# Lifetime of the mesic molecule $dt\mu$

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(Submitted 29 April 1982)
Zh. Eksp. Teor. Fiz. **83**, 1615–1622 (November 1982)

A lifetime of $\tau \approx 10^{-11}$ sec is calculated for the mesic molecule $dt\mu$ produced resonantly in the excited rotational-vibrational state $J = v = 1$.

PACS numbers: 36.10.Dr, 33.70.Fd

## 1. INTRODUCTION

It is known that in a dense mixture ($\rho \sim 4\times 10^{22}$ cm$^{-3}$) of deuterium and tritium $\mu^-$ mesons with energy $\sim 10$ keV are captured after a time $\sim 10^{-12}$ sec by highly excited states of the mesic atoms $d\mu$ and $t\mu$,[1] go over after a time $\tau_a \lesssim 2\times 10^{-11}$ sec to the ground state,[2] and finally, after a time $\tau_{dt} \approx 3\times 10^{-9}$ sec, all mesons reach the ground state of the atom $t\mu$ via the isotopic exchange process $d\mu + t \to t\mu + d$.[3,4] The fraction of muons that decay during the formation of the mesic atoms $t\mu$ is $\sim \tau_{dt}/\tau_0 \approx 1.5\times 10^{-3}$, where $\tau_0 = 1/\lambda_0 = 2.2\times 10^{-6}$ sec is the lifetime of the free muon.

In collisions of the mesic atoms $t\mu$ with the molecules $D_2$ and DT, the mesic molecules $dt\mu$ are formed[4,5] during a time $\tau_{dt\mu} < 10^{-8}$ sec in the resonance reactions

$$t\mu + D_2 \to [(dt\mu)_{Jv} d2e]^*, \tag{1a}$$

$$t\mu + DT \to [(dt\mu)_{Jv} t2e]^* \tag{1b}$$

in the excited rotational-vibrational $(Jv)$ state with quantum numbers $J = v = 1$.[5] The produced mesic molecules are de-excited by the Auger transitions[6]

$$[(dt\mu)_{Jv} d2e] \to [(dt\mu)_{J'v'} de]^+ + e. \tag{2}$$

In each of the $(Jv)$ states of the mesic molecule $dt\mu$ the nuclear fusion reactions

$$dt\mu \begin{cases} \nearrow {}^4\mathrm{He} + n + \mu^- & \text{(3a)} \\ \searrow \mu {}^4\mathrm{He} + n & \text{(3b)} \end{cases}$$

take place with rate $\lambda_{Jv}^f$ (Refs. 7 and 8) and the muons decay: $\mu \to e^- + \nu_\mu + \tilde{\nu}_e$.

In the present paper, we consider the de-excitation cascade of the mesic molecule $dt\mu$ with allowance for nuclear absorption and we calculate the lifetime $\tau_m$ of the mesic molecule (the corresponding probability of muon decay during the cascade time is $\omega_m = \tau_m/\tau_0$). The value of $\omega_m$ is needed for detailed description of the kinetics of muon catalysis.[9]

## 2. CHARACTERISTICS OF THE BASIC PROCESSES

The nonrelativistic level $J = v = 1$ of the mesic molecule $dt\mu$ with energy $\varepsilon_{11} = -0.64$ eV (Ref. 10) is split by the spin-spin and spin-orbit interaction of the muon and the nuclei into 10 sublevels $\varepsilon_{11}^{\mathscr{L}N}$ of the fine and hyperfine structure.[11] Here, $\vec{\mathscr{L}} = \mathbf{S} + \mathbf{J}$ is the total angular momentum, $\mathbf{J}$ is the orbital angular momentum, $\mathbf{S} = \mathbf{S}_t + \mathbf{S}_d + \mathbf{S}_\mu$ is the total spin of the particles, and the index $N$ labels the sublevels $\varepsilon_{11}^{\mathscr{L}N}$ in a multiplet with given $\mathscr{L}$ (which are degenerate in the nonrelativistic limit).

