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AUTHOR(S).
H. M. Hofmann, Inst. for Theoretical Physics, Erlangen, W. Germany
G. M. Hale, T-2
R. Wolker, Inst. for Theoretical Physics, Erlangen, W. Germany

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NUCLEAR PHYSICS ASPECTS OF POLARISED FUSION*

H. M. Hofmann
Institute for Theoretical Physics, Erlangen, W-Germany and
Los Alamos National Laboratory, Los Alamos, USA

G. M. Hale
Los Alamos National Laboratory, Los Alamos, USA

R. Wölker
Institute for Theoretical Physics, Erlangen, W-Germany

ABSTRACT

Handwaving arguments stimulated the idea of a neutron-free fusion reactor via the $^3He(d,p)\alpha$ - reaction by polarising deuterons in the $S = 2$ state. We give counter-arguments why the neutron-producing competing d - d reaction will not be suppressed in this way. The existing d - d reaction data allow no definite conclusion and theoretical studies gave controversial answers. We present an R-matrix analysis of all numerically existing $A = 4$ data and a microscopic calculation of that system employing a realistic NN-interaction. The results of both methods agree almost perfectly for the $S = 2$ matrixelements and predict no suppression. Additionally we discuss why the controversial DWBA approach is inapplicable at these low energies.

INTRODUCTION

During the last years the idea of using polarised particles in a fusion device[1] aroused great enthusiasm, because the break-even point of gaining energy seemed to lie just around the corner[2,3]. Especially the fusion of deuterons and ^3He seemed to be a very promising reaction[2] since it produces no neutrons and offers the possibility of direct conversion because only charged particles participate in the reaction.

In a plasma, however, also the deuterons fuse by themselves via $^2H(d,p)T$ and $^2H(d,n)^3He$. At energies relevant in a fusion reactor the cross sections of the d-d reactions exceed the d-^{3}He one[3,4]. An early handwaving argument[5] predicted that the competing d-d reactions will be suppressed if both deuteron spins were parallel ($S = 2$) since a nucleon spin has to flip and furthermore the nucleons in the entrance channel are in a Pauli-forbidden state because at these low energies

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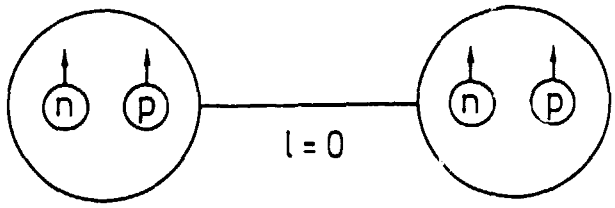

Figure 1
Diagram of the two (S-state) deuterons with spin $S = 2$ and relative orbital angular momentum $L = 0$ demonstrating that this state is Pauli forbidden, if the deuterons come near to each other.

two deuterons are predominantly in an S-state, see fig. 1. Thus the use of polarised deuterons was to improve the performance of a fusion reactor in two ways, first the advantages[3)] in the standard fusion reactions and second the suppression of the competing d-d reaction. Whereas the merits of using polarised particles in the T(d,n)α reaction are well understood[3)] and "solely" technical problems are left[3)], poses the d-d reaction still severe nuclear physics problems. Contrary to the d-T reaction, where only S-waves contribute dominated by a $J^{\pi} = 3/2^{+}$ resonance in the compound system[6)] with possible small contributions[7)] from the $1/2^{+}$-channel, the d(d,n)^{3}He and d(d,p)T reactions are even at very low energies extremely complex: In the compound nucleus ^{4}He there exist broad overlapping resonances[8)] of different spin and parity, none of which dominates; even at center-of-mass energies below 50 keV P waves contribute significantly to the reaction cross section[9)] and three channel spins $S = 0$, 1 and 2 may contribute thus leading to an extremely large number of matrix elements (ME) necessary for the analysis. Because of these unresolved problems we will concentrate our considerations in the following mainly to the d-d reactions.

