Experimental study of spin effects in the resonant formation of muonic deuterium molecules

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The temperature dependences of the rates of formation of $dd\mu$ molecules from the two states of the hyperfine structure of the $d\mu$ atom and the transition rate between these two states have been measured in experiments with high density deuterium ($\phi \cong 1$). A comparison of the results with measurements at a deuterium density $\phi = 0.02$ indicates the possibility of a density effect in the formation of $dd\mu$ molecules from the upper spin state of the $d\mu$ atom.

Problems that arise in the explanation of the results of experimental investigations of muon catalysis in a mixture of $D_2 + T_2$ have prompted a resort to measurements that may be simpler and can be interpreted more reliably. Thus, in RAL and PSI (Paul-Scherrer Institute) attempts were made to measure directly the most important quantity—the probability of sticking of a muon to helium in the nuclear fusion reaction $d + t$. Another important direction is the study of the process of muon catalysis in pure deuterium (Fig. 1.).

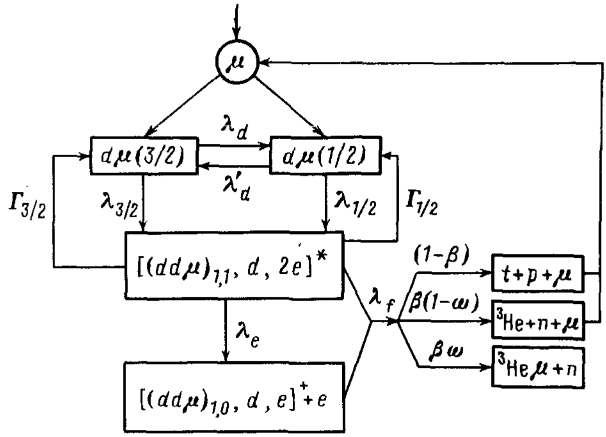

FIG. 1. Diagram of the process of muon catalysis in pure deuterium.

It is characteristic that in the recent international conference on muon catalysis (Vienna, 1990) three papers were presented at once on studies of the process

$$d\mu + D_2 \rightarrow dd\mu \longrightarrow \begin{cases} {}^3He + n + \mu & (1a) \\ t + p + \mu & (1b) \end{cases}$$

In these studies the temperature dependence of the rate of formation, $\lambda_{dd\mu}$, of $dd\mu$ molecules was measured: In Refs. 1 and 2 the Vienna-PSI group measured this quantity for both spin states, $F = 3/2$ and $1/2$, of the $d\mu$ atom ($\lambda_{3/2}$ and $\lambda_{1/2}$) and in the papers of the Leningrad Institute of Nuclear Physics, Academy of Sciences of the USSR,[3] and the Joint Institute for Nuclear Research, Moscow,[4] it was studied for the lower spin state of the $d\mu$ atom (more precisely, the average over spin states, the so-called steady-state value). In Ref. 5 we estimated the value of $\lambda_{3/2}$. The results of the measurements reported in Refs. 1–5 were found to be in good agreement with each other and with the calculations[6,7] carried out within the "standard" model of Vesman.[8]

Measurements of $\lambda_{3/2}(T)$ were carried out by only one group, and that was with a low deuterium concentration $\phi = 0.02$–0.04 (as usual, the density is referred to the density of liquid hydrogen, $n_0 = 4.25 \times 10^{22}$ nuclei/cm^3). The object of the present investigation was to measure $\lambda_{3/2}(T)$ and $\lambda_{1/2}(T)$ for a deuterium density $\phi \simeq 1$. It follows from theory[6,7] that the function $\lambda_{3/2}(T)$ should be extremely sensitive, especially in the temperature range $T \leqslant 120$ K, to the energy of the weakly bound state in the $dd\mu$ system responsible for its resonant formation.[9]

Another important aspect of the problem is that the theory predicts the existence of nontrivial density effects in $\lambda_{3/2}(T)$ due to collisional broadening of the resonance.[7,10,11]

