Fusion of Polarized Deuterons

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The nuclear physics aspects of the d-d reactions initiated by low-energy polarized deuterons are discussed. It is shown that the use of polarized deuterons does not suppress the fusion of deuterons with deuterons and hence does not suppress neutron production. Therefore a recently proposed "neutron-free" d-^{3}He fusion reactor is unlikely to work.

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A recent Letter[1] proposed to improve the performance of thermonuclear fusion reactors by injection of fuel atoms whose spins are polarized relative to the plasma confining field. It is indicated that polarization of nuclei in a plasma is maintained with a probability near 100% during the lifetime of the nuclei in the reactor, including possible recycling (see also, however, Lodder[2]). As demonstrated very recently nuclear-spin-polarized fuel can be used in an inertial fusion reactor too.[3]

A nuclear-spin-polarized plasma in general allows the increase or decrease of nuclear reaction rates and/or the change of the direction of the emission of reaction products. A "neutron-free" d-^{3}He fusion reactor[4] might be possible if the neutrons from the d-d fusion could be suppressed considerably. It was argued that this can be achieved by use of deuterons with spins in the direction of the plasma confining field. But, whereas predictions of the influence of nuclear polarization on reaction rates are easy to make for d-^{3}H or d-^{3}He fusion, they are at present controversial for d-d fusion because of the complexity of the reaction. With $\sigma_{m,m'}$ denoting the d-d fusion cross section for spin states m and m' of both deuterons and σ the total fusion cross section, the predictions for $\sigma_{1,1}/\sigma$ range from around 1 to about 0 for energies of interest ($E_{\text{c.m.}} \approx 20$ keV).[4] The complexity of the reactions $d(d,p)^3$H and $d(d,n)^3$He stems from the extraordinarily large number of matrix elements (ME) entering their description even at lowest energies. On one side, three channel spins $S=0,1,2$ may contribute, and on the other side, the structure of the ^{4}He compound nucleus[5] just above the d-d threshold causes, even at center-of-mass energies below 50 keV, the P waves and thus the $S=1$ channel spin to contribute significantly to the reaction cross section.[6] At low energies usually the angular momenta in the entrance channel are restricted to the S and P waves ($l=0,1$) by barrier penetration arguments. Nevertheless, despite these restrictions in general many more ME's enter the analysis than can be determined even from experiments with polarization observables.

The cross section $\sigma_{1,1}$ is intimately connected with the ME's with channel spin $S=2$. Their unambiguous determination is prevented by the fact that the contribution of the $S=2$ ME's often can hardly be distinguished from that of a P-wave ME with channel spin $S'=0$ in the exit channel. Since the early days of theoretical considerations on the d-d reactions,[7,8] $S=2$ ME's were assumed to be small on the basis of two rather weak arguments: To initiate a reaction a close approach of the deuterons is required which does not happen in the $S=2$ state because of the Pauli exclusion principle. Furthermore, for the $S=2$ state a change of the channel spin has to occur which is generally assumed to be weak. An analysis with this assumption led to a value of around 1:15[1] for $\sigma_{1,1}/\sigma$, whereas an R-matrix analysis[9] which includes all available tabulated data arrives at a value of around 1:1.

Nuclear reaction theories on which most of the analysis in the past relied (e.g., Refs. 7 and 8) were rather rudimentary as compared to modern theories which rely on the capability of running complex computer codes.[10] It is the purpose of this Letter to use such calculations to answer the question on the $S=2$ contribution to the reaction $d(d,n)^3$H at low energies and to provide support for further analysis of d-d reaction data.

The calculations were performed in the framework of the refined resonating-group model[10] which allows one to take into account simultaneously many binary fragmentations and coupled channels.

The structures $p+{}^3H$, $n+{}^3He$, and $d+d$ were considered explicitly. The closed deuteron breakup channels were approximately taken into account by channels formed with the physically unbound d. However, omitting these channels does not modify the results discussed below. All angular momenta were restricted to $l \leq 3$, thus limiting the number of ME's to be calculated to 23. In extension of an earlier calculation[11] of the $A=4$ system in ${}^3H$ and ${}^3He$, a D-state admixture of some 4% was allowed in order to reproduce all particle thresholds within 50 keV. As a result of computer time limitations D-state admixture could not be allowed in both of the deuterons. The good reproduction of the particle thresholds is the main improvement of these new calculations as compared to the earlier ones.[11] In the calculations two different potentials are employed, a standard potential (called S)[12] which was used with great success from $A=4$ to $A=7$ and a potential (called T)[13] especially tailored to describe the $A=4$ system. It should be mentioned, however, that both of these potentials were developed to describe the d, ${}^3H$, and ${}^3He$ without D-state admixtures.

For the lowest and highest center-of-mass energies considered in the calculations, Table I lists the modulus of the ME's for the reaction $d(d,n){}^3He$ for both potentials. ME's not listed are at least an order of magnitude smaller than those listed. An inspection of the results for 20 keV shows clearly that the $S=2$ ME's are of the same size as the $S=0$ and $S=1$ ME's. Even though details of the calculations may change these results both potentials employed give the same trend. Going from lower to higher energies we see that the importance of the P- and D-wave ME's increases, which reflects the reduced importance of the Coulomb barrier at higher energies.

