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APPLICATION OF POLARIZED NUCLEI TO FUSION

By

R.M. Kulsrud

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PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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APPLICATION OF POLARIZED NUCLEI TO FUSION

Russell M. Kulsrud

Plasma Physics Laboratory, Princeton University

P.O. Box 451

Princeton, New Jersey 08544

ABSTRACT

It is shown that the d-t fusion reaction can be modified by polarizing nuclear spins. The ways in which this improves reactor performance are mentioned and the feasibility of the process of spin polarization for magnetic fusion is discussed.

MASTER

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I. THE D-T NUCLEAR REACTION

It is known that the cross section for a nuclear reaction depends on the relative orientation of the spins of the nuclei just before they react.¹ In general, in a fusing plasma the spins are randomly oriented with respect to each other (unpolarized) so that the appropriate cross section determining the rate of reactions is an average of the spin-dependent cross section over all relative spin orientations. Because this averaged cross section is less than the cross section maximized over spin direction, it is, in principle, possible to increase the nuclear reaction rate by properly orienting the spins of the nuclei to attain this maximum.² A similar remark applies to the directionality of the reaction products. For an unpolarized plasma the reaction products are emitted isotropically, but different spin orientations lead to specific directional distributions for the reaction products. By polarizing one may thus control this directionality to some extent, and this choice can also produce benefits for the performance of a nuclear reactor.

We illustrate these remarks by reference to one of the most important reactions for nuclear fusion, the deuterium-tritium reaction. This reaction proceeds through a well-defined quantum state of ${}^5\text{He}$ which lies 107 keV in energy above the energy of a free deuteron and free tritium.³ It has even parity and spin $3/2$. One can analyze the quantum states of the free d and t just prior to a nuclear collision into angular momentum states in which the angular momentum is nearly all supplied by addition of the d spin of one and the t spin of one-half. The two angular momentum states have $1/2$ and $3/2$ units of angular momentum. The latter state matches the angular momentum of the resonant state in the compound nucleus and produces a reaction, provided that the coulomb barrier is penetrated. For the other state the chance of the reaction is smaller by a factor of about one hundred and can be neglected.⁴

The spin dependence of the cross section is given essentially by this simple consideration.

The spins of the d and t are defined relative to the confining magnetic field. Let the probabilities for a deuteron to be in a state with magnetic quantum number m be d_m ($m = -1, 0, 1$) and correspondingly let t_m be the probability for a triton ($m = -1/2, 1/2$). Then the cross section for a d-t reaction can be written as^{2,5}

$$\sigma = \sigma_{3/2} (a + 2/3b + 1/3c) , \quad (1)$$

where $\sigma_{3/2}$ is the maximum cross section and

$$a = d_1 t_{1/2} + d_{-1} t_{-1/2}$$

$$b = d_0 \quad (2)$$

$$c = d_1 t_{-1/2} + d_{-1} t_{1/2} .$$

In these equations the probability for parallel alignment is a, for orthogonal alignment is b, and for antiparallel alignment is c. Of course, $a + b + c = 1$. For random orientation of spins $a = b = c = 1/3$ and $\sigma_0 = 2/3 \sigma_{3/2}$. For total polarization along B, $d_1 = t_{1/2} = 1$, $a = 1$, and $\sigma = \sigma_{3/2} = 3/2 \sigma_0$. For fractional alignment, say $d_1 = 1 - \epsilon$, $d_0 = \epsilon$, $t_{1/2} = 1 - \epsilon'$, $t_{-1/2} = \epsilon'$, and $\sigma = (3/2 - \epsilon' - \epsilon/2 + \epsilon\epsilon') \sigma_0$. Further, for orthogonal alignment $d_0 = 1$, and $\sigma = \sigma_0$, while for antiparallel alignment $d_{-1} = t_{1/2} = 1$ and, say $\sigma = 1/2 \sigma_0$. The above cases illustrate the possibilities. The cross section ranges between $1/2 \sigma_0$ to $3/2 \sigma_0$ and it is possible to decrease the cross section by 2 or increase it by fifty percent.