In contrast to ordinary atoms and molecules, the spin-spin interaction in the mesic molecule $dt\mu$, as in the atom $t\mu$, is much stronger than the spin-orbit interaction, and therefore the structure of the multiplet is largely determined by the interaction of the spins of the particles (Fig. 1). The splitting of the levels $(\mathscr{L}N)$ that differ in the value of $\mathbf{F} = \mathbf{S}_\mu + \mathbf{S}_t$ is greatest and is $\sim 0.2$ eV, which is comparable with the splitting of the ortho- and para-states of the mesic atom $t\mu$.[12] The $S$ splitting for given $F$ is an order of magnitude less ($\lesssim 10^{-2}$ eV) and, finally, the fine splitting with respect to $\mathscr{L}$ for given $F$ and $S$ does not exceed $10^{-3}$ eV (Table I). Thus, the relativistic structure of the levels of the $dt\mu$ molecule is to a large degree dictated by the hyperfine splitting of the levels of the $t\mu$ atom, and therefore each of the sublevels $(\mathscr{L}N)$ of the multiplet $(Jv)$ can be classified with respect to the values of $F$, and also with respect to the values of $S$ and $\mathscr{L}$. With allowance for the relativistic structure of the levels of the mesic atom $t\mu$ and the mesic molecule $dt\mu$ (see Fig. 1) the scheme (1) of resonance formation of $dt\mu$ mesic molecules in the state $J = v = 1$ takes the form

$$(t\mu)_{F_a} + D_2 \to [(dt\mu)_{FS\mathscr{L}} d2e]^*, \tag{4}$$

where $F_a$ is the spin of the mesic atom $t\mu$. Only the levels $(FS\mathscr{L})$ for which the value of $F$ is equal to the spin $F_a$ are

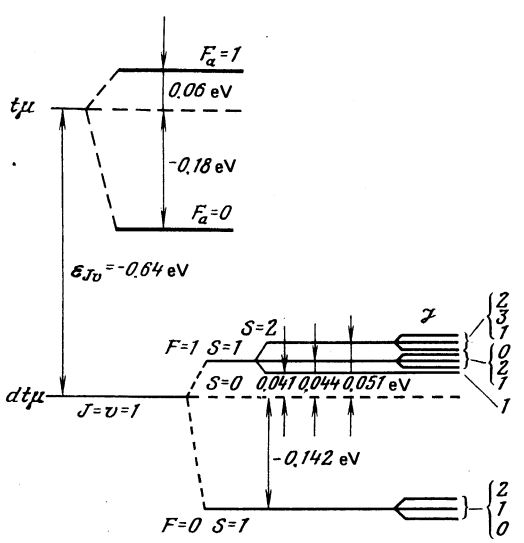


FIG. 1. Scheme of the hyperfine structure of the levels of the atom $t\mu$ and the molecule $dt\mu$. The spins $\mathbf{F}_a$ of the mesic atom $t\mu$, the deuteron, and the total orbital angular momentum $\mathbf{J}$ of the system $dt\mu$ are added successively to the total spin $\mathbf{S} = \mathbf{F} + \mathbf{S}_d$ and the total angular momentum $\vec{\mathscr{L}} = \mathbf{S} + \mathbf{J}$ of the mesic molecule.

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TABLE I. Relativistic structure of the multiplet $(FS\mathscr{J})$ of the level $J = v = 1$ of the mesic molecule $dt\mu$.

| $F$ | $S$ | $\mathscr{J}$ | $N$ | $\Delta\varepsilon^{\mathscr{J}N}$, eV |
|---|---|---|---|---|
| 1 | 2 | 2 | 3 | 0.0511 |
| | | 3 | 1 | 0.0508 |
| | | 1 | 4 | 0.0501 |
| | 1 | 0 | 1 | 0.0445 |
| | | 2 | 1 | 0.0443 |
| | | 1 | 2 | 0.0439 |
| | 0 | 1 | 1 | 0.0407 |
| 0 | 1 | 1 | 3 | −0.1422 |
| | | 2 | 2 | −0.1424 |
| | | 0 | 2 | −0.1424 |

**Note.** The table is based on the data of Ref. 11. The energies of the sublevels of the multiplet are measured from the nonrelativistic energy $\varepsilon_{11} = -0.64$ eV of the level $J = v = 1$.

populated, since the electric dipole transition (4) leading to the production of mesic molecules does not affect the spins of the particles to accuracy $\sim\alpha^2$.

