

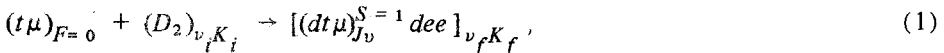
# Experimental limitations on the binding energy of $J=v=1$ states of the $d\text{t}\mu$ mesic molecule

L. I. Men'shikov and L. I. Ponomarev

(Submitted 23 February 1987; resubmitted 15 April 1987)  
 Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 10, 471-473 (25 May 1987)

Analysis of experimental data on the formation rates of  $d\text{t}\mu$  mesic molecules at low temperatures yields an estimate of the energy of the transition from the  $F=0$  spin state of the mesic atom  $\text{t}\mu$  to the weakly bound  $J=v=1$  state of the mesic molecule  $d\text{t}\mu$ , with a total spin  $S=1$ . This estimated transition energy is  $\Delta\epsilon = 0.597 \pm 0.002$  eV. An estimate making use of theoretical values of the relativistic corrections then leads to the following binding energy of the  $J=v=1$  state of the mesic molecule  $d\text{t}\mu$ :  $|\epsilon_{11}| = 0.656 \pm 0.002$  eV.

The high rate  $\lambda_{d\text{t}\mu}$  of the resonant production of the  $d\text{t}\mu$  mesic molecule, which has been observed experimentally<sup>2,3</sup> in the liquid mixture  $D_2 + T_2$ , can be explained, as was shown in Ref. 1, in terms of collisions of thermalized  $\text{t}\mu$  atoms with  $D_2$  molecules in the reactions



where  $F$  and  $S$  are the total spins of the  $\text{t}\mu$  atom and of the  $d\text{t}\mu$  molecule, respectively;  $J=v=1$  are the quantum numbers of the weakly bound state of the  $d\text{t}\mu$  molecule;  $v_i=0$  and  $v_f=2$  are the vibrational quantum number of the  $D_2$  molecule and of the mesic-molecule complex  $MD \equiv [(d\text{t}\mu)\text{dee}]$ ; and  $K_i$  and  $K_f$  are their rotational quantum numbers.

At the temperature  $T=23$  K (corresponding to the experimental conditions of Ref. 3) and at a mixture density  $\varphi = N/N_0 = 1.2$  ( $N_0 = 4.25 \times 10^{22} \text{ cm}^{-3}$ ), the population of the  $D_2$  states with  $K_i \geq 1$  is small ( $\sim 3.6\%$ ), so that it is sufficient to consider the transitions  $(K_i=0) \rightarrow (K_f=0,1,2,3)$ . The resonance condition is<sup>4,5</sup>

$$\epsilon_{K_i K_f}^r = \Delta E_{K_i K_f} - \Delta\epsilon, \quad (2)$$

where  $\Delta\epsilon$  is the energy of the transition  $(\text{t}\mu)_{F=0} \rightarrow (d\text{t}\mu)_{J=v=1}^{S=1}$ , and  $\Delta E_{K_i K_f} = E_{v_f, K_f}(MD) - E_{v_i, K_i}(D_2)$  is the difference between the levels of the complex  $MD$  and of the molecule  $D_2$ .

According to the calculations of Ref. 6, the values of  $\Delta E_{K_i K_f}$  are  $\Delta E_{00} = 0.5794$  eV,  $\Delta E_{01} = 0.5842$  eV,  $\Delta E_{02} = 0.5939$  eV, and  $\Delta E_{03} = 0.6085$  eV.

The width ( $\Gamma_{K_f}$ ) of the states  $K_f$  of the  $MD$  complex is determined by the rate of de-excitation,  $(J=v=1) \rightarrow J'v'$ , of the  $d\text{t}\mu$  molecule:  $\lambda_{\text{dex}} = 1.2 \times 10^{12} \text{ s}^{-1} = 0.8 \times 10^{-3} \text{ eV} \equiv \Gamma_v$  (Ref. 8). It is also determined by the collisional width<sup>10</sup>  $\Gamma_\varphi$ , which is, according to the calculations of Ref. 11,  $\Gamma_\varphi = 0.004\varphi$  eV. In other words,

the total width of the resonances is  $\Gamma_{K_f} \approx \Gamma = \Gamma_\varphi + \Gamma_\nu = 0.004(\varphi + 0.2)$  eV.