We have described the experimental apparatus previously.[12–14] Its principal components are the high-pressure gaseous deuteron target[13] and the highly efficient total-absorption neutron spectrometer.[14] Neutrons of energy 2.45 MeV from reaction (1a) were detected. In this experiment we modified the experimental setup and the data processing method[15] because of the necessity of measuring small time intervals accurately (the lifetime of the $d\mu$ atom in the state with $F = 3/2$ for $\phi \simeq 1$ is at most 20 to 30 ns). The experiments were carried out at temperatures $T = 22$ K ($\phi = 1.18$), $T = 48, 80, 91, 105, 120$ K ($\phi = 0.88$) and $T = 162, 205$ K ($\phi = 0.50$). The impurity content in the deuterium for $x > 1$ was $\simeq 10^{-7}$ by volume and that of protium was lower than 1%.

The parameters of the process were determined from an analysis of the time distributions of the first detected neutrons, which were fitted with a curve of the form described in Refs. 1, 2, 6, and 16:

$$dN_n/dt = c[A_{\mathrm{fa}}\exp(-\lambda_{\mathrm{fa}}t) + A_{\mathrm{sl}}\exp(-\lambda_{\mathrm{sl}}t)], \tag{2}$$

convoluted with the time resolution function of the detector.[15] The parameter c is a normalizing factor that takes into account the number of detected electrons from muon decay and the efficiency of detection of the neutrons (ϵ_n). The quantity ϵ_n also appears in other parameters of formula (2) (Refs. 16 and 17). The values of ϵ_n of various measurement conditions were calculated by the Monte Carlo method.[18]

Expression (2) is the sum of two exponentials—a fast and a slow one—with parameters A_{fa}, λ_{fa} and A_{sl}, λ_{sl} which are functions of the quantities $\lambda_{3/2}$, $\lambda_{1/2}$, and λ_d that we wish to determine.

$$\lambda_{\mathrm{fa}} \cong \lambda_d\phi + \lambda'_d\phi + \lambda_0 + 1/3\lambda_{3/2}\phi + 2/3\lambda_{1/2}\phi;\quad \lambda_{\mathrm{sl}} \cong \lambda_0 + (\epsilon + \omega)\beta\phi\lambda_{1/2};$$

$$A_{\mathrm{fa}} \cong 2/3A_s(\lambda_{3/2} - \lambda_{1/2})/\lambda_{1/2};\quad A_{\mathrm{sl}} = \bar{\lambda} \cong k\lambda_{1/2}\phi;\quad (|k-1| = 5 - 15\%), \tag{3}$$

where $\lambda_0 = 0.455\ \mu s^{-1}$ is the decay rate of a muon, $\omega = 0.12$ (Ref. 19) is the probability of sticking of a muon to helium in reaction (1a). The values of $\lambda_{3/2}$, $\lambda_{1/2}$, and λ_d were determined by a numerical solution of the system of differential equations for the functions $n_{d\mu(3/2)}(t)$, $n_{d\mu(1/2)}(t)$, and $n_n(t)$, set up in accordance with the diagram of the processes shown in Fig. 1 (Refs. 1, 2, 6, and 16). The observed rates of formation of $dd\mu$ molecules are the "effective" values:[6] $\lambda_{3/2,1/2} = \Lambda_{3/2,1/2}\tilde{\lambda}_f/(\tilde{\lambda}_f + \Gamma)$, where Λ is the rate of formation of the $[(dd\mu)_{1,1}, d, 2e]^*$ complex, $\tilde{\lambda}_f = \lambda_f + \lambda_c$ is the effective rate of the d–d nuclear reaction in the $dd\mu$ molecule, $\lambda_f = 0.43 \times 10^9\ \mathrm{s}^{-1}$ (Ref. 20), $\lambda_c = 0.022 \times 10^9\ \mathrm{s}^{-1}$ (Ref. 21), and $\Gamma = \Gamma_{1/2} + \Gamma_{3/2}$ is the rate of the inverse decay of the complex. The rate λ_d of the transitions $3/2 \to 1/2$ takes into account not only the spin-exchange $d\mu + d$ collisions, but also the possible change in the population of the spin states of the $d\mu$ atom in the inverse decay of the complex.[22,6]