According to the theoretical[5] and experimental[4] estimates, the rate of resonance production of $dt\mu$ molecules is $\lambda_{dt\mu} > 10^8$ sec. The mesic atoms $t\mu$ are produced in the states with total spin $F_a = 1$ and $F_a = 0$ with probabilities 3/4 and 1/4, respectively. From the state $F_a = 1$ there is an irreversible spin flip reaction:

$$(t\mu)_{F_a=1} + T_2 \to (t\mu)_{F_a=0} + T_2, \tag{5}$$

whose rate $\lambda_t = 10^9$ sec$^{-1}$ (Ref. 13) is comparable with the rate $\lambda_{dt\mu}$ of resonance production (4) of the mesic molecules. The competition between these processes determines the populations $P_F$ of the multiplet $(FS\mathscr{J})$ of the level $(Jv) = (11)$ with given $F$:

$$P_{F=1} = \frac{3}{4}\frac{\lambda_{dt\mu}(F=1)}{\lambda_t + \lambda_{dt\mu}(F=1)}$$
$$P_{F=0} = \frac{1}{4} + \frac{3}{4}\frac{\lambda_t}{\lambda_t + \lambda_{dt\mu}(F=1)}, \tag{6}$$

where $\lambda_{dt\mu}(F = 1)$ is the rate of production of $dt\mu$ molecules in the reaction (4) for $F = F_a = 1$.

The sublevels $(FS\mathscr{J})$ of the level $(Jv) = (11)$ of the mesic molecule $dt\mu$ for given $F$ are populated, with probabilities $P_{FS\mathscr{J}}$ proportional to their statistical weights, already at temperatures $T > 300$ K, since the width of the Maxwellian distribution with respect to the energies of the atoms $t\mu$ at this temperature exceeds the splitting of the level $F$ with respect to $S$, which, as can be seen from Table I, is of order 0.01 eV. Note that sublevels $(FS\mathscr{J})$ with different $\mathscr{J}$ for given $F$ and $S$ are populated statistically even at the liquid hydrogen temperature $T \approx 30$ K. The populations $P_{FS}$ of the components $(FS)$ of the hyperfine structure are determined by

$$P_{FS} = \sum_{\mathscr{J}} P_{FS\mathscr{J}} = P_F \sum_{\alpha_f} \frac{(2\mathscr{J}+1)}{(2F+1)(2S_d+1)(2J+1)}$$
$$= P_F \frac{(2S+1)}{3(2F+1)}. \tag{7}$$

The populations $P_F$ depend on the particular conditions of the experiment, in particular, the temperature and density of the $D_2 + T_2$ mixture, variation of which can change the relationship between the rates $\lambda_{dt\mu}(F = 1)$ and $\lambda_t$.

The rate $\lambda^f_{JvFS}$ of the nuclear reaction (3) from the state $(JvFS)$ is equal to the sum of the rates $\lambda^f_{JvFS}(j^\pi)$ from the states of the relative motion of the nuclei $d$ and $t$ with total angular momentum $j$ and parity $\pi$:

$$\lambda^f_{JvFS} = \lambda^f_{JvFS}(^3/_2{}^+) + \lambda^f_{JvFS}(^1/_2{}^+) + \lambda^f_{JvFS}(j^-). \tag{8}$$

By virtue of the resonance nuclear interaction of $d$ and $t$ in the state $j^\pi = 3/2^+$ near the $dt$ threshold, the rate $\lambda^f_{JvFS}(3/2^+)$ is dominant for the states $(FS)$ of the mesic molecule that admit parallel orientations of the spins $I = 3/2$ of the nuclei. The quantities $\lambda^f_{JvFS}(3/2^+)$ are related to the previously calculated[7,8] rates $\lambda^f_{Jv}(3/2^+)$ of the reactions (3) from the states $(Jv)$ of the mesic molecule $dt\mu$ with zero orbital angular momentum, $L = 0$, of the relative motion of the nuclei $d$ and $t$ and total spin $I = 3/2$ of the nuclei as follows:

$$\lambda^f_{JvFS}(^3/_2{}^+) = a_{FS}\lambda^f_{Jv}(^3/_2{}^+). \tag{9}$$

Here, $a_{FS}$ are the weights of the configurations with total spin $I = 3/2$ of the nuclei in the hyperfine structure states $(FS)$[1]: $a_{01} = 2/3$, $a_{12} = 1$, $a_{11} = 1/3$, $a_{10} = 0$.

In the state $(FS) = (10)$, the rate (8) of the nuclear reaction (3) is determined by the value of $\lambda^f_{Jv10}(1/2^+)$, which can be obtained by using the experimental data[14] on elastic and inelastic $dt$ scattering at energies $E \lesssim 3.4$ MeV:

$$\lambda^f_{Jv10}(^1/_2{}^+) = 3.6\cdot 10^{-2}\lambda^f_{Jv}(^3/_2{}^+). \tag{10}$$

Note that the estimate (10) is based essentially on the assumption of Ref. 14 that there exists a broad $1/2^+$ resonance in the cross sections of the reactions $dt \to n^4$He and $dt \to dt$. The errors in the estimate we have given depend on the accuracy in the determination of the parameters of this resonance.

