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DETERMINATION OF THE TRANSITION AMPLITUDES OF THE D(d,n)$^3$He AND D(d,p)$^3$H REACTIONS FOR $E_d \leq 500$ keV

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Abstract - An analysis of all available experimental data of the mirror fusion reactions D(d,n)$^3$He and D(d,p)$^3$H below 500 keV is presented. Account is taken of S-, P-, and D-waves in the input channels of the reactions. All 16 participating transition amplitudes are obtained by a fit to the experimental data. In accordance with refined resonating group calculations no suppression of quintet entrance-state transitions and therefore no neutron suppression in "polarized fusion" can be derived.

1 - INTRODUCTION

Due to the unusual properties of the two D-D fusion reactions D(d,n)$^3$He and D(d,p)$^3$H and in view of astrophysical and possible fusion energy applications the knowledge of the transition matrix of these reactions is of special interest. For these two reactions a large body of experimental data of different types of observables exists at projectile energies below 500 keV. Most of the data result from experiments with incident polarized deuterons on unpolarized targets. For the investigation of special questions, such as the possible suppression of D-D neutron production in fusion energy devices, polarization correlation or polarization transfer measurements would be preferable but have not been done yet. The task of extracting the transition matrix from existing data meets the difficulty that 16 transitions have to be considered since D-waves appear already significant above 150 keV.

Up to the present different approximative approaches to a theoretical description of the D-D reactions have been undertaken. These include a simple potential model /1,2,3/ where the energy dependence of the transition amplitudes $T_{\text{BA}}(E)$ is assumed to be governed solely by Coulomb and centrifugal barriers in the entrance channel. The present calculations are based on this model. Furthermore there are an R-matrix parametrization approach /4,6/, DWBA calculations /7,8/ and resonating group (RRGM) calculations /9/. Only recently microscopic 4-body (Faddeev) calculations have been performed for the four-nucleon system though with very limited complexity and without taking Coulomb forces into consideration /10/.

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2 - METHOD

In this study all relevant transition matrix elements for both reactions have been determined by a straightforward least-squares fit on the basis of all experimental data /11,12/ (for a discussion of the experimental situation see, e.g., ref. /13/). Most of the information was obtained from experiments with polarized particles including recent extensive measurements of the vector and tensor analyzing powers for both reactions /12, E.Pfaff, private communication/. In the above-mentioned potential model the transition amplitudes $T_{\beta\alpha}(E)$ factorize like:

\[ T_{\beta\alpha}(E) = C_{\tau\alpha}(E) \tilde{T}_{\beta\alpha} \]

The amplitudes $\tilde{T}_{\beta\alpha}$ do not depend on energy and the Coulomb functions $C_{\tau\alpha}(E)$ are calculated for an interaction radius of 7 fm /1/. The absolute values of the penetrabilities for incoming S-, P-, and D-waves are shown in figure 1.

![Penetrabilities](image)

Fig. 1 - Absolute values of the penetrabilities $C_{\epsilon}(E)$ for $\ell = 0, 1, 2$

The experimental data enter the calculations as Legendre expansion coefficients $a_{\ell}^i(E)$ of the angular distributions of the observables $A^i(E,\theta)$:

\[ A^i(E,\theta) \sim \sum_{\ell} a_{\ell}^i(E) P_{\ell}^i(\cos \theta) \]

The observables are bilinear functions of the transition amplitudes:

\[ A^i(E,\theta) \sim \sum_{mn\ell} b_{mn}^i \left( \text{Re} \left( T_{mn}^* \right) \right) p_{\ell}^i(\cos \theta) \]

Thus:

\[ a_{\ell}^i(E) \sim \sum_{mn} b_{mn}^i \left( \text{Re} \left( T_{mn}^* \right) \right) \]

A unique set of reaction matrix elements $T_{mn}$ was found by fitting the expansion coefficients $a_{\ell}^i(E)$ according to eq. (4) to the experimental ones. The fits were performed by means of a derivative-free form of the Levenberg-Marquardt algorithm (for more details see ref. /14/).

3 - RESULTS

In table 1 the absolute values of the resulting 16 energy independent transitions $\tilde{T}_{\beta\alpha}$ are shown. According to their orbital angular momentum $\ell$, they have to be multiplied by the penetrabilities $iC_{\tau\alpha}$ when comparing their respective influence on the observables such as cross sections.

We learn from table 1 that the quintet transition amplitudes $\langle S_2^0 | 2 | D_2 \rangle$ and $\langle S_2^0 | 2^+ | D_2 \rangle$ are of the same order of magnitude as the singlet transition $\langle S_0^0 | 0^+ | S_0 \rangle$, which rules out the possibility of a neutron-lean fusion reactor by polarizing the nuclear fuel. Our results...
Table 1 - The absolute values of the constant transition amplitudes $\hat{T}_{\alpha \alpha}$. They have to be multiplied with the energy dependent penetrabilities $C_{\alpha \alpha}(E)$ (see fig. 1). The notation is: $\hat{T}_{\alpha \alpha} = \langle \text{in} \mid JF \mid \text{out} \rangle = \langle 2S_\alpha \mid t_{\alpha \alpha} \mid 2S_\beta \rangle$. The errors are specified in parentheses.