For the $dd\mu$ molecules formed from the state of the $d\mu$ atom with $F = 3/2$ (resonant formation), the partial probability of reaction 1a is assumed to be $\beta = 0.58$ (Ref. 19). For $dd\mu$ molecules formed from the state with $F = 1/2$ we also took into account (in accordance with the calculations of Ref. 6) the contribution of nonresonant formation, for which it was assumed that $\beta = 0.50$. During the analysis we also varied the position of the zero of time, τ_0, in the spectrum (2), and it was also checked from the position of the peak due to the meson x-ray photons, generated from muons stopped in the wall of the target.

The values of $\lambda_{3/2}$ and $\lambda_{1/2}$ determined in the analysis are shown in Fig. 2. The

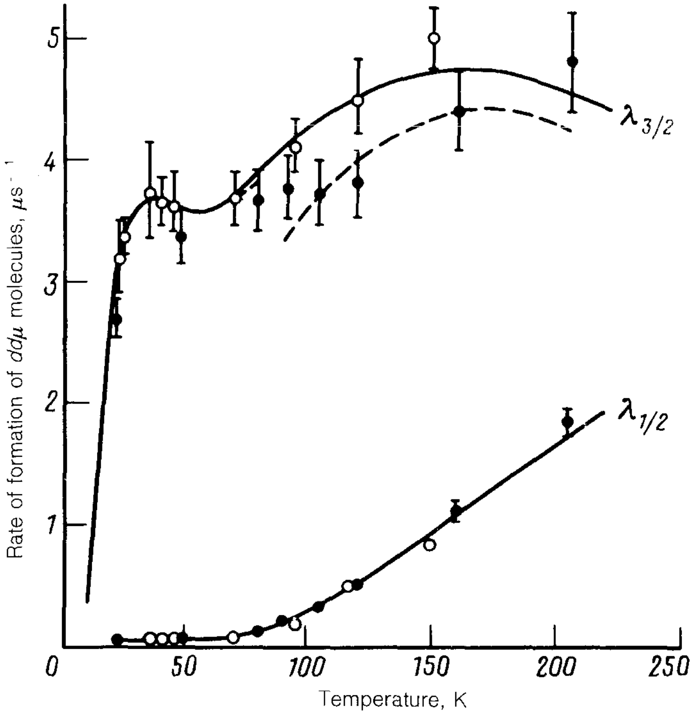

FIG. 2. Curves of $\lambda_{3/2}(T)$ and $\lambda_{1/2}(T)$ measured in this investigation and in the work of Refs. 1 and 2. Points ● our data; ○ measurements of Refs. 1 and 2. The solid line represents the calculation of Ref. 7, based on the Vesman model; the dashed line represents the calculation of Ref. 7 that takes into account the effect of broadening of the resonance in the formation of the $dd\mu$ molecules.

error in these values includes statistical and systematic errors. The principal errors are the indeterminacy in the detection efficiency (4–5%) and in the deuterium density.

It can be seen from Fig. 2 that $\lambda_{1/2}(T)$ is in good agreement with our data and with the measurements[2] carried out with deuterium of low density ($\phi = 0.02$ and 0.04) as well as with the calculations of Refs. 6 and 7. Some difference was observed between our results for $\lambda_{3/2}(T)$ and the experimental data.[2] For six of our points for $T = 80$–205 K the deviation from the optimum curve of $\lambda_{3/2}(T)$ derived in Ref. 2 with the calculational scheme of Ref. 6 corresponds to the value $x^2 = 16$. The deviation is more striking if we display the data of the measurements in the form of the ratio $\lambda_{3/2}/\lambda_{1/2}$ and in this way essentially exclude the systematic error associated with inaccuracies in the values of ϵ_n and ϕ.