The rate of resonance process (1), referred to a density  $\varphi = 1$ , can be written

$$\lambda_{dt\mu}^0 = \sum_{K_f} \lambda_{0K_f}^0, \quad (3)$$

where the partial rates  $\lambda_{K_i K_f}^0$  are given at high densities  $\varphi \gtrsim 0.2$ , i.e., at  $\Gamma_\varphi \gtrsim \Gamma_\nu$ , by the expressions<sup>11</sup>

$$\lambda_{K_i K_f}^0 = \begin{cases} \text{for } |\epsilon_r| \lesssim \Gamma, \\ 2N_0 \Gamma \pi^{-1/2} T^{-3/2} \int_0^\infty \frac{d\epsilon \sqrt{\epsilon} V_{K_i K_f}^2(\epsilon) \exp(-\epsilon/T)}{(\epsilon - \epsilon_r)^2 + \Gamma^2/4}; \quad (4a) \\ \text{for } \epsilon_r \gtrsim \Gamma, \\ N_0 \cdot 4(\pi\epsilon_r)^{1/2} T^{-3/2} V_{K_i K_f}^2(\epsilon_r) \exp(-\epsilon_r/T); \quad (4b) \\ \text{for } \epsilon_r \lesssim -\Gamma, \\ \lambda_{qr}. \quad (4c) \end{cases}$$

where the matrix elements  $V_{K_i K_f}^2(\epsilon)$ , calculated from the expressions of Refs. 4 and 14, are shown in Fig. 1, while the rates ( $\lambda_{qr}$ ) of the production of the  $dt\mu$  molecules in ternary collisions of the type



were calculated in Ref. 12.

At  $\varphi \lesssim 0.2$ , i.e., at  $\Gamma_\varphi \lesssim \Gamma_\nu$ , regardless of the relation between  $\epsilon_r$  and  $\Gamma$ , the rates  $\lambda_{K_i K_f}^0$  are calculated from expression (4a), which was first proposed by Petrov<sup>11</sup> (Ref. 10).

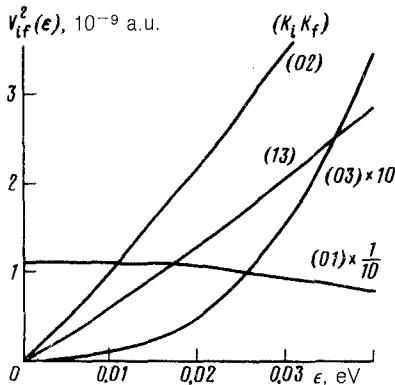


FIG. 1. The matrix elements  $V_{K_i K_f}^2(\epsilon)$  corresponding to the transitions  $K_i \rightarrow K_f$ .

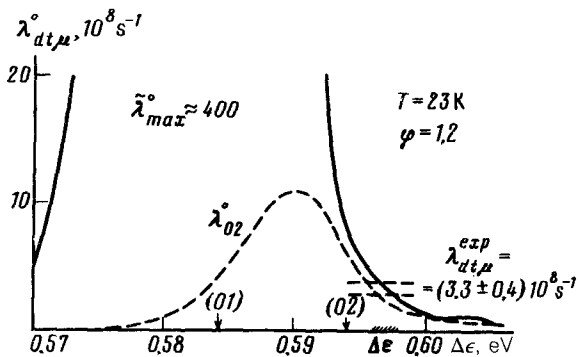


FIG. 2. The reduced rate  $\lambda_{dt\mu}^0$  of the resonant production of  $dt\mu$  molecules as a function of the transition energy  $\Delta\epsilon$ . The dashed line shows the rate of the transition ( $K_i = 0$ )  $\rightarrow$  ( $K_f = 2$ ). The arrows show the values of  $\Delta\epsilon = \Delta E_{K,K_f}$  for which we have  $\epsilon_{K,K_f}^r = 0$ .

Figure 2 shows the rates  $\lambda_{dt\mu}^0$  calculated from (4) at  $T = 23$  K and  $\varphi = 1.2$ , as functions of the transition energy  $\Delta\epsilon$ .

The experimental value<sup>3</sup> of the reduced rate  $\lambda_{dt\mu}^0$  at  $T = 23$  K and  $\varphi = 1.2$  is  $\lambda_{dt\mu}^{exp} = (3.3 \pm 0.4) \times 10^8$  s<sup>-1</sup>. It follows from Fig. 2 that this value is achieved at the transition energy

$$\Delta\epsilon = 0.597 \pm 0.002 \text{ eV.} \quad (6)$$

It can also be seen from Fig. 2 that the only major contribution to the value of  $\lambda_{dt\mu}^0$  comes from the single transition ( $K_i = 0$ )  $\rightarrow$  ( $K_f = 2$ ), with a resonance energy  $\epsilon_{02}^r = -0.003$  eV. Despite the large value of the matrix element  $V_{01}(\epsilon)$  (Fig. 1), the transition ( $K_i = 0$ )  $\rightarrow$  ( $K_f = 1$ ) is strongly suppressed, because its rate is determined by three-particle reaction (5), which is improbable at the resonance energy<sup>12</sup>  $\epsilon_{01}^r = -0.013$  eV corresponding to this transition.