As was noted in Refs. 7 and 8, the rates $\lambda^f_{Jv}(j^-)$ of the nuclear reaction (3) form the state of relative motion of the nuclei $d$ and $t$ with orbital angular momentum $L = 1$ can be appreciable only for the states of the mesic molecule with angular momenta $J = 1$ and $J = 2$. To estimate $\lambda^f_{Jv}(j^-)$, we have used the data of Ref. 15, according to which the $p$-wave cross section $\sigma_p$ of the reaction (3) at energy $E_{cms} = 240$ keV is $\sim 1\%$ of the total cross section. Taking the value $\sigma_p = 8$ mb, for the constant $A_p$ of the nuclear reaction (3) we obtain

$$A_p = \lim_{v\to 0}(v\sigma_p/9k^2C_1^2) = 1.2\cdot 10^{24}\ \text{F}^5/\text{sec}. \tag{11}$$

Here, $v$ is the relative velocity, $k$ is the relative momentum of the $d$ and the $t$, and

$$C_1^2 = {}^2/_9\pi\eta(1+\eta^2)(e^{2\pi\eta}-1)^{-1}$$

is the Gamow factor for the $p$ wave ($\eta = \alpha c/v$). The rate $\lambda^f_{Jv}(j^-)$ of the nuclear reaction is related to the reaction constant $A_p$ by an equation that can be obtained by the method explained in Ref. 16 for the $s$ wave:

$$\lambda^f_{Jv}(j^-) = A_p \int d^3r |\nabla_{\mathbf{R}}\Psi_{Jv}(\mathbf{r},\mathbf{R})|^2_{R=0}, \tag{12}$$

where $\Psi_{Jv}(\mathbf{r},\mathbf{R})$ is the wave function of the mesic molecule[10,17] in the state $(J, v)$. In the following calculations, we set

TABLE II. Binding energies $-\varepsilon_{Jv}$ of the states $Jv$ of the mesic molecule $dt\mu$, Auger transition rates $\lambda_{nn'}$, and the nuclear reaction rates $\lambda^f_{Jv}(3/2^+)$ and $\lambda^f_{Jv}(j^-)$.

| $n$ | $(Jv)$ | $-\varepsilon_{Jv}$, eV | $\lambda_{nn'}$, | $10^{11}$ sec$^{-1}$ | $\lambda^f_{Jv}$ ($^3/_2^+$), sec$^{-1}$ | $\lambda^f_{Jv}$ ($j^-$), sec$^{-1}$ |
|---|---|---|---|---|---|---|
| 5 | (11) | 0.64 | $n'=\begin{cases}4\\3\\1\end{cases}$ | 11.4<br>1.3<br>0.02 | $3.9\cdot10^7$ | $1.3\cdot10^7$ |
| 4 | (01) | 34.9 | $n'=2$ | 0.44 | $1.0\cdot10^{12}$ | $3.6\cdot10^4$ |
| 3 | (20) | 102.5 | $n'=2$ | 0.56 | $1.0\cdot10^5$ | $2.1\cdot10^3$ |
| 2 | (10) | 232.4 | $n'=1$ | 0.42 | $1.0\cdot10^8$ | $3.1\cdot10^7$ |
| 1 | (00) | 319.2 | – | – | $1.2\cdot10^{12}$ | $4.8\cdot10^4$ |

$$\lambda^f_{JvFS}(j^-)=\lambda^f_{Jv}(j^-).$$

In Table II, we give the energies $\varepsilon_{Jv}$ of the states $n=(Jv)$ of the $dt\mu$ mesic molecule,[10] to rates $\lambda^f_{Jv}(3/2^+)$ of the nuclear reaction,[7,8] and the rates $\lambda^f_{Jv}(j^-)$ calculated in accordance with Eq. (12). In calculating the rates $\lambda_{nn'}$, we used the values of the Auger transition rates $\lambda^{(2)}_{nn'}$ (Ref. 6) in the molecule $dt\mu$, which is the "core" of the molecular complex $[(dt\mu)^+d\,2e]$, and we also took into account the results of Ref. 18, in which a study was made of the molecular-ion reactions accompanying the investigated cascade in the molecule $dt\mu$. The molecular ion $[(dt\mu)^+de]^+$ formed during the first transition (2) of the cascade in the molecule $dt\mu$ participates with rate $\lambda\gtrsim10^{13}$ sec$^{-1}$ in the reaction

