\phi', \quad (5)$$

where $\phi = \int_0^t \omega_i(t) dt$ is the precession phase, θ is the angle of the direction of the field relative to some fixed direction in space, and $\omega_i(t)$ is the local precession frequency of nucleon i (D or T). If the magnetic moment of the nucleus is g nuclear magnetons (a nuclear magneton is $eh/2m_p c$), then $\omega_i = g_i eB/(2_p c I) \approx (g_i/I)\Omega_2$, where Ω_2 is the deuteron gyration frequency and I the spin of the nucleus ($\omega = .86\Omega_2$ for deuterons and $5.94 \Omega_2$ for tritons). Equation (5) was derived assuming that $\underline{B}$ is always in a single plane, but it gives essentially the correct result even for a 3-D field if account is taken of the fact that it is only the left circularly polarized component of the change in $\underline{B}$ as seen by the moving nucleon that produces depolarization.

Examination of Eq. (5) shows that the change in β is given essentially by that harmonic of $\theta(t)$ at $(g/I)\Omega_2$. Thus, if $v/\Omega \sim 1$ cm and the direction of the field varies by $\delta\theta$ over a typical scale $\lambda = 10^2$ cm, then the change in β

is of order $\delta\theta \exp(-100)$ and is quite negligible. Equation (5) also applies to the nucleus when it is in the atomic state and being injected into the reactor. For example, it is possible design a field variation in a neutral beam injector which makes $(\Delta\beta)^2$ very small ($< .1\%$) during the passage from the neutralizer cell (where $\underline{B}$ is necessarily along the direction of acceleration) into the plasma-confinement region of the reactor.

B. Collisions

For reactor plasma parameters, nuclei suffer many binary Coulomb collisions per fusion reaction. During a collision with a moving charge, rapid fluctuating magnetic fields will be produced at the nuclei, which can produce depolarization (this is denoted as spin-orbit coupling). In addition, the interaction of the magnetic moments of the colliding particles can produce spin exchange and depolarization (spin-spin coupling). Finally, because the deuteron has a quadrupole electric moment, it can be depolarized by direct electric interaction. However, because of the very short duration of the collisions and the relative weakness of the interactions, the actual amount of depolarization is very small in practice. To quantify this, let us introduce an effective cross section σ_i for depolarization by each process. Each collision produces a randomly phased change in β , the amplitude of the undesired state. These $\Delta\beta$ add incoherently. We may write

$$\frac{d(\Delta\beta)^2}{dt} = \sum_i n v \sigma_i, \quad (6)$$

where σ_i is the contribution to the cross section of each process. Values of σ_i are given in Table 1.

From inspection of the table we see that the cross sections are very small; those of electrons being comparable to those of ions. Because of the factor v in Eq. (6), depolarization by electrons predominates. Adding up all the σ_1 's for electrons, we find the total depolarization cross section is $1.7 \times 10^{-29} \text{ cm}^2$ for tritons, and $.7 \times 10^{-30} \text{ cm}^2$ for D nuclei in the $m_s = \pm 1$ states. (For deuterons in the $m_s = 0$ the depolarization cross section must be doubled since there are two adjacent states to depolarize to.)

The corresponding rates for a reactor with $n_e = 2 \times 10^{14} \text{ cm}^{-3}$ are $d(\Delta\beta)^2/dt = 2 \times 10^{-5} \text{ s}^{-1}$ for T, and $1.75 \times 10^{-6} \text{ s}^{-1}$ for D in the $m_s = 0$ state, and $.9 \times 10^{-6} \text{ s}^{-1}$ for D in the $m_s = \pm 1$ states. During a 20 second residence time, a triton will be depolarized by .04% and a deuteron by .004%.