A slightly more complicated analysis gives the directionality of the nuclear reaction products of the reactions, i.e., is the alpha particle and the neutron.⁵ These energies 3.5 MeV and 14.6 MeV are much larger than the kinetic energy of the compound nucleus, so for each reaction the alpha particle and the neutron leave with almost oppositely directed velocities. Thus, we need only consider the angular distribution of one of them, say the neutron. The orbital state of the neutron-alpha particle system must be even, while the spin of the neutron is one-half and that of the alpha particle is zero. Thus, they must be in a $D^{3/2}$ state, the neutron spin being oppositely directed to the orbital angular momentum. The spin state of the compound nucleus can be found from the initial spin states of the d and t. Then, resolving the $3/2$ spin state of the compound nucleus, one finds the angular distribution of the n, alpha state. This gives the differential cross section as

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

where θ is the angle the neutron makes with the magnetic field. The resultant angular distribution of the neutron is symmetric under $\theta \rightarrow \pi - \theta$ so the alpha particle has the same distribution. Thus, for the case of parallel alignment, the relative distribution of intensity is proportional to $\sin^2\theta$ per steradian. The reaction products for the parallel case are emitted roughly perpendicular to B while for the other two cases the relative distribution of intensities is proportional to $1 + 3 \cos^2\theta$ and the emission is primarily along B . If one is concerned about the spin of the neutron as well, one finds that the distribution of spins parallel to B is different from the distribution antiparallel to B and more complicated than Eq. (3). However, it is worth

remarking that for perfect alignment of the d and t, the neutron is totally polarized for $\theta = \pi/2$.

II. DEPOLARIZATION

We now see that by polarizing nuclear spins it is possible to increase the reactivity of a fusing plasma by fifty percent. However, it is important that the polarized plasma remain polarized since there does not seem to be any way to polarize the plasma once it is ionized. Thus, it is necessary in the case of a magnetically confined fusion reactor to polarize the plasma outside the reactor. If the depolarization in the plasma is at all rapid then the mean polarization of the spins would be low and no change in reactivity would be attained.

Therefore, it is important to ascertain what physical processes can lead to depolarization of the plasma. There is a magnetic interaction of the spins with the confining field of the plasma but this is very small. The magnetic moments of the deuteron and tritium are

$$\begin{aligned}\mu_D &= 0.86\mu_N \\ \mu_T &= 5.94\mu_N\end{aligned}\tag{4}$$

where $\mu_N = e/2m_p c = 6 \times 10^{-24}$ ergs/gauss. Thus, in a 10^5 gauss field the difference in the spin states is 2×10^{-6} keV and is even smaller for the deuteron. These energies are far too small to produce any effect on the distribution of spins. Collisions should lead to randomization of spins. However, because the magnetic moments are very small, the collisional rate of depolarization is very small. For example, if the tritons are all initially

polarized in the $1/2$ state, $t_{1/2} = 1$, then one can calculate the rate of depolarization by electrons² as

$$\frac{d t_{1/2}}{dt} = - n_e \langle \sigma v \rangle \quad (5)$$

where

$$\sigma = 200 \left(\frac{e^2}{m_p c^2} \right)^2 = 2 \times 10^{-29} \text{ cm}^2 \quad (6)$$

This is the fastest collisional rate. Summing over v , one finds that the time scale for depolarization at $T_e = 10$ keV, $n = 10^{15} \text{ cm}^{-3}$, is 10^4 sec, which is a very long time. A plasma confined for 10 sec would still have a polarization significantly greater than 99%.

The recent recognition (1982) of this remarkably slow depolarization due to collisions is probably responsible for the burst of interest in polarization as a useful process for fusion. The fact that collisions, whose interaction energy (~ 10 keV) is eleven orders of magnitude larger than the interaction energy of the magnetic moment with the confining field, do not rapidly depolarize a plasma is at first appearance surprising and counter-intuitive. The strong feeling researchers had that polarization could not survive in a hot plasma led them to discount earlier suggestions⁶ that polarization be used to improve the plasma fusion performance.

Other mechanisms that lead to depolarization are magnetic fluctuations, which resonate with the precession frequency of the nuclear spins, and the interaction of the polarized nuclei with surrounding walls.⁵ The question of depolarization by waves is discussed by Pegoraro.⁷

A possible effect of an inhomogeneous field on the depolarization of d has been suggested by Lodder.⁸ The precession frequency of a deuteron is $\Omega_p = \mu B / \hbar = 0.86 \text{ eB} / (2m_p c)$, that is, 86% of its cyclotron frequency. Therefore, if the magnetic field has a shear with scale length L , the deuteron sees a small oscillation in the direction of the field at its cyclotron frequency Ω_{cD} as the deuteron moves in its gyrotron orbit of radius ρ . This near resonance with the precession frequency leads to a small oscillation in spin direction (or state). This oscillation is interrupted by random collisions that affect the gyration orbit and produces a random walk in spin direction, leading eventually to depolarization of the deuteron spin. The time of depolarization τ_L is⁵

$$\tau_L = \frac{2L^2}{v_0 \pi^2} \frac{(\Omega_p - \Omega_{cD})^2}{\Omega_{cD}^2} \quad (7)$$

where v_0 is the rate of pitch angle scattering. In cgs units

$$\tau_L = \frac{6 L_2^2 B_4^2 T_4^{1/2}}{n_{14}} \text{ sec} \quad (8)$$

where L_2 is L in units of 10^2 cm , B_4 is B in 10^4 gauss , T_4 is T in 10^4 eV , and n_{14} is n in 10^{14} cm^{-3} . Taking as typical values $B_4 = 5$, $T_4 = 1$, $n_{14} = 3$, and L_2 is 10, we get 5000 seconds. Thus, under standard conditions this process of depolarization is not important.