$$[(dt\mu)^+de]^+ + D_2 \begin{cases}\to [(dt\mu)^+2d2e]^+ + D\\ \to (dt\mu)^+e + D_3^+\end{cases}$$

with probabilities 3/4 and 1/4, respectively. These reactions are, respectively, analogs of the molecular reactions[19]

$$DH^+ + H_2 \to DH_2^+ + H, \quad DH^+ + H_2 \to H_3^+ + D.$$

According to Ref. 18, the rates of the Auger transitions from the final states are, respectively, $\lambda^{(3)}_{nn'}=0.78\lambda^{(2)}_{nn'}$ and $\lambda^{(1)}_{nn'}=0.66\lambda^{(2)}_{nn'}$, i.e., the second transition of the cascade takes place with rate

$$\lambda_{nn'}={}^1/_4\lambda^{(1)}_{nn'}+{}^3/_4\lambda^{(3)}_{nn'}=0.75\lambda^{(2)}_{nn'}.$$

The sequence of molecular-ion reactions accompanying the Auger transitions in the systems $[(dt\mu)^+2d\,2e]$ and $(dt\mu)^+e$ has the consequence that the final (third) transition of the cascade in the molecule $dt\mu$ occurs in the molecular complexes $[(dt\mu)^+2d\,2e]$ and $(dt\mu)^+e$ with probabilities 7/8 and 1/8, respectively,[18] i.e., with rate

$$\lambda_{nn'}=({}^7/_8\cdot0.78+{}^1/_8\cdot0.66)\lambda^{(2)}_{nn'}=0.77\lambda^{(2)}_{nn'}.$$

The calculated values of the rates $\lambda_{nn'}$ are given in Table II.

### 3. DE-EXCITATION CASCADE IN THE MESIC MOLECULE $dt\mu$

The de-excitation cascade in the mesic molecule $dt\mu$ (Fig. 2) begins from the state $J=v=1$, in which it is produced in accordance with (1).

In electromagnetic transitions, the quantum numbers $F$ and $S$ are conserved with accuracy $\sim\alpha^2$, and therefore the cascades from the different states $(FS)$ develop independently. (At the same time, the statistical population with respect to $\mathscr{L}$ of the sublevels $(FS\mathscr{J})$ is conserved during the cascade.) Knowing the characteristics of the cascade for unit initial populations $P_{FS}=1$, we can calculate the cascade time for the real $P_{FS}$ (6) determined by the experimental conditions.

Introducing abbreviated notation for the states $n=(Jv)$ (see Table II) and omitting the indices $(FS)$, we determine the populations $P_n=P_{nFS}$ of the states $n=(Jv)$ of the mesic molecule, the probabilities $r_n$ of the nuclear reactions (3) from these states, and the intensities $y_{nn'}$ of the Auger transitions from the states $n$ to $n'<n$ by means of the following formulas:

$$P_n=\sum_{n'>n}y_{n'n},\quad P_5=1,\quad y_{nn'}=(\lambda_{nn'}/\tilde{\lambda}_n)P_n,$$
$$r_n=(\lambda_n{}^f/\lambda_n)P_n,\quad \lambda_n=\lambda_n{}^f+\sum_{n'<n}\lambda_{nn'}. \tag{13}$$

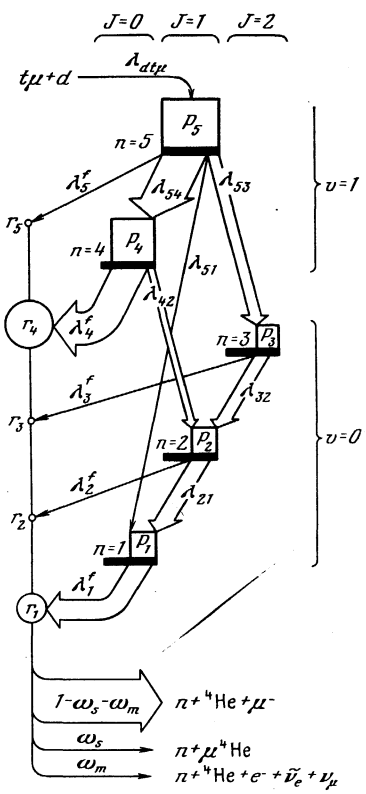


FIG. 2. Scheme of cascade processes in the mesic molecule $dt\mu$.