In order to check the theoretical results against experimental ones the upper part of Fig. 1 shows a comparison of the calculations with the measured cross sections σ[14] and the anisotropy factors C_2/C_0 of the angular distributions[15] for the $d(d,n)$ reaction $[\sigma(\theta)=C_0+C_2P_2(\cos\theta)+\ldots]$. The calculations are without any normalization factor. In particular, at the lowest energies which are the most important ones for fusion the experiments are described fairly well. In the lower part of Fig. 1 the predictions for the attenuation factor $\sigma_{1,1}/\sigma$ are displayed as a function of the center-of-mass energy. Both potentials give similar results. The attenuation $\sigma_{1,1}/\sigma$ is in the vicinity of 1 at low energies and decreases smoothly with energy. This reflects the large contributions of $S=2$ ME's at low energies and the increasing importance of P waves at higher energies. It should be mentioned also that for $\sigma_{0,0}/\sigma$ values around 1 are predicted. Predictions from an R-matrix analysis[9] including all data available in numerical form for the $d(d,n)$ reaction up to 1982 agree very well with these calculations. Thus two completely independent approaches predict attenuation factors around 1, and only predictions based on the assumption that the $S=2$ ME's vanish disagree necessarily.

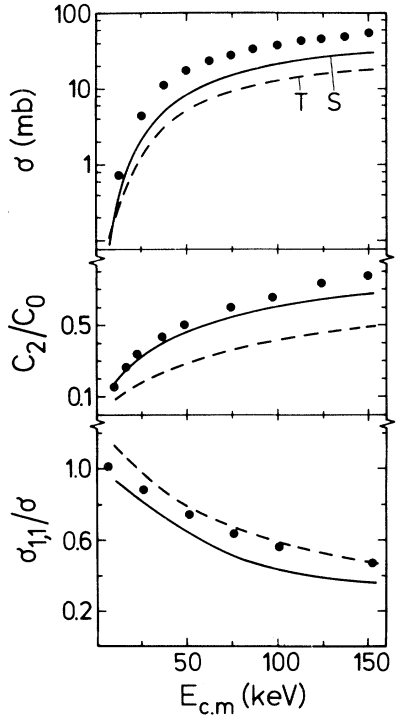

FIG. 1. Excitation functions of the total reaction cross section σ, of the anisotropy of the angular distributions C_2/C_0, and of the attenuation $\sigma_{1,1}/\sigma$ as a function of center-of-mass energy for the reaction $d(d,n){}^3He$. For σ and C_2/C_0 the points are data (Refs. 14 and 15, respectively), whereas for $\sigma_{1,1}/\sigma$ the points stem from an R-matrix analysis (Ref. 9). The solid and dashed lines are the results of calculations with two different nucleon-nucleon potentials, set S (Ref. 12) and set T (Ref. 13), respectively.

The calculations show clearly that below 150 keV all possible S and P waves and one particular D wave contribute to the d-d reactions (Table I). Restricting our consideration to those ME's, the ME's with channel spin $S=2$ affect the analyzing powers for polarized deuterons characteristically. For vanishing ME's with $S=2$ the angular distributions of T_{20} and T_{22} (A_{zz} and A_{xx-yy}) have to be symmetric around 90° and iT_{11} and T_{21} (A_y and A_{xz}) have to vanish at 90°. An inspection of the experimental

TABLE I. Absolute values of matrix elements $\langle LS|J^\pi|L'S'\rangle$ for the reaction $d(d,n)^3$He for two different nucleon-nucleon potentials [set S (Ref. 12) and set T (Ref. 13)].

$\langle LS\|J^\pi\|L'S'\rangle$ \ c.m. energy	20 keV S	20 keV T	140 keV S	140 keV T
$\langle 00\|0^+\|00\rangle$	0.36×10^{-2}	0.36×10^{-2}	0.27×10^{-1}	0.24×10^{-1}
$\langle 02\|2^+\|20\rangle$	0.22×10^{-2}	0.23×10^{-2}	0.19×10^{-1}	0.18×10^{-1}
$\langle 02\|2^+\|21\rangle$	0.33×10^{-2}	0.34×10^{-2}	0.28×10^{-1}	0.25×10^{-1}
$\langle 11\|0^-\|11\rangle$	0.38×10^{-2}	0.21×10^{-2}	0.63×10^{-1}	0.30×10^{-1}
$\langle 11\|1^-\|11\rangle$	0.35×10^{-2}	0.40×10^{-2}	0.56×10^{-1}	0.56×10^{-1}
$\langle 11\|2^-\|11\rangle$	0.23×10^{-2}	0.04×10^{-2}	0.38×10^{-1}	0.07×10^{-1}
$\langle 20\|2^+\|20\rangle$	0.04×10^{-2}	0.04×10^{-2}	0.16×10^{-1}	0.16×10^{-1}

results, in particular of the contour diagrams of the most recent experiment,[16] reveals clearly that these requirements are not fulfilled, even at the lowest center-of-mass energy (30 keV) investigated in this experiment. Hence ME's with $S=2$ contribute to the d-d reaction in a manner opposite to previous assumptions (see Ref. 4). Nevertheless, a careful and detailed study of deuteron analyzing powers below 30 keV and also of $\sigma_{1,1}$—if possible at all—is very desirable.

To finish this Letter a hand-waving argument may elucidate why the $S=2$ channel spin contributions are much larger than expected by the simple arguments given earlier. The answer lies in the D-state component of ^{3}He (and ^{3}H) which was neglected previously. As in the deuteron the nucleon-nucleon tensor force generates a certain amount of D-state component in ^{3}He (and ^{3}H). In this configuration the three nucleons in, e.g., ^{3}He have parallel spins. Hence, the $S=2$ d-d state can easily decay into this configuration via the strong central forces, thus leading to the large ME's with $S=2$. Model calculations[11] without a D-state component in ^{3}He and ^{3}H gave ME's with $S=2$ reduced by a factor of 3 to 10.

Summarizing, it is fair to state that a "neutron-free" fusion reactor based on the attenuation of neutrons from the d-d reaction by the use of polarized deuterons is very unlikely to work because of nuclear physics reasons. The arguments presented here are based on theoretical calculations, on a comparison with data,[16] and on an R-matrix analysis[9] of all data.

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