Restricting at low energies the angular momenta in the d-d entrance channel to S and P waves by barrier penetration arguments, results in a total number of 7 ME, see table 1, much too many to be determined from experiments even with polarisation observables. To gain any predictive power one had to rely on theoretical arguments to reduce[10,11)] the number of ME: All spin-flip ME were assumed to be small due to the weakness of the spin-dependent nucleon-nucleon forces; besides this, the $S = 2$ ME were believed to be small because of the Pauli exclusion principle. Ad'yasevich et al[12] were able to fit their early $^2H(d,p)$ analyzing-power data at $E_d = 320$ keV under the above assumption, yielding suppression factors[2] in excess of 10 for the reaction using polarised deuterons compared to unpolarised ones. An early R-matrix analysis[13] of all tabulated data, however, arrived at a ratio of about 1. A first microscopic calculation[14] employing effective nucleon-nucleon forces corroborated the R-matrix results yielding $S = 2$ ME of the same order of magnitude as $S = 0$ ME. These results were, however, very sensitiv[14] to D-state admixtures in T or ^3He. Both theoretical approaches had some weak points, the R-matrix analysis did not include the data of ref. 12, and the microscopic calculation did not allow for D-state admixtures in the deuterons. Furthermore the use of effective forces restricted the validity of the microscopic calculation to energies around and below the d - d threshold. When Liu[15] and coworkers presented a DWBA of the $^2H(d,n)^3He$ reaction claiming again small $S = 2$ ME we started new calculations to settle the above discrepancies.

DESCRIPTION OF THE CALCULATION

The resonating group calculation of ref. 14 showed the sensitivity of the $S = 2$ ME to the D-state admixture in ^3He and ^3H. Because of computer-time limitations, no effort was made to include D-state admixture also in the two deuterons of the entrance channel. In addition the effective nucleon-nucleon interaction used, would bind a deuteron with D-state admixture by more than 5 MeV, resulting in a wrong order of the thresholds. In order to get the thresholds correct and the binding energies of all particles reasonable, we had to use a realistic nucleon-nucleon force, at the expense of a much more complicated wave function for all particles, because of the soft-core of the force[16]. At least 3 Gaussian width parameters are needed to bind the deuteron at all. Analogously, we used 3 Gaussian width parameters for each internal coordinate in ^3He and ^3H (details will be published elsewhere). With these wave functions we found binding energies for deuteron, ^3He and ^3H of 1.675, 6.383 and 7.038 MeV respectively; thus reproducing the thresholds reasonably well. More complex components of the ^3H/ ^3He wave function, like D waves on both coordinates, which would give some 300 keV more binding energy had to be neglected because of computing time limitations. On the other hand, we do not expect, that these components would modify our results significantly.

As discussed in ref. 14, S = 2 ME are possible without any spin-flip due to D-state admixtures. Since this is the crucial argument besides our numerical microscopic calculation, we give it here once more for the case of a D-state admixture in the deuterons. In fig. 2 the interference is shown of one deuteron in the D-state and the other in the S-state with parallel total angular momentum. Noting that the spins of the individual nucleons are opposite in the two deuterons, it is obvious that this state feels no Pauli repulsion and the central part of the nucleon-nucleon force can mediate a transition to the exit channel. The orbital angular momentum $l_f = 2$ in the exit channel does not suppress appreciably the ME because of the Q-value of about 4 MeV.

The calculation itself follows along the lines of ref. 17. From the multichannel scattering wave function, determined by a variational principle we calculate the reactance matrix K, details are given elsewhere[18,19]. The K-matrix is related to the S-matrix, which we parametrize as $S_{ab} = \eta_{ab} \exp(2i\delta_{ab})$.