The lifetime $\tau_n = \tau_{nFS}$ of the molecule $dt\mu$ in the state $n$ and the total time $\tau_{FS}$ of the cascade from the state $(FS)$ of the level $n = 5$ are

$$\tau_n = P_n/\lambda_n, \qquad \tau_{FS} = \sum_n \tau_{nFS}. \tag{14}$$

The results of the calculations are given in Table III. For $(FS) = (01), (12), (11)$ the cascade develops as follows (see Fig. 2). From the initial state $n = 5$, the mesic molecule $dt\mu$ goes over with probability 0.9 to the state $n = 4$, where the probability 0.80–0.86 the nuclear fusion reactions (3) take place. The ground state ($n = 1$) is populated with probabilities 0.20–0.14 mainly through the intermediate state $n = 2$, the rate of the nuclear reaction from this state being much less than the rate of Auger de-excitation. Thus, for population of the hyperfine structure states $(FS) = (01)$, (12), and (11) the nuclear fusion reaction takes place with probability effectively equal to 1 from the mesic-molecular states $n = 1$ and $n = 4$ with $J = 0$, and the rates $\lambda^f_{J\upsilon FS} \approx \lambda^f_{J\upsilon FS}(3/2^+)$ of the nuclear reaction significantly exceed the rates $\lambda_{nn'}$ of the Auger transitions. The total cascade time in this case is determined basically by the de-excitation rates $\lambda_{nn'}$ and is $\tau_{FS} \lesssim 10^{-11}$ sec.

For $(FS) = (10)$, the rates of de-excitation are large compared with the rates of the nuclear reaction (3), and it therefore takes place with probability 0.60 from the ground state $n = 1$ of the mesic molecule $dt\mu$ and only with probability 0.40 from the state $n = 4$. The lifetime of the mesic molecule in this case is determined not only by the de-excitation rates $\lambda_{nn'}$ but also by the nuclear reaction rates $\lambda^f_{0\upsilon 10}(1/2^+)$ and is $\tau_{10} = 4\times 10^{-11}$ sec.

The lifetime $\tau_m$ of the mesic molecule is calculated in accordance with

$$\tau_m = \sum_{FS} P_{FS}\tau_{FS}, \tag{15}$$

where $P_{FS}$ and $\tau_{FS}$ are determined by Eqs. (6), (7), and (14). In the limiting cases, we find:

a) $\lambda_{dt\mu}(F=1) \gg \lambda_t$,

$\tau_m = {}^3/_4({}^1/_9\tau_{10} + {}^1/_3\tau_{11} + {}^5/_9\tau_{12}) + {}^1/_4\tau_{01} = 1.1\cdot 10^{-11}$ sec;

b) $\lambda_{dt\mu}(F=1) \ll \lambda_t$, $\tau_m = \tau_{01} = 0.8\cdot 10^{-11}$ sec.

Thus, the lifetime of the molecule $dt\mu$ is in the range

$$0.8\cdot 10^{-11} < \tau_m < 1.1\cdot 10^{-11}, \tag{16}$$

and the probability of decay of the $\mu^-$ meson during the time of the cascade in the molecule $dt\mu$ does not exceed

$$\omega_m = \tau_m/\tau_0 \approx 5\cdot 10^{-6}. \tag{17}$$

To determine $\tau_m$ and $\omega_m$ more accurately, we need to know the rates $\lambda_{dt\mu}(F=1)$ and $\lambda_{J\upsilon 10}(1/2^+)$ more accurately.

## 4. CONCLUSIONS

The muon, released in the reaction (3a) with energy $\sim 10$ keV, returns after the chain of muon catalysis reactions

$$\mu^- \xrightarrow{\tau_a} t\mu \xrightarrow{\tau_{dt\mu}} dt\mu \xrightarrow{\tau_m} \mu^-, \tag{18}$$

$$\mu^- \xrightarrow{\tau_a} d\mu \xrightarrow{\tau_{dt}} t\mu \xrightarrow{\tau_{dt\mu}} dt\mu \xrightarrow{\tau_m} \mu^- \tag{19}$$

to the start of the muon catalysis cycle[20] after times $\tau = \tau_a + \tau_{dt\mu} + \tau_m$ and $\tau = \tau_a + \tau_{dt} + \tau_{dt\mu} + \tau_m$.

