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POLARIZED ADVANCED FUEL REACTORS

By

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POLARIZED ADVANCED FUEL REACTORS

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ABSTRACT

The d-^{3}He reaction has the same spin dependence as the d-t reaction. It produces no neutrons, so that if the d-d reactivity could be reduced, it would lead to a neutron-lean reactor. The current understanding of the possible suppression of the d-d reactivity by spin polarization is discussed. The question as to whether a suppression is possible is still unresolved. Other advanced fuel reactions are briefly discussed.

I. INTRODUCTION

The two nuclear reactions of most interest for advanced fuel reactors are the d-d reactions d(dp)t and d(dn)^{3}He, which d represents a deuteron and the d-^{3}He reaction. As in the d-t reaction, which is the principle reaction of interest in nuclear fusion, these advanced fuel reactions also depend on the spin of the reacting particles.[1]

II. THE d-^{3}He REACTION

Let me first consider the ^{3}He(dp)^{4}He reaction. This reaction is the mirror image of the t(dn)^{4}He reaction since interchanging neutrons and protons in the second reaction changes d to d, t to ^{3}He, and ^{4}He to ^{4}He. Like t, ^{3}He has spin 1/2. Therefore, at least to first approximation, one has the same spin dependence of the two reactions.

Both reactions proceed through a resonant state of the corresponding compound nuclei, ^{5}He and ^{5}Li, respectively. These states both have 3/2 units of angular momentum and even parity. However, the ^{5}He state contributes more than 99% to the reaction because ^{5}He has no other resonant states close by. Thus, for the d-t reaction the spin dependence is very simple. The cross section can be increased by a factor greater than 1.49. For the ^{5}Li compound nucleus there is another resonant state within 2 MeV of the principal one, so that the contribution of the principal resonant state to the d-^{3}He reaction is closer to 95% than to 100% of the total cross section. Thus, the maximum enhancement of the cross section is less than 1.5. (The resonant state is 467 keV above that of a free ^{3}He, t pair.)

Ignoring this small change the d-^{3}He reaction is identical to the d-t reaction in all respects. Further, the depolarization rates of a polarized d-^{3}He plasma are also very similar because the magnetic moment of ^{3}He is nearly the same as that of t.

The reaction $^{3}He(dp)^{4}He$ has only charged reaction products so that a thermonuclear reactor based on this reaction alone has no neutrons. This makes it a more desirable reaction than the $t(dn)^{4}He$ reaction because the absence of neutrons makes the reactor much easier to handle and more economical to construct.[2] However, in general, neutrons are not entirely absent because the deuterons are energetic enough to react and the $d(dn)^{3}He$ reaction yields enough neutrons to require some shielding and to produce some activation of the walls surrounding the plasma. If the reactor has both the ^{3}He and the d polarized along the magnetic field, then the spin dependence of the $d(dn)^{3}He$ reaction must be considered.

III. THE D-D REACTION

Unfortunately, the spin dependence of the d-d reaction has not been determined by direct experimental measurements and some controversy surrounds the question. In particular, even the order of magnitude of the d-d cross section for the case in which both spins are aligned is under active debate. For this case, the total spin is two and the state is denoted as the quintuplet state. Originally, it was argued[3,4] that the contribution of this state to the d-d reaction should be much smaller than other states for two reasons. First, the nucleon spins in each d are parallel. If the d spins are parallel, all four spins are lined up. In the final state the spins of nucleons in the ^{3}He nucleus are not lined up so that the spin of one nucleon must flip over. Thus, it was argued that the central nuclear force could not produce a d-d reaction from the quintuplet state. Hence, only the spin-dependent nuclear forces could produce such a reaction. Since these forces are weaker than the central nuclear force, the cross section for the quintuplet state should be much smaller than the unpolarized cross section.

(The central force can produce reactions out of other spin states, such as the state of antialigned d spins where no spin flip is required and the central force produces most of the unpolarized reaction.) The second reason for the reduction is the Pauli exclusion principle that makes it difficult for nuclei to approach each other when the nucleon spins are all parallel.[5]

The argument that the central force plays no role in the reaction from the quintuplet state is not quite correct.[6] The reason is that the ^{3}He nucleus has a 4% mixture of a D state in which the nucleons are all aligned, and the central force can cause a transition from the quintuplet state to this D state plus a neutron with spin in the same direction.