On the other hand, wall interactions of the nuclei during plasma recycling are certainly important. The confinement time for a nucleus is much shorter than the time for it to make a nuclear reaction. A typical nucleus may leave the plasma, penetrate the limiter or divertor plate, reside there for tens of milliseconds, and then reenter the plasma. Depending on

conditions at the limiter or on the pumping speed of the divertor, this may happen ten or twenty times before the nucleus undergoes a nuclear reaction, or before it is finally removed from the confinement chamber and repolarized.

If the wall material in which the nucleus resides is metallic, the nucleus quickly becomes depolarized in only a few milliseconds and reenters the confinement region as an unpolarized nucleus. Thus, during one "recycling" time, the plasma will become depolarized.

Greenside, Budny, and Post⁹ have analyzed depolarization rates of hydrogen isotopes in various possible wall materials. They find that if a nonmagnetic material with no unpaired electrons is chosen, the depolarization time of a nucleus during its period in the material can be much longer. An attractive wall material is amorphous graphite for which the depolarization time could be as long as from one to five seconds. This is longer than the total residence time of a nucleus in the wall by a factor of fifty to a hundred. However, a graphite wall in a reactor cannot be treated as pure as it would probably contain many hydrogen isotope nuclei at any one time, and these nuclei can interact with each other. Also, the graphite would suffer damage from neutron bombardment and would gradually become impure. These impurities could also produce depolarization. Some simple experimental tests bolster the conclusions of Greenside, Budny, and Post that pure amorphous graphite (unloaded by hydrogen isotopes) does not rapidly depolarize hydrogen.⁹ Unfortunately, it is difficult to draw conclusions about the amount of depolarization that is produced by wall interactions with amorphous graphite under actual reactor conditions.

III. ADVANTAGES OF SPIN-POLARIZED FUSION

What advantages in reactor performance may we expect if polarizing a large plasma proves feasible? Are these advantages worth the cost and effort of polarization of the plasma?

First, one must distinguish between the cases of d-t fusing plasmas and other "advanced fuel" plasmas. The advantages to be gained by polarizing advanced fuel plasmas is more uncertain, but they appear to be more substantial than those related to d-t fusion.

Second, it is recognized that the gains from polarizing to enhance the cross section a factor of 1.5 are much larger in inertial confinement fusion.¹¹ This is because the nuclear cross section enters to the third power in the required energy of the driver needed to achieve a specified gain. More detailed estimates show that the required energy of the driver may be reduced by as much as a factor of three. The reduction in cost is much more. For this reason spin polarization of the d-t core of the pellet is of considerable interest to the ICF community. On the other hand, the difficulties in achieving polarization of tritium at cryogenic temperatures and keeping it for a sufficient time are also considerable (because of its radioactivity).

Third, the benefits of polarization to magnetic confinement fusion depend on conditions. If the situation is marginal, the gain in benefit from enhancing the nuclear reactivity by 1.5 can translate to a larger gain in marginal situations.¹² For example, one can write the power balance equation for ignition as

$$P_{\text{nuc}} = P_{\text{loss}} + P_{\text{brem}} \quad (9)$$

where P_{nuc} is the nuclear power, P_{brem} is the loss due to bremsstrahlung, and

P_{loss} represents all other losses and is represented by the Lawson parameter nr . Let 1 be close to the ignition temperature for unpolarized plasma and let the required loss be P_{loss} . Then by Eq. (9) the required limit on the loss with polarization P_{loss}' is given by

$$\frac{P_{\text{loss}}'}{P_{\text{loss}}} = \frac{1.5 - b}{1 - b}, \quad (10)$$

where $b = P_{\text{brem}}/P_{\text{nuc}}$ (unpolarized). If $b = 1/2$, then the loss can be twice as great as for an unpolarized plasma. Other marginal situations can be envisioned in which enhancement of the cross section by polarization could make the difference between ignition and nonignition.