Our investigation shows that at liquid hydrogen density in the mixture $D_2 + T_2$ the lifetime $\tau_m \approx 10^{-11}$ sec of the mesic molecule $dt\mu$ (like the cascade time $\tau_a < 2\times 10^{-11}$ sec

TABLE III. Characteristics of cascades in the mesic molecule $dt\mu$.

| | $n$ | $P_n$ | $r_n$ | $n \to n'$ | | $\tau_n$, psec |
|---|---|---|---|---|---|---|
| | | | | $n'$ | $y_{nn'}$ | |
| $F=0$ | 5 | 1 | $3.1\cdot 10^{-5}$ | 4 | 0.90 | |
| $S=1$ | | | | 3 | 0.10 | 0.8 |
| $\tau_{01}=7.7$ psec | | | | 1 | $1.6\cdot 10^{-3}$ | |
| | 4 | 0.90 | 0.84 | 2 | 0.055 | 1.2 |
| | 3 | 0.10 | $1.3\cdot 10^{-7}$ | 2 | 0.10 | 1.8 |
| | 2 | 0.16 | $3.7\cdot 10^{-4}$ | 1 | 0.16 | 3.7 |
| | 1 | 0.16 | 0.16 | – | – | 0.2 |
| $F=1$ | 5 | 1 | $4.1\cdot 10^{-5}$ | 4 | 0.90 | |
| $S=2$ | | | | 3 | 0.10 | 0.8 |
| $\tau_{12}=6.9$ psec | | | | 1 | $1.6\cdot 10^{-3}$ | |
| | 4 | 0.90 | 0.86 | 2 | 0.037 | 0.9 |
| | 3 | 0.10 | $1.9\cdot 10^{-7}$ | 2 | 0.10 | 1.8 |
| | 2 | 0.14 | $4.3\cdot 10^{-4}$ | 1 | 0.14 | 3.3 |
| | 1 | 0.14 | 0.14 | – | – | 0.1 |
| $F=1$ | 5 | 1 | $2.1\cdot 10^{-5}$ | 4 | 0.90 | |
| $S=1$ | | | | 3 | 0.10 | 0.8 |
| $\tau_{11}=10$ psec | | | | 1 | $1.6\cdot 10^{-3}$ | |
| | 4 | 0.90 | 0.80 | 2 | 0.10 | 2.2 |
| | 3 | 0.10 | $6.9\cdot 10^{-8}$ | 2 | 0.10 | 1.8 |
| | 2 | 0.20 | $3.1\cdot 10^{-4}$ | 1 | 0.20 | 4.8 |
| | 1 | 0.20 | 0.20 | – | – | 0.5 |
| $F=1$ | 5 | 1 | $1.1\cdot 10^{-5}$ | 4 | 0.90 | |
| $S=0$ | | | | 3 | 0.10 | 0.8 |
| $\tau_{10}=40$ psec | | | | 1 | $1.6\cdot 10^{-3}$ | |
| | 4 | 0.90 | 0.40 | 2 | 0.50 | 11.3 |
| | 3 | 0.10 | $1.0\cdot 10^{-8}$ | 2 | 0.10 | 1.8 |
| | 2 | 0.60 | $4.9\cdot 10^{-4}$ | 1 | 0.60 | 14.3 |
| | 1 | 0.60 | 0.60 | – | – | 13.9 |

in the atoms $d\mu$ and $t\mu$) is negligibly small compared with the times $\tau_{dt}$ and $\tau_{dt\mu}$ of the isotopic exchange $d\mu \rightarrow t\mu$ and production of the $dt\mu$ molecules. Therefore, in a study of the kinetics of muon catalysis in the mixture $D_2 + T_2$ the probability $\omega_a + \omega_m$ of muon decay during the time of the mesoatomic and mesomolecular cascades can be ignored compared with the probability $\omega_S = 0.009$ of "poisoning of the catalyst" in the process (3b).[21,22]

In this paper, we have shown that the nuclear reaction (3) in the mesic molecule $dt\mu$ takes place with overwhelming probability from states with total angular momentum $J = 0$. This fact was used earlier in Refs. 21 and 22 without justification in the calculation of the sticking probability $\omega_s$.

We should like to thank D. D. Bakalov, S. I. Vinitskiĭ, L. I. Men'shikov, L. N. Somov, and M. P. Faĭfman for assistance and fruitful discussions.

[11]The values of $a_{FS}$ were calculated with allowance for the relativistic effects $\sim\alpha^2$ in Ref. 11.