C. Magnetic Fluctuations.

According to Eq. (5) any changing magnetic field that the nucleus sees in its frame will produce depolarization. Subsection II (A) refers to static externally produced inhomogeneities in the field. Fluctuating currents in the plasma itself are known to produce additional time-dependent fluctuations that the nuclei will see, and they will produce depolarization. If these fluctuations are small, one can evaluate Eq. (5) statistically to obtain the result of many incoherent fluctuations,

$$\frac{d(\Delta\beta)^2}{dt} = \frac{g^2 e^2 I_o^2(\omega_1)}{4m_p^2 c^2}, \quad (7)$$

where $I_0(\omega_i)$ is the intensity at the precession frequency of left circularly polarized magnetic fluctuations seen by the moving spiralling nucleus, $(\delta B)^2 = \int I_0(\omega) d\omega$. One may easily translate this to the intensity spectrum of waves in the laboratory frame $I(\omega, k_z, k_\perp)$

$$\frac{d(\Delta\beta)^2}{dt} = \sum_n \left(\frac{q_i}{2m c} \right)^2 J_n^2(k_\perp \rho_\perp) I(\omega_i - k_z v_z - n\Omega_i, k_z, k_\perp), \quad (8)$$

where z refers to the direction along the field. The argument of the Bessel function is $k_\perp \rho_\perp \equiv k_\perp v_z / \Omega_i$, as usual.

To determine depolarization by magnetic fluctuations from Eq. (8), it is necessary to estimate the fluctuation intensity. Depolarization by thermal fluctuations can be shown to be extremely small; the main danger is from fluctuations produced by instabilities, for which there is no simple way of predicting the mean level of intensity. For a triton, the resonant frequency for $n=0$ is $\omega_3 \approx 6\Omega_2$. Because parallel propagating waves at this frequency are whistler waves, which are right-circular polarized, it is only the left-circular polarized component of off-angle propagating whistler waves that can produce depolarization. Making use of Eq. (8) we find $d(\Delta\beta)^2/dt = .45 (\delta B)^2 (\omega_3/\Delta\omega) S^{-1}$ where $\Delta\omega$ is the band over which $(\delta B)^2$ is calculated. ($\delta B \sim .05g$, $\Delta\omega \sim \omega_3$ would produce 1% depolarization in 20s.)

For depolarization of deuterons with $n=0$, one finds $d(\Delta\beta)^2/dt = 0.1(\delta B)^2 (\omega_2/\Delta\omega)$ (so that $\delta B \sim .07g$, $\Delta\omega \sim \omega_2$ would produce 1% depolarization in 20 s). For deuterons $\omega_2 = .86\Omega_2$, so this frequency is near the ion cyclotron wave band. However, in a plasma consisting of 50% D, 50% T the

waves cut off below $.833\Omega_2$; thus the dangerous waves are relatively fast and their wave lengths have to be rather large. In an inhomogenous field, such as that of a tokamak, the wavelengths may be too large to fit into a localized region where ω_2 is sufficiently constant to cause an interaction at $n=0$.

It might be suspected that the anisotropies generated by the alpha particle velocity distributions as displayed in Eq. (2) could generate instabilities. Again, it is found that only frequencies very close to cutoff, $.833\Omega_2$, can resonate with the alpha particles of sufficiently high energy to be anisotropic. Such waves are also very long. Further, if the polarization mode is chosen so that alpha particles are emitted predominately along $\underline{B}$, the alpha distribution is such as to suppress rather than to amplify these waves.

Finally, one must consider $n=-1$ in Eq. (8). These waves are at a frequency $\sim .14\Omega_2$ and so they are Alfvén waves. If $k_{\perp}\rho_{\perp}$ is small, the Bessel function factor greatly reduces their depolarization efficiency. If $k_{\perp}\rho_{\perp}$ is large, they are subject to substantial ion cyclotron damping and are not likely to reach a large amplitude. In any event, this frequency is considerably larger than drift-wave frequencies, so there is no apparent reason for amplification.

In summary, no specific instability mechanism has been identified thus far that appears to be dangerous to maintenance of adequate polarization. Of course, any heating by externally driven waves, such as ion-cyclotron heating, must be planned with particular caution if polarization is to be maintained.

D. Ionization, Recombination and Charge Exchange.

Atomic processes are relatively unimportant while the nucleus is in the hot interior of the reactor. However, during the time between polarization of

the nucleus as a neutral atom outside the reactor plasma and its injection into the reactor, either by gas puffing or as an accelerated neutral, several atomic processes may be expected to occur. Further, depending on the particular reactor design, the nucleus may leave the reactor plasma, recombine, and reenter as many as twenty times before being pumped away. If during this recycling process a nucleus has a substantial probability of being depolarized, the general level of polarization will be reduced by dilution.