<table>
<thead>
<tr>
<th>$\hat{T}_{\alpha \alpha}$</th>
<th>$D(d,p)^3H$</th>
<th>$D(d,n)^3He$</th>
<th>$\hat{T}_{\alpha \alpha}$</th>
<th>$D(d,p)^3H$</th>
<th>$D(d,n)^3He$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;S_0 \mid 0^* \mid S_0&gt;$</td>
<td>3.81 (0.15)</td>
<td>4.04 (0.26)</td>
<td>$&lt;S_2 \mid 2^* \mid D_2&gt;$</td>
<td>1.85 (0.07)</td>
<td>1.38 (0.11)</td>
</tr>
<tr>
<td>$&lt;P_0 \mid 0^* \mid P_0&gt;$</td>
<td>4.02 (0.43)</td>
<td>6.5 (1.1)</td>
<td>$&lt;S_0 \mid 0^* \mid S_0&gt;$</td>
<td>15.4 (1.3 )</td>
<td>19.1 (3.7)</td>
</tr>
<tr>
<td>$&lt;P_1 \mid 1^* \mid P_1&gt;$</td>
<td>4.39 (0.12)</td>
<td>4.33 (0.20)</td>
<td>$&lt;S_2 \mid 2^* \mid D_2&gt;$</td>
<td>6.46 (0.77)</td>
<td>7.6 (1.9)</td>
</tr>
<tr>
<td>$&lt;P_1 \mid 1^* \mid S_0&gt;$</td>
<td>7.78 (0.20)</td>
<td>8.90 (0.37)</td>
<td>$&lt;S_2 \mid 2^* \mid S_2&gt;$</td>
<td>1.37 (0.05)</td>
<td>1.71 (0.09)</td>
</tr>
<tr>
<td>$&lt;P_2 \mid 2^* \mid P_2&gt;$</td>
<td>1.17 (0.18)</td>
<td>2.89 (0.38)</td>
<td>$&lt;S_1 \mid 1^* \mid S_1&gt;$</td>
<td>8.0 (1.1)</td>
<td>1.8 (1.9)</td>
</tr>
<tr>
<td>$&lt;D_2 \mid 2^* \mid D_2&gt;$</td>
<td>5.7 (1.2)</td>
<td>7.6 (2.3)</td>
<td>$&lt;S_1 \mid 1^* \mid D_2&gt;$</td>
<td>3.4 (1.2)</td>
<td>11.2 (3.4)</td>
</tr>
<tr>
<td>$&lt;D_2 \mid 2^* \mid S_3&gt;$</td>
<td>0.2 (1.3)</td>
<td>6.3 (0.95)</td>
<td>$&lt;S_3 \mid 3^* \mid S_3&gt;$</td>
<td>8.03 (0.75)</td>
<td>6.9 (1.4)</td>
</tr>
<tr>
<td>$&lt;P \mid 3^* \mid P&gt;$</td>
<td>2.23 (0.21)</td>
<td>0.59 (0.32)</td>
<td>$&lt;S_3 \mid 3^* \mid D_2&gt;$</td>
<td>3.25 (0.94)</td>
<td>3.4 (1.1)</td>
</tr>
</tbody>
</table>

Table 2 - Relative S-wave quintet state transitions of the $D(d,n)^3He$ reaction compared to RRGM results at $E_{lab} = 80$ keV.

<table>
<thead>
<tr>
<th></th>
<th>$\langle S_2 \mid 2^* \mid D_2 \rangle$</th>
<th>$\langle S_2 \mid 2^* \mid S_2 \rangle$</th>
<th>$\langle S_0 \mid 0^* \mid S_0 \rangle$</th>
<th>$\langle S_0 \mid 0^* \mid D_2 \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{lab}$</td>
<td>0.12 RRGM /4/</td>
<td>0.24 RRGM /4/</td>
<td>0.34 this work</td>
<td>0.43 this work</td>
</tr>
</tbody>
</table>

E.g. for the S-wave quintet transitions agree reasonably well with RRGM calculations /4/ (table 2). Furthermore the results are in qualitative agreement with an R-Matrix analysis /6/ but contradict strongly the DWBA calculations of Zhang et al. /8/.

From the knowledge of $\hat{T}_{\alpha \alpha}$ it is possible to predict all observables which have not yet been investigated experimentally. Below, for both reactions the predictions for the polarization transfer observables $T_{11}$ and $T_{21}$ are shown as an example. For the $D(d,n)$ reaction $T_{11}$ is in agreement with a qualitative observation of Janett et al. /5/ . At $E_{lab} = 460$ keV, $\delta_{lab} \approx 90^o, 110^o$ they found polarization values $\leq 15\%$.

Fig. 2 - Polarization transfer observable $T_{11}$ for $D(d,n)^3He$ and $D(d,p)^3H$ calculated with the reaction matrix $T_{\beta \alpha}(E)$ (eq. [1]).
Fig. 3 - Polarization transfer observable $T_{21}^{11}$ for $^3$He and $^3$H calculated with the reaction matrix $T_{p\alpha}(E)$ (eq. 1)

/1/ E. J. Konopinski and E. Teller, Phys. Rev. 73, 822 (1948)
/2/ J.R. Pruett, F. M. Beiduk and E. J. Konopinski, Phys. Rev. 77, 628 (1950)