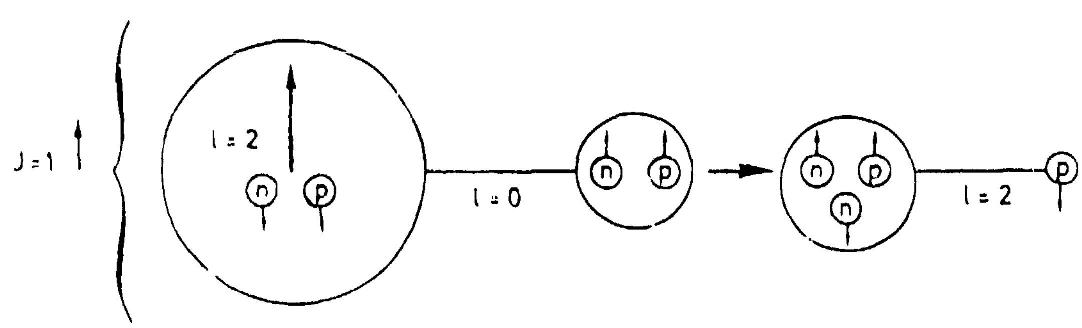

Figure 2
Diagram of two deuterons, one in the D-state the other in the S-state, with spin S = 2 and relative orbital angular momentum l = 0 demonstrating that this state is Pauli allowed and that a transition to the T - p channel can be mediated by central forces.

In fig. 3 - 4 phase shifts for various channels are displayed over a wide energy range and compared to existing analysis. From the overall good agreement, we conclude that we can trust the calculation also in the neighbourhood of the d-d threshold, the energy range vital to the fusion process.

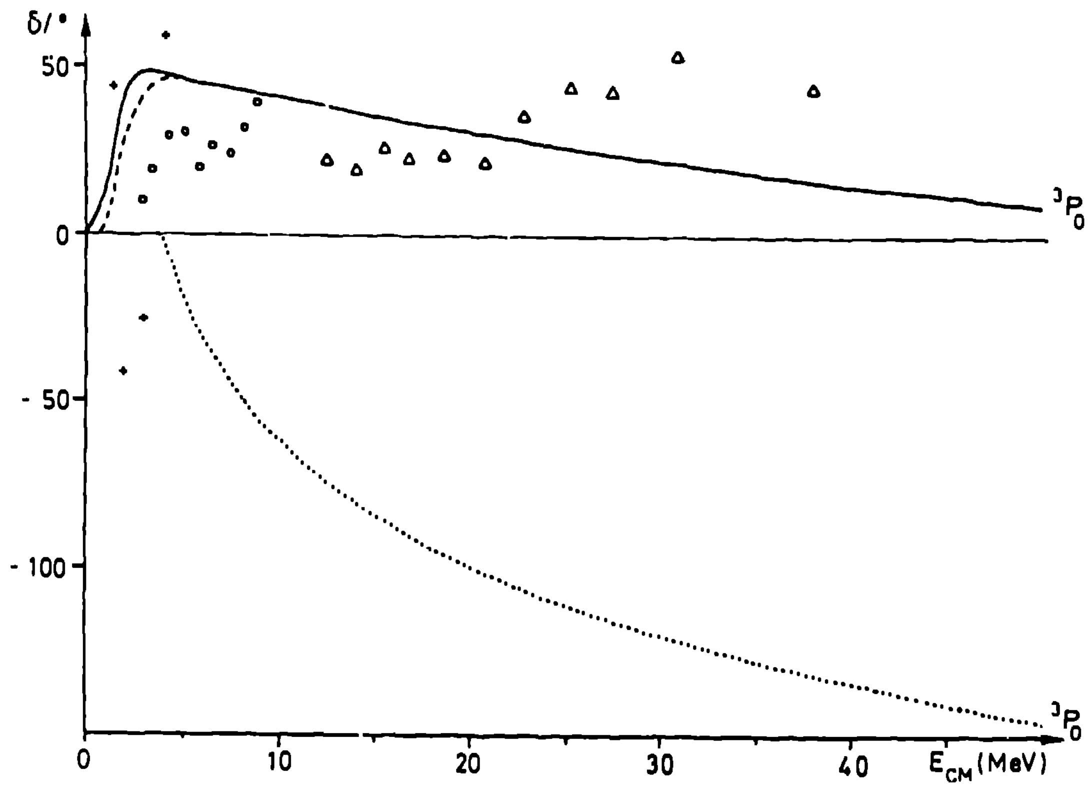

Figure 3
Diagonal phase shifts for $J^\pi = 1^-$ for the T - p - (full), the ^{3}He - n (dashed) and the d - d - channel (dotted). The data are an R-matrix analysis[13,21] (crosses) and phase shift analysis[22] of T - p scattering (circles) and a phase shift analysis[20] of ^{3}H-n scattering (triangles).