The ionization process is fast enough so that there is little chance for a change in polarization. During recombination or charge exchange the bare nucleus will pick up an electron whose state of polarization is either parallel to the nucleus or antiparallel. If it is parallel, there will be no change in polarization. If it is antiparallel, the resulting atomic state will be a superposition of two states, one with the nuclear polarization unchanged and the electron spin opposite to it, and a second state of amplitude $\epsilon_0 = B_C/2B_0$ with the spins exchanged. B_C is the so-called critical field at which the Zeeman splitting equals the hyperfine splitting due to the interaction of the magnetic moments of the nucleus and the electron in the ground state. ($B_C \approx 300$ gauss for deuterium and 10^3 gauss for tritium.) B_0 is the strength of the field in which the recombination occurs. When the atom is reionized the chance of an increase in depolarization of the nucleus is represented by ϵ_0^2 . Thus, for an arbitrary direction of electron spin we get $\Delta\beta^2 = 1/2 \epsilon_0^2 = B_C^2/(8B_0^2)$ per recombination event.

In mirror machines, recycling is expected to be unimportant, but in toroidal reactor design, it is convenient to let the nuclei recycle about twenty times. If a nucleus goes to the wall, recombines on the surface, and then reenters the plasma twenty times, one can estimate the total

depolarization. Assuming a 50 kilogauss field at the wall, each deuteron suffers a depolarization of $.5(300/10^5)^2 = .5 \times 10^{-5}$ per recombination or a total depolarization of $10^{-4} = .01\%$. For tritons the total figure is $.1\%$. The most dangerous process that can occur is that the nuclei embed themselves in a metal surface. The depolarization relaxation time is then very short (10 ms - 100 ms), so that the depolarization during 100 ms would be 100%. If the surfaces that bound the hot plasma are made of graphite, however, the best estimate for the relaxation time is 100 s [4], so that the depolarization during 100 ms is $.1\%$. These considerations would tend to reinforce the attractiveness of graphite as the optimal material for plasma-contact surfaces.

III. Conclusion

While there are many processes that can reduce the polarization of nuclei in a plasma, our initial studies of these processes indicate they may all be small enough so that polarization in a reactor may be maintainable at close to one hundred percent. It appears that taking account of nuclear spins could lead to fundamental improvements in performance of nuclear fusion reactors.

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TABLE I

P-D Enhancements

E	50	100	300
$\delta^2/ \alpha_0 ^2$	.01	.01	.01
$ \alpha_1 ^2/ \alpha_0 ^2$	.10	.20	.50
E_{11}	.067	.055	.035
E_{00}	2.27	1.85	1.20
E_{10}	$.53 - .25 \sin^2\theta_0$	$.85 - .40 \sin^2\theta_0$	$1.34 - .66 \sin^2\theta_0$
E_{1-1}	$2.25 + .5 \sin^2\theta_0$	$1.84 + .81 \sin^2\theta_0$	$1.19 + 1.32 \sin^2\theta_0$

TABLE II

Cross Sections for Collisional Depolarization

$$\left[r_p = \frac{e^2}{m_p c^2}, \omega_p^2 = \frac{4\pi n e^2}{m}, p_0 = \frac{e^2}{T}, \lambda = \frac{h}{mv} \right]$$

Depolarization Mechanism	Cross Section	For $D(\text{cm}^2)$	For $T(\text{cm}^2)$
<u>by electrons</u>			
spin-orbit	$4\pi g^2 r_p^2 \ln(c/\omega_p \lambda)/3$	1.45×10^{-30}	1.76×10^{-29}
spin-spin	$(11/9)\pi g^2 r_p^2$	$.73 \times 10^{-31}$	$.81 \times 10^{-30}$
quadrupole		7.3×10^{-38}	
<u>by deuterons</u>			
spin-orbit	$(\pi/3)g^2 r_p^2 \ln(c/\omega_p p_0)$	3.7×10^{-31}	4.4×10^{-30}
spin-spin	$(\pi/3)g^2 g_2^2 r_p^2$	1.1×10^{-32}	1.3×10^{-31}
quadrupole		2.3×10^{-31}	
<u>by tritons</u>			
spin-orbit	$(\pi/3)g^2 r_p^2 \ln(c/\omega_p p_0)$	3.7×10^{-31}	4.4×10^{-30}
spin-spin	$(\pi/3)g_3^2 g^2 r_p^2$	1.2×10^{-31}	1.6×10^{-30}
quadrupole		2.3×10^{-31}	