Below is a summary of the evidence for and against suppression by spin polarization.

The first experimental evidence bearing on the problem can be abstracted from a paper of Ad'yasevitch and Fomenko[7] in 1969 on the d(dp)t. They analyzed data, taken at different energies, on the singular distribution of protons from a polarized beam of deuterons impinging on a thin unpolarized target. Assuming that the energy dependence contributed by various channels was only due to variation of the penetrability of the Coulomb barrier, they were able to determine the various matrix elements for the reaction at 290 keV bombarding energy. These matrix elements depended on the initial and final spins, on the orbital angular momenta L, and on the total angular momentum J. The largest contributions came from initial J,L,S = 1,1,1 and 0,0,0. There was a small contribution from the initial state 2,0,2 corresponding to the quintuplet state of interest. Making use of these matrix elements, it is straightforward to calculate the relative cross section of the various spin states and, therefore, the suppression of the d(dp)t cross section achieved by polarizing the spins of the d along the magnetic field. The relative cross section for the quintuplet state, of the proton channel at 290 keV of bombarding energy is found to be a factor of 30 smaller than the unpolarized cross section. This energy corresponds to a center of mass energy of 145 keV. It is of interest that this center of mass energy is the energy at which the bulk of the d-d reactions should occur if the temperature of the d-^{3}He plasma were 50 keV, a figure often mentioned as an appropriate temperature for a d-^{3}He reactor. This suppression refers to the proton channel of the d-d reaction, but it may be presumed that the neutron channel is also suppressed by a similar factor since the d(dn)^{3}He reaction is the mirror image of the d(dp)t reaction.

Although these results appear to give a direct experimental answer to the question of the spin dependence of the neutron production, some caution must be exercised in accepting them. The matrix elements that have been determined empirically are sums of matrix elements corresponding to different nuclear forces. It is therefore possible that the smallness of the contribution from the quintuplet state is produced by a cancellation between either these component matrix elements or interference among different angular momentum states. In this case the cancellation may not persist at other energies so that an appropriate energy average over Maxwellian velocity distributions would yield much smaller suppressions.[8]

The next contribution to the determination of the spin dependence of the d-d reaction was due to Hale and Doolen, who in 1983 calculated the relative cross section for various initial spin states from an R-matrix analysis of all the data bearing on this four-nucleon system.[9,10] Their results are presented in Table I and can be seen to differ considerably from the conclusions drawn from Ad'yasevitch and Fomenko's matrix elements. In fact, from their results one sees that the proton reaction is only slightly suppressed in the quintuplet state at 300 keV. The reason for the discrepancy is not clear. One possible explanation is that the R-matrix analysis makes use of some thick target data in which scattering in the target distorts the time angular distribution and artificially enhances the contribution from the quintuplet state. On the other hand, the assumption by Ad'yasevitch and Fomenko concerning the energy dependence of the matrix elements may be wrong and lead to incorrect matrix elements.

In order to resolve this question Hoffman and Fick in 1984[6] attempted to calculate the cross section from first principles employing a resonating group method. An essential ingredient in their analysis was the inclusion of the 4% D state on the ^{3}He nucleus. They found that the conversion of d-d to n^{3}He can occur by the central force through this D state, and further that the rate of this process was comparable to the rate of unpolarized d-d reactions. The rough implication is that the rate of conversion of d-d to this D state with all nuclei aligned is twenty-five times stronger than the d-d reaction in other states such as the singlet state where no spin flip is needed. The reason for this surprisingly strong effect is not indicated in their paper, although it must represent an important result. The conclusion of their paper is that their calculated results agree well with the R-matrix analysis[10] and that there is no appreciable suppression of the d-d reaction by polarizing in the quintuplet state.

This work was criticized by Liu, Zhang, and Shuy[5] in 1985 primarily on the grounds that the angular momentum of individual nucleons in the ^{5}S d-d channel will not match the angular momentum of the nucleons in the ^{3}He D state. They calculated the rates using a distorted wave Born approximation and found the contribution from this state was suppressed by one or two orders of magnitude, not enhanced. These results were reported last fall. The discrepancy between these two sets of workers is a factor of 10^3 to 10^4 between the contribution from the central force to the d-d quintuplet channel. It is difficult to think that this large discrepancy is due merely to the different methods of calculation.