In table 1 we give all S and P wave ME for the ^{2}H(d,p)^{3}H-reaction at 20 keV center-of-mass energy which we have calculated till now and compare them to the results of ref. 14 and an R-matrix analysis[23]. At other energies the agreement of the parameter free RGM-calculation and the R-matrix analysis is as good as shown in table 1. One feature common to all columns, is the tiny spin flip ME $^3P_1 \rightarrow {^1P_1}$, which is in accordance with previous arguments. For the $^1S_0$ channel, we quote no results, because till now our calculation underbinds the ^{4}He ground state and also the first excited 0^+-state, therefore the calculated phase shifts in this channel cannot reproduce the experimental ones. Further structures like deuterons in relative D-wave, which increase the binding energy, have been omitted till now because of computing time limitations.

In table 2 we compare the $J = 2^+$ S-matrix elements calculated microscopically to the R-matrix analysis of the experimental data. The agreement of the whole S-matrix is almost perfect; especially for the reaction ME relevant to the fusion process.

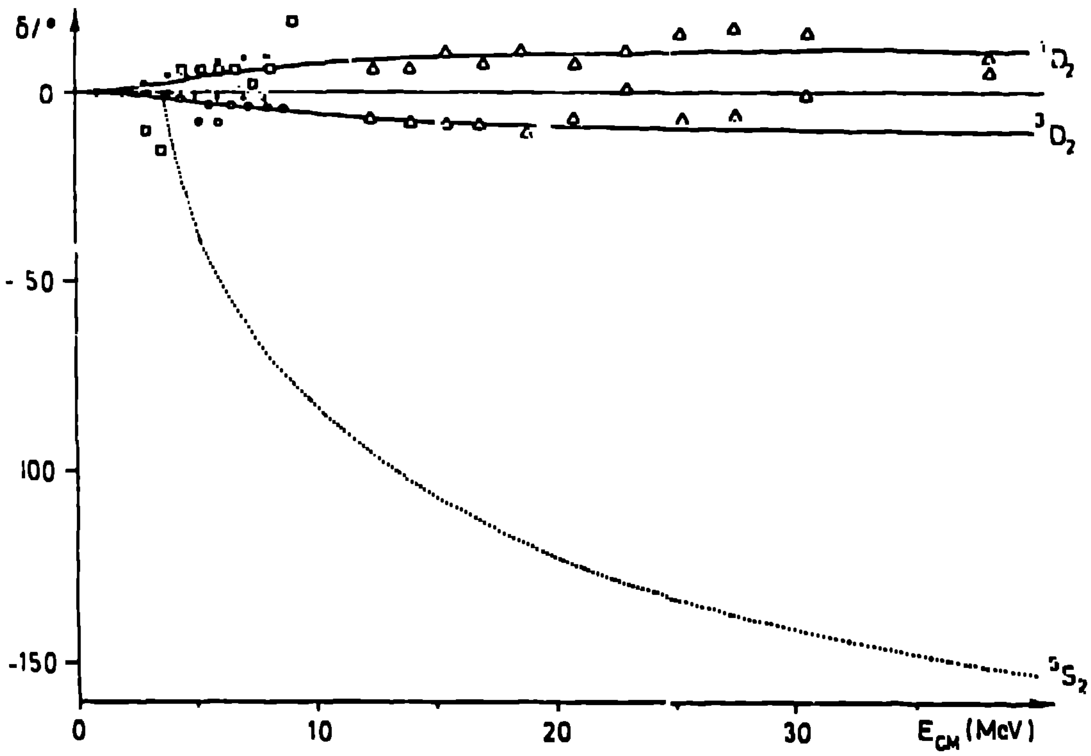

Figure 4
Same as fig. 3, but for $J^\pi = 2^+$. As in many cases, for the $^3D_2$ and $^1D_2$ channels the T - p and ^{3}He - n phase shifts agree almost completely.