It is accordingly of interest to interpret these results on the basis of a theory that takes into account broadening of the resonance in collisions of the $[(dd\mu),d,2e]$ complex with D_2 molecules.[7,10,11] The broadening of the resonance, which is dominant in the formation of $dt\mu$ molecules, should appear only at high deuterium densities $\phi \geqslant 1$ for $dd\mu$. The dashed line in Fig. 2 shows the results of calculation[7] of $\lambda_{3/2}$ for $\phi = 1.2$. The break in the temperature region where the elastic width is about equal to the resonance energy is an indication of the deficiencies of calculations based on specific models, but the variation of $\lambda_{3/2}$ with increasing density in the temperature range $T = 70$–120 K is quite apparent.

It is thus possible to reconcile the two groups of experimental data for $\lambda_{3/2}(T)$, our data for a density $\phi \cong 1$ and that of the Vienna-PSI group for $\phi = 0.02$ to 0.04, within the framework of a theory that takes into account collisional broadening of the resonance. To further clarify this point, it would be desirable to take measurements of $\lambda_{3/2}(T)$ at high and low deuterium concentrations in a single experiment.

The analysis of the experimental data for the time distributions of the neutrons also provided data on the rate λ_d of the transitions $F = 3/2 \rightarrow F = 1/2$ between the spin states of the $d\mu$ atom. These data are shown in Fig. 3.

The values of λ_d that we obtained are in good agreement with the results of the measurements of Refs. 1 and 2 and with the temperature-averaged value $\bar{\lambda}_d = 37.3 \pm 1.5$ obtained in Ref. 3. Figure 3 shows that the experimental data are in poor agreement with calculations[23] that take into account that the effective rate of the transitions $3/2 \rightarrow 1/2$ increases because of the decay of the $[(dd\mu),d,2d]^*$ complex. The reason for this discrepancy is still not clear.

To conclude, we should like to make one more point. The absolute calibration of the zero of time of the neutron detector, carried out by detecting the meson x rays from the walls of the target permits us to estimate the time for the $d\mu$ atom to slow from its initial energy $E_0 = 1$–2 eV to the energy $E = 0.02$–0.03 eV. According to our estimates, this time is no greater than 2 ns. It would be interesting to carry out experiments with lower-density deuterium, which would be more sensitive in this application.

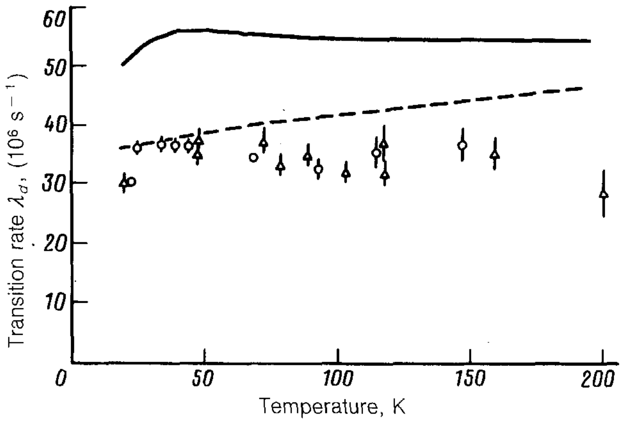

FIG. 3. Rates of transition between the states of the hyperfine structure of the $d\mu$ atom as functions of the temperature of the deuterium. Points: △ are the data of the present investigation and the results of Ref. 5; the points ○ are the measurements of Refs. 1 and 2. The dashed line represents the calculations of Ref. 23 for the $3/2 \rightarrow 1/2$ transition rate in collisions of $d\mu$ atoms (molecules) with deuterium; the solid line is the same, but with allowance for the variation in the population of the states with $F = 3/2$ and $F = 1/2$ in the inverse decay of the $[(dd\mu),d,2e]$ complex.

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