[1]M. Leon and H. Bethe, Phys. Rev. **127**, 636 (1962); G. Ya. Korenman, Yad. Fiz. **32**, 916 (1980) [Sov. J. Nucl. Phys. **32**, 472 (1980)].
[2]V. E. Markushin, Zh. Eksp. Teor. Fiz. **80**, 35 (1981) [Sov. Phys. JETP **53**, 16 (1981)].
[3]L. I. Ponomarev, Proceedings of Sixth Int. Conf. on Atomic Physics, 17–22, August, Riga (1978); Zinatne and Plenum Press (1979), p. 182.
[4]V. M. Bystritskiĭ, V. P. Dzhelepov, Z. B. Ershova, *et al.*, Pis'ma Zh. Eksp. Teor. **31**, 249 (1980) [JETP Lett. **31**, 228 (1980)]; Zh. Eksp. Teor. Fiz. **80**, 1700 (1981) [Sov. Phys. JETP **53**, 877 (1981)].
[5]S. I. Vinitskiĭ, L. I. Ponomarev, I. V. Puzynina, T. P. Puzynina, L. N. Somov, and M. P. Faĭfman, Zh. Eksp. Teor. Fiz. **74**, 849 (1978) [Sov. Phys. JETP **47**, 444 (1978)].
[6]S. I. Vinitskiĭ, L. I. Ponomarev, and M. P. Faĭfman, Preprint R4-81-572 [in Russian], JINR, Dubna (1981).
[7]L. N. Bogdanova, V. E. Markushin, V. S. Melezhik, and L. I. Ponomarev, Yad. Fiz. **34**, 1191 (1981) [Sov. J. Nucl. Phys. **34**, 662 (1981)].
[8]L. N. Bogdanova, V. E. Markushin, and V. S. Melezhik, Zh. Eksp. Teor. Fiz. **81**, 829 (1981) [Sov. Phys. JETP **54**, 442 (1981)].
[9]S. S. Gershteĭn, Yu. V. Petrov, L. I. Ponomarev, L. N. Somov, and M. P. Faĭfman, Zh. Eksp. Teor. Fiz. **78**, 1099 (1980) [Sov. Phys. JETP **51**, 554 (1980)].
[10]S. I. Vinitskiĭ, V. S. Melezhik, L. I. Ponomarev, I. V. Puzynin, T. P. Puzynina, L. I. Somov, and N. F. Truskova, Zh. Eksp. Teor. Fiz. **79**, 698 (1980) [Sov. Phys. JETP **52**, 353 (1980)].
[11]D. Bakalov, S. I. Vinitskiĭ, and V. S. Melezhik, Zh. Eksp. Teor. Fiz. **79**, 1629 (1980) [Sov. Phys. JETP **52**, 820 (1980)].
[12]D. Bakalov, Phys. Lett. **93B**, 265 (1980).
[13]A. V. Matveenko and L. I. Ponomarev, Zh. Eksp. Teor. Fiz. **59**, 1593 (1970) [Sov. Phys. JETP **32**, 871 (1971)].
[14]M. Kaoua, M. Allab, C. Gerardin, and R. Seltz, Nuovo Cimento **54A**, 321 (1979).
[15]F. Ajzenberg-Selove, Nucl. Phys. **A320**, 1 (1979).
[16]S. Deser, M. L. Goldberger, K. Baumann, and W. Thirring, Phys. Rev. **96**, 774 (1974).
[17]S. I. Vinitskiĭ, V. S. Melezhik, and L. I. Ponomarev, Preprint R4-80-755 [in Russian], JINR, Dubna (1980).
[18]L. I. Men'shikov, Preprint No. 4237 [in Russian], Institute of Atomic Energy (1981).
[19]W. A. Chupka, M. E. Russel, and K. Refaev, J. Chem. Phys. **48**, 1518 (1968).
[20]L. I. Ponomarev, Talk at the Tenth European Conf. on Controlled Fusion and Plasma Physics, Moscow, September 14–19 (1981); Preprint R4-81-800 [in Russian], JINR, Dubna (1981).
[21]S. S. Gershteĭn, Yu. V. Petrov, L. I. Ponomarev, N. P. Popov, L. P. Presnyakov, and L. N. Somov, Zh. Eksp. Teor. Fiz. **80**, 1690 (1981) [Sov. Phys. JETP **53**, 872 (1981)].
[22]L. Bracci and G. Fiorentini, Nucl. Phys. **A364**, 383 (1981).

Translated by Julian B. Barbour