DISCUSSION

The possibility of a neutron free fusion reactor on the basis of the $^3He(d,p)\alpha$ - reaction is closely related to the smallness of the S = 2 ME of the competing d-d reactions. In the previous section we demon-

$< L_i S_i \mid J^\pi \mid L_f S_f >$	R-matrix ref. 23	RGM[14] effective interaction	RGM realistic interaction
$< 00 \mid 0^+ \mid 00 >$	0.60	0.36	
$< 02 \mid 2^+ \mid 20 >$	0.26	0.22	0.28
$< 02 \mid 2^+ \mid 21 >$	0.45	0.33	0.59
$< 11 \mid 0^- \mid 11 >$	0.06	0.38	0.35
$< 11 \mid 1^- \mid 10 >$	0.01	0.00	0.00
$< 11 \mid 1^- \mid 11 >$	0.47	0.35	0.78
$< 11 \mid 2^- \mid 11 >$	0.12	0.23	0.66

Table 1
Comparison of matrix elements $< L_i S_i \mid J^\pi \mid L_f S_f >$ for the reaction $H(d,n)^3He$ for $E_{CM} = 20$ keV. All ME have to be multiplied by 10^{-2}.

channel \ channel		T + p		^{3}He + n		d + d
		$^3D_2$	$^1D_2$	$^3D_2$	$^1D_2$	$^5S_2$
T + p	$^3D_2$	0.999/0.997 -1.5/-0.1				
	$^1D_2$	0.003/0.004 56/60	0.987/0.977 2.7/4.8			
^{3}He + n	$^3D_2$	0.006/0.062 -49/-45	0.005/0.008 -51/-39	0.999/0.997 -1.2/0.1		
	$^1D_2$	0.005/0.008 -50/-39	0.159/0.210 -47/-41	0.003/0.004 56/61	0.987/0.977 2.2/3.9	
d + d	$^2S_2$	0.051/0.050 48/43	0.024/0.029 43/47	0.049/0.045 -48/-47	0.023/0.026 -43/-42	0.997/0.997 -4.4/-5.8

Table 2
Comparison of the RGM calculation and the R-matrix analysis for the $J^\pi = 2^+$ S-matrix corresponding to $E_{CM} = 140$ keV in the d-d channel. For each channel combination we give in the first line the modulus of the S-matrix element in the form RGM-calculation / R-matrix analysis and in the second line the phase shift in degrees in the same form.

