Determination of the Reaction-Matrix Elements 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. All available data of the mirror fusion reactions D(d, n)\(^3\)He and D(d, p)\(^3\)H have been subjected to a new analysis in order to extract the matrix elements of all 16 transitions necessary for inclusion of all \(l \leq 2\) waves. Their energy dependence was assumed to be governed solely by Coulomb penetrabilities. The Levenberg-Marquardt algorithm was used to fit all experimental data. The experimental data are reproduced satisfactorily. The results compare well with an \(R\)-matrix analysis and with refined resonating group calculations. No suppression of quintet entrance-state transitions and therefore no neutron suppression in “polarized fusion” can be derived from this analysis.

1 Introduction

The different observables of the D(d, n)\(^3\)He and D(d, p)\(^3\)H mirror fusion reactions at low energies (\(\leq 500\) keV) have been studied for many years. These studies included measurements of the total [1] and differential [2–4] cross sections, of the polarization of the outgoing nucleons (for a summary see ref. [5]) and measurements with a polarized incident beam [6–11]; however, no polarization-transfer measurements and no polarization-correlation experiments have been performed so far. The need for many different and mostly polarization measurements in these two reactions arises from at least two sources. One is the unusual complexity of these reactions even at every low energies, thus the lack of a workable theory or even of a simple model; to improve this situation requires more observables and more complex ones than just unpolarized cross sections. Another is the recent proposal of using polarized particles in future fusion reactors either to enhance the reaction rate of the desired reaction or to suppress the rate of unwanted reactions.

As to the theoretical description of the \(D+D\) reactions, expansions of the observables in terms of combinations of contributing matrix elements have been

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given by several authors [12, 13]. The most comprehensive of these analyses was performed by Ad'yasevich et al. [14]. As new measurements at increasingly lower energies became available, it became also clear that the $D + D$ reactions display unusual features: The anisotropy of the unpolarized cross sections even at energies as low as $E_{\text{c.m.}} = 15$ keV (see, e.g., the most recent results by Krauss et al. [4] and references therein) shows the contribution from $P$-waves (i.e. the coefficient of $P_2(\cos \Theta)$ in the Legendre expansion), and $D$-waves (coefficient of $P_4(\cos \Theta)$) appear already significantly above 100 keV for the $D(d, p)$ reaction and above 150 keV for the $D(d, n)$ reaction. The vector-analyzing powers $A_v$, which are mainly due to interference terms between different waves (predominantly $S$- and $P$-waves at the lower energies, i.e. terms such as $\text{Im}(\alpha_0 \beta_{11}^*)$ in the notation of ref. [14]), appeared significantly different from zero even at 30 keV [15].

Another interesting question, especially in connection with fusion-energy research, is the contribution (or suppression) of quintet states in the two reactions and possible channel-spin transitions with $\Delta S = 1$ (such as triplet-singlet transitions: matrix element $\beta_{11}$, and quintet-triplet transitions: matrix elements $\delta_1$ to $\delta_4$) or $\Delta S = 2$ (quintet-singlet transitions, matrix elements $\gamma_1$, $\gamma_2$, and $\gamma_3$). Contributions from quintet states have in the past been excluded by an argument based on the Pauli principle [16–18]. This argument may be considered very weak because of the extremely large interaction radius of two deuterons. In fact, a careful analysis of the data of the $D(d, p)$ reaction at 290 keV in terms of partial waves [14] showed a certain amount of quintet-state suppression. A later analysis of data by the same group [19] and comparison with all other available data in the energy range below 485 keV showed in addition that transitions from the quintet $S$ state of the $D(d, n)$ branch appear to be hindered relative to the $D(d, p)$ branch.

A renewed interest in the $D + D$ reactions at low energies results from the proposal of an advanced “neutron-lean” fusion-reactor concept based on the $^3\text{He}(d, p)^4\text{He}$ reaction [20, 21]. Such a reactor will be aneutronic only if the $D(d, n)^3\text{He}$ reaction rate could be substantially suppressed. If quintet states were strongly suppressed in the $D(d, n)$ reaction, then the use of deuterons polarized along the direction of the plasma-confining magnetic field would lead to a suppressed neutron-production rate and in conjunction with polarized $^3\text{He}$ nuclei to a possible rate increase (or lower ignition limit) for the $^3\text{He}(d, p)^4\text{He}$ fusion in analogy to the $^3\text{H}(d, n)^4\text{He}$ case.

Different approximative approaches to a theoretical description of the $D + D$ reactions have been undertaken. These include a simple potential model [16–18], an $R$-matrix parametrization approach [22, 23], DWBA calculations [13, 24, 25], and resonating group (RRGM) calculations [26, 32]. Only recently microscopic 4-body (Faddeev) calculations have been performed for the four-nucleon system though with very limited complexity [27]. Especially on the question of quintet-state suppression these approximative approaches have produced vastly different predictions.

In order to contribute not only to this question but more generally in an attempt to determine all transition matrix elements of both reactions a new straightforward analysis of all available data with $E_d \leq 500$ keV was performed. The approach is similar to Ad’yasevich’s [14] and the method and additional results will be published elsewhere in more detail. This approach was chosen as the least-model-dependent