Once a working reactor is achieved, polarization could best be employed to make the reactor cheaper. The critical question then becomes, is the reduction in cost less than the cost to polarize the plasma? For a lower limit to the reduction in cost one can assume the total magnetic field is reduced by a factor of the fourth root of 1.5 and the plasma is polarized so that, for fixed plasma beta, the nuclear reactivity is unchanged. This corresponds to a savings of approximately twenty percent in the cost of the magnetic system assuming the cost is proportional to the field squared.¹³ As an example, taking the magnetic system of a reactor to cost about \$200M, the savings is about \$50M. On the other hand, a proposed reactor system has been optimized using polarization and it has been found possible to reduce the size of the reactor by a third.¹⁴ If the reactor core costs \$500M, this would correspond to a savings of \$200M. Thus, a fair figure for the cost saving could be \$100M.

In order to have a basis to estimate the cost of a polarization, one must have a particular method of polarization in mind. Let us consider optical

pumping by a tuned continuous power laser.¹⁵ The number of particles that must be polarized per second depends on whether the wall interaction depolarizes the nuclei. If it does, then each nucleus must be polarized in one confinement time, which we take as one second. A rough value for the number of particles in a gigawatt reactor is 10^{22} particles so that 10^{22} particles/sec must be polarized. On the other hand, if the nuclei can be safely recycled twenty times without loss of polarization at the wall, then the rate is 5×10^{20} /sec. It is the nature of optical pumping that a photon at the resonance wave length of an alkali (say, $8000^{\circ}\text{\AA}$ for rubidium) puts $\hbar$ units of angular momentum into a gas of deuterium or tritium atoms.¹⁵ Since a fully polarized tritium atom has $\hbar$ units of angular momentum while a fully polarized deuterium atom has $3/2 \hbar$ units of angular momentum, roughly $3/2 \text{ eV}$ must be supplied for each elementary polarization process. For the recycled plasma (5×10^{20} /sec) this means that polarizing lasers with powers of 120 watts are required, while for uncycled plasma twenty times this power is required. Currently, a one watt laser costs about \$50,000, so assuming linear scaling in cost, a one hundred watt laser would cost \$5M and twenty times this would cost \$100M. However, it is likely that these costs could be lowered by a factor of five if there is an incentive such as fusion.

It appears evident that the effect of wall interactions on polarization is fairly critical to the practical use of the polarization process for magnetic confinement devices using d-t fusion. If recycling is permitted, it appears fairly certain that polarization can be employed to effect considerable savings in the cost of fusion. Also, it could play an important role in the program to achieve ignition.

IV. PRINCETON EXPERIMENTS

Efforts are being made at the Princeton Plasma Physics Laboratory (PPPL) to develop these optically pumped polarized ion sources.^{15,16} Although sources have been described by Gruebler¹⁷ I should like to describe very recent results at PPPL which are quite exciting. The optical pumping method for polarizing hydrogen is quite old. However, recently, in connection with the possible application of polarization to fusion, an effort has been made to use lasers to polarize hydrogen in quantity. This is made possible by the tunable dye-laser as a source of intense light at the resonant frequency of the rubidium atom. The method is essentially to polarize a small sample of rubidium mixed with a large quantity of hydrogen. The rubidium then transfers its spin to the electron on the hydrogen atom which shares the spin with the hydrogen nucleus.

These experiments were originally carried out by Knize and Happer.^{15, 6} They uncovered two difficulties. The first was rapid depolarization on walls. To overcome this they worked at pressures of 10-100 torr to reduce diffusion to the walls. The experiment was carried out in a small vessel (100 cm³) at a temperature sufficient to vaporize rubidium. The second was that it was difficult to dissociate molecular hydrogen at high pressure so that the densities of atomic hydrogen were only 10^{12} cm⁻³.

In the late fall of 1985 they decided to overcome these difficulties by disassociating the hydrogen in a separate tube from the polarization tube. The walls of the latter were covered with paraffin, which produced much less depolarization. Unfortunately, while the new apparatus was being constructed, funding was terminated and the experiment was halted at the end of 1985. No further work was done in 1986, but at the beginning of 1987, new funding was found and the experiment continued. The apparatus was completed and the

hydrogen density was raised by a factor of ten in the first two months.¹⁸ In March, 1987 the apparatus was improved and hydrogen densities of $10^{15}/\text{cm}^3$ are now expected.¹⁸ It is next planned to polarize the hydrogen with their laser and to attempt to polarize deuterium. It appears that an exciting new source of atomic polarized hydrogen is becoming available.

V. CONCLUSION

Progress in the development of the theory and experiments on polarized fusion has continued. At present the prospects for the employment of spin polarized nuclei to aid the development and use of d-t fusion seem considerably brighter than they at first appeared.

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