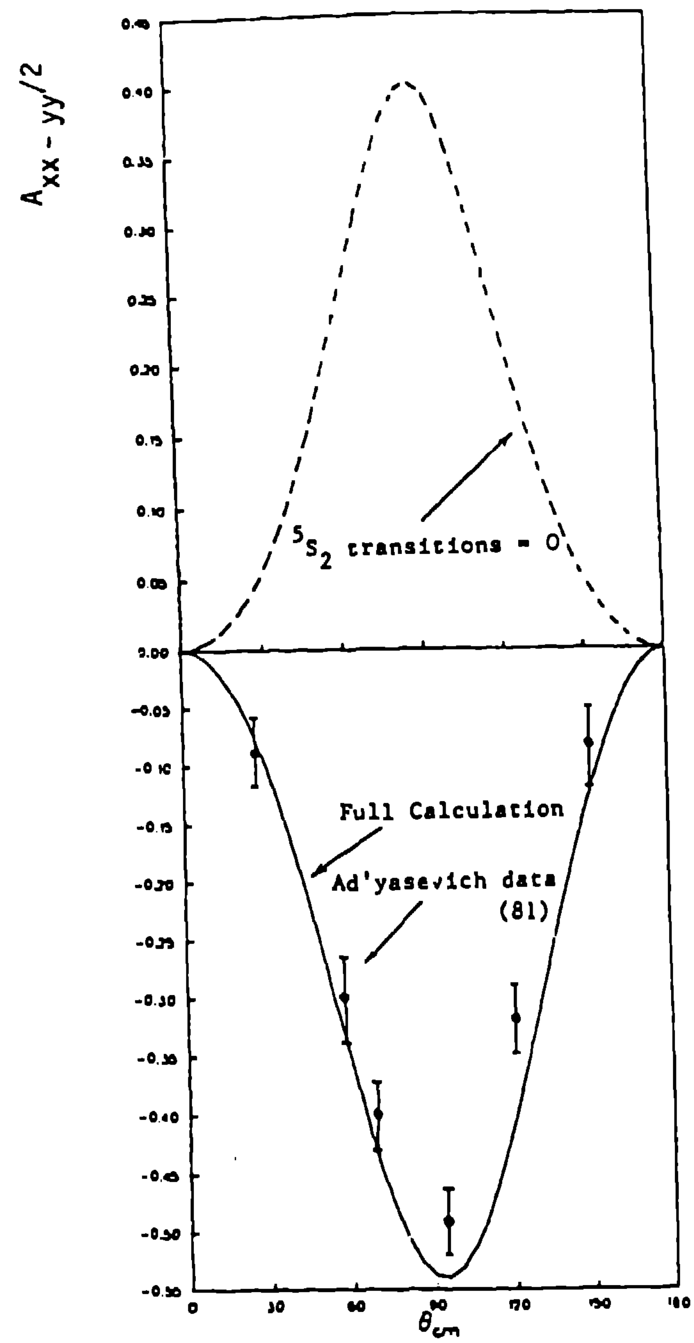

Figure 5
R-matrix calculations are displayed for $A_{xx-yy}/2$ for the reaction d(d,p)T at 50 keV both with (solid curve) and without (dashed curve) the $^5S_2$ transition. One sees that the low-energy data of Ad'yasevich require the presence of dominant $^5S_2$ transitions.

strated the close agreement between R-matrix analysis of the data and the microscopic calculation for those ME. Fig. 5 demonstrates that existing data can only be reproduced if sizeable S = 2 ME are taken into account[21]. It should be noted that the R-matrix analysis does not include the data of ref. 12, but they are beautifully reproduced by the full calculation. The R-matrix analysis and the RGM calculation supplement each other extraordinary well, because one is just a parametrisation of existing data, the other starts from a realistic NN-interaction and contains no free parameter, yet both calculation agree totally in the S-matrix elements vital for polarised fusion.

Even though the criticisms of Liu et al[15] based on DWBA calculations no longer apply to the work reported here we want to give some further arguments: The D-state probability of 4 - 6 percent gives a reduction factor of 5 - 4 for the $S = 2$ ME compared to $S = 0$ ME, but in the 0^+-channel there is the ^4He ground state (and the first excited state) below the d-d threshold onto which the scattering wave function has to be orthogonal. Hence, the ME is suppressed by the necessary node, which shows up in the repulsive $^1S_0$ d-d phase shift[17]. Since for the $S = 2$ wave functions there is no node, the ME is enhanced relative to $S = 0$ ME leading to the same size for both MEs.

In ref. 14 the D-state in the ^3H / ^3He wave functions consisted of an S-state deuteron and a valence nucleon in relative D-state. Whereas the D-state of Liu[15] contains a D-state deuteron and a valence nucleon in relative S-state. Such a type of D-state is also used in the present work. Omitting the D-state admixtures in the deuterons we can thus simulate the DWBA calculation with the result that ME Nr. 3 of table 1 is almost unchanged, whereas ME Nr. 2 is down by about a factor 10. Because of the similarity of the ^3D and ^1D wave functions, such a result is not possible in first order DWBA, thus adding to the arguments against the use of DWBA near the d - d threshold already given[24].

As long as there are no new experiments contradicting the R-matrix predictions, we see no possibility for a neutron free fusion reactor.

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