Using the relativistic corrections  $\Delta\epsilon_{11}^{rel} = 0.023$  eV and the hyperfine splitting of the levels of the  $t\mu$  atom and of the  $dt\mu$  molecule,  $\Delta\epsilon_{FS} = 0.036$  eV (see the review in Ref. 15 and the bibliography there), we can find a nonrelativistic value for the binding energy of the molecule:

$$|\epsilon_{11}| = \Delta\epsilon + \Delta\epsilon_{11}^{rel} + \Delta\epsilon_{FS} = 0.656 \pm 0.002 \text{ eV.} \quad (7)$$

This result is in reasonable agreement with the most recent theoretical calculations.<sup>13,16</sup> The indicated errors in  $|\epsilon_{11}|$  do not include the errors in the theoretical value of  $\Delta\epsilon_{11}^{rel}$  or the errors in the theoretical values of  $\lambda_{dt\mu}$ , which stem from the approximate calculation of the transition matrix elements  $V_{K,K_f}$ .

It is our pleasure to thank Yu. V. Petrov for lengthy and useful discussions of the effect of a finite level width on the rate of resonant production of mesic molecules. We also thank A. A. Zverev, T. A. Strizh, and M. P. Faifman for assistance in the numerical calculations.

<sup>11</sup> Under the condition  $\Gamma_\varphi \gtrsim \Gamma_0$  the resonance retains its Lorentzian shape only under the condition  $|\epsilon - \epsilon_r| \lesssim \Gamma$ ; at the wings of the resonance curve, i.e., at  $|\epsilon - \epsilon_r| \gtrsim \Gamma$ , its shape is very different from

Lorentzian.<sup>11</sup> (A similar phenomenon is well known in the theory of the collisional broadening of spectral lines.)

<sup>1</sup>L. I. Men'shikov and L. I. Ponomarev, *Pis'ma Zh. Eksp. Teor. Fiz.* **45**, 329 (1987) [*JETP Lett.* **45**, 430 (1987)].

<sup>2</sup>S. E. Jones, A. N. Anderson, A. J. Caffrey *et al.*, *Phys. Rev. Lett.* **51**, 1757 (1983); **56**, 588 (1986).

<sup>3</sup>W. H. Breunlich, M. Cargnelli, P. Kammel *et al.*, *Phys. Rev. Lett.* **53**, 1137 (1984).

<sup>4</sup>L. I. Men'shikov, *Yad. Fiz.* **42**, 1184 (1985) [*Sov. J. Nucl. Phys.* **42**, 750 (1985)].

<sup>5</sup>M. P. Faifman, L. I. Men'shikov, L. I. Ponomarev, and T. A. Strizh, Preprint JINR-E4-86-541, Dubna, 1986.

<sup>6</sup>M. P. Faifman, L. I. Men'shikov, L. I. Ponomarev *et al.*, *Z. Phys.* **D2**, 79 (1986).

<sup>7</sup>M. Leon, *Phys. Rev. Lett.* **42**, 605 (1984).

<sup>8</sup>S. I. Vinitskiĭ, L. I. Ponomarev, and M. P. Faifman, *Zh. Eksp. Teor. Fiz.* **82**, 985 (1982) [*Sov. Phys. JETP* **55**, 578 (1982)].

<sup>9</sup>L. N. Bogdanova, V. E. Markushin, V. S. Melezhik, and L. I. Ponomarev, *Zh. Eksp. Teor. Fiz.* **83**, 1615 (1982) [*Sov. Phys. JETP* **56**, 931 (1982)].

<sup>10</sup>Yu. V. Petrov, *Phys. Lett.* **B163**, 28 (1985).

<sup>11</sup>L. I. Men'shikov, Preprint IAÉ-4295/12, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1987.

<sup>12</sup>L. I. Men'shikov and L. I. Ponomarev, *Phys. Lett.* **B167**, 141 (1985).

<sup>13</sup>A. D. Gocheva, V. V. Gusev, V. S. Melezhik *et al.*, *Phys. Lett.* **153B**, 349 (1985).

<sup>14</sup>L. I. Men'shikov and L. I. Ponomarev, Preprint IAÉ-4297/12, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1987.

<sup>15</sup>L. I. Ponomarev, Talk at the Tenth International Conference on Atomic Physics, Tokyo, Japan, August 25–29, 1986.

<sup>16</sup>S. I. Vinitskiĭ, V. I. Korobov, and I. V. Puzynin, *Zh. Eksp. Teor. Fiz.* **91**, 705 (1986) [*Sov. Phys. JETP* **64**, 417 (1987)].

Translated by Dave Parsons