Zhang, Lui, and Shuy conclude that the principal contribution to the quintuplet d-d channel is from the spin-dependent forces. These are much smaller than the central force that is the main contributor to the unpolarized reaction. Hence, they feel that the d-d reaction can be strongly suppressed (by a factor of at least ten) and that a neutron-free d-^{3}He reactor may be indeed possible if the fuel spin is polarized.

We thus have two votes for suppression -- Zhang, Lui, and Shuy[5] and Ad'yasevitch and Fomenko[7] and two votes for no suppression -- Hale and Doolen[10] and Hofmann and Fick.[6] Each conclusion is based on a different method. Hence, it was impossible to determine from these papers whether a polarized neutron-free reactor is possible.

In table I the relative cross sections for the d(dp)t reaction calculated from Ad'yasevitch and Fomenko's matrix elements[11] are present. We compare these results with those given by Hale and Doolen calculated from the R-matrix analysis. In the table, σ_0 is the unpolarized cross section and σ_{ij} is the cross section when one deuteron has a magnetic quantum number m_s = i and the other has m_s = j. The ratio σ_{ij}/σ_0 is the enhancement of the d-d reactivity. The values at center of mass energies different from 145 keV are derived by assuming that the energy dependence of the matrix elements is proportional to the penetration probability of the Coulomb barrier.

The Hale-Doolen results are underlined and have been averaged over angle. E_{cm} represents the center of mass energy. Only the σ_{11} and σ_{00} cross sections apply to a thermal situation, while σ_{10} and σ_{1-1} correspond to beamdriven systems. The angle between the relative motions of the deuterons and the magnetic field is θ.

In Table I one sees the large discrepancy in the results for the quintuplet state cross section and the corresponding suppression of the d-d reactions. It is probably necessary to perform a direct experiment to resolve this discrepancy.

If instead of suppression one wishes to enhance the d-d cross section as in a d-d reactor or in a catalyzed d-d reactor, one should polarize the deuterons in the m = 0 state. The corresponding cross sections are predicted to be enhanced by as much as a factor of two at lower energies, based on the extrapolation of the Ad'yasevitch and Fomenko results. Again the enhancement is not borne out by the R-matrix calculations. Further, it should be noted that at the energies of interest for a d-d reactor E_c(keV)) ≈ 150, even the first enhancement is reduced.

IV. OTHER ADVANCED FUEL REACTIONS

Finally, it is possible to modify other advanced fuel nuclear reactivities. A possible reaction of interest to fusion is the $^6Li(p,{}^3He)^4He$ reaction. It proceeds through a $5/2^-$ resonance state of ^7B_e. Since ^6Li has spin one, it can be shown that by polarizing the spins of p and ^6Li along the confining field the polarized cross section is fifty percent larger than the unpolarized cross section.

Similarly, the p ^{11}B reaction proceeds through a 2^+ resonant compound state of ^{12}C. Its cross section can be enhanced by 14/9 ≈ 1.56 by polarizing the spins of p and ^{11}B parallel to the confining field.

V. CONCLUSION

Of all the possible benefits from spin polarizing the fusion plasma, the most attractive would be the suppression of neutrons to make a nearly neutron-free reactor. It is unfortunate that nuclear physics is not able at this time to tell us definitely whether this is possible. It is hoped that new experiments will lead to a resolution of this question.

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TABLE I

E_c(keV))	σ_{11}/σ_0	σ_{00}/σ_0	σ_{10}/σ_0	σ_{1-1}/σ_0
25	0.067 1.15	2.27 1.17	$0.53-0.25\ \sin^2\theta$ 0.914	$2.25 + 0.5\ \sin^2\theta$ 0.933
50	0.055 1.03	1.85 1.04	$0.85-0.4\ \sin^2\theta$ 0.98	$1.43-0.66\ \sin^2\theta$ 0.99
150	0.035 0.933	1.20 0.93	$1.34-0.66\ \sin^2\theta$ 1.04	$1.19+1.32\ \sin^2\theta$ 1.03

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