Superthermal mechanism for the formation of $dt\mu$ muonic molecules

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The resonant formation of $dt\mu$ muonic molecules reaches a large observable value at low temperatures in a $D_2 + T_2$ mixture in the reaction $t\mu + D_2 \rightarrow [(dt\mu)dee]$ when the $t\mu$ atoms have a kinetic energy $E \sim kT$.

1. A superthermal mechanism for the formation of $dt\mu$ molecules was discussed in Refs. 4–5 in order to explain the large observed rate $\lambda^{0}_{dt\mu-d}$ of the resonant formation of $dt\mu$ muonic molecules in the reaction

$$t\mu + D_2 \rightarrow [(dt\mu)dee] \qquad (1)$$

at low temperatures ($T \lesssim 30$ K) in a $D_2 + T_2$ mixture.[1–3] This mechanism can be summarized as follows: A fraction N^{0}_{F} of the $t\mu$ muonic atoms produced in the isotope

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exchange reaction

$$d\mu + t \rightarrow t\mu + d \tag{2}$$

with an energy $E \approx 20$ eV participates in reaction (1) before these atoms have time to slow to the average energies $E \sim kT \approx 3$ meV corresponding to the temperature of the $D_2 + T_2$ mixture. The fraction of fast $t\mu$ atoms, N_F^0, should in this case be comparable to the fraction (N_S^0) of slow $t\mu$ atoms ($N_F^0 + N_S^0 = 1$).

At first glance, it would seem that this explanation is supported by the experimental data of Ref. 2, which show the rate $\lambda_{dt\mu}$ increasing sharply with increasing temperature of the medium and thus with increasing average kinetic energy of the $t\mu$ atoms. The naive basis (not always explicitly stated) for such conclusions consists of the use of the "natural" relation

$$\lambda_{dt\mu} \approx \lambda_F N_F^0 + \lambda_S N_S^0, \tag{3}$$

where λ_F and λ_S are the rates of reaction (1) for fast (superthermal) and slow (thermalized) $t\mu$ atoms.

Further calculations[5,6] have shown, however, that the relation $N_F^0 \ll 1$ holds (at mixture densities $\varphi \sim 1, \varphi = N/N_0$, N is the number of nuclei per cubic centimeter of the mixture, and $N_0 = 4.25 \times 10^{22}$ cm^{-3}), so that in order to preserve the previous explanation, it is necessary to assume the validity of the relation[5]

$$\lambda_F N_F^0 \gg \lambda_S N_S^0, \tag{4}$$

which seems plausible even under the condition $N_F^0 \ll N_S^0$, since we have $\lambda_F \gg \lambda_S$ (in accordance with experiment).

Another explanation for the observed facts is based on the idea that all of the $t\mu$ atoms are thermalized quite rapidly and that the rate (λ_S) at which they enter resonance reaction (1) is quite high, even if the mixture is at a low temperature. We will now show that this second explanation of the corresponding experimental data is preferable to the first.

2. We distinguish between two groups of $t\mu$ atoms: fast atoms, N_F, with an energy $E \sim 0.1$–0.3 eV and slow atoms, N_S, with an energy $E \sim 0.003$ eV. We introduce λ_F and λ_S, the rates at which they enter reaction (1), and the thermalization rate λ_T, i.e., the rate of the transition of $t\mu$ muonic atoms from group N_F to group N_S. In this two-group approximation, the basis scheme of the processes resulting in the formation of $dt\mu$ muonic molecules and the subsequent nuclear fusion,

$$dt\mu \xrightarrow[\lambda_f]{} \begin{cases} \xrightarrow{1-\omega_s} {}^4\mathrm{He} + n + \mu^- \\ \xrightarrow{\omega_s} \mu^4\mathrm{He} + n \end{cases}, \tag{5}$$

is as shown in Fig. 1, where the following notation[7] is also introduced: $\lambda_f \approx 1.1 \times 10^{12}$ s^{-1} is the rate of fusion (5) (Ref. 8), $\omega_S \approx 0.5 \times 10^{-2}$ is the coefficient of the attachment of the muon to helium,[3,9,10] and $\lambda_0 = 0.46 \times 10^6$ s^{-1} is the muon decay rate.

Since we have $\lambda_f \gg \{\lambda_F, \lambda_S, \lambda_T\}$ at $t \gg \lambda_f^{-1}$ there is a quasisteady regime, with[7,11] $dN_{dt\mu}/dt \approx 0$. The corresponding solution with the initial conditions

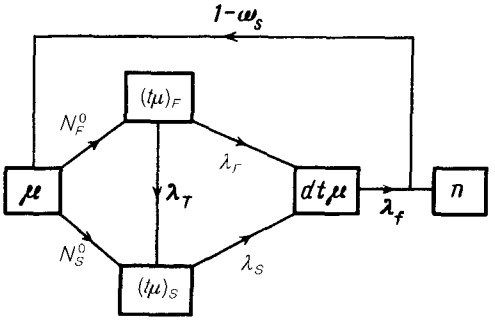

FIG. 1.

$$N_F(0) = N_F^0,\ N_S(0) = N_S^0,\ N_{dt\mu}(0) = N_n(0) = 0 \tag{6}$$

can be written

$$\begin{aligned} &N_F(t) = N_F^0(1-\lambda_S/\lambda)\exp\{-\lambda t\} + N_F^0(\lambda_S/\lambda)\exp\{-(\lambda_0+\omega_S\lambda_c)t\},\\ &N_S(t) = \exp\{-(\lambda_0+\omega_S\lambda_c)t\} - N_F(t),\\ &\lambda = \lambda_T + \lambda_F N_S^0 + \lambda_S N_F^0 = \lambda_T + \lambda_F + (\lambda_S - \lambda_F)N_F^0,\\ &\lambda_c = \lambda_S(\lambda_T+\lambda_F)\lambda^{-1} = \lambda_S\left(1+\frac{\lambda_S-\lambda_F}{\lambda_T+\lambda_F}N_F^0\right)^{-1}. \end{aligned} \tag{7}$$

The time-dependent distribution of fusion neutrons, dN_n/dt, and the total yield of these neutrons (the number of cycles of μ catalysis, X_c) are given by

$$\begin{aligned} &\frac{dN_n}{dt} = \lambda_c\exp\{-(\lambda_0+\omega_S\lambda_c)t\} + N_F^0(\lambda_F-\lambda_S)(1-\lambda_S/\lambda)\exp\{-\lambda t\},\\ &X_c = (\omega_S + \lambda_0/\lambda_c)^{-1} + N_F^0(\lambda_F-\lambda_S)(1-\lambda_S/\lambda)\lambda^{-1}. \end{aligned} \tag{8}$$

In the single-group approximation, i.e., with $\lambda_T = N_F^0 = 0$, $\lambda_F = \lambda_S$, Eqs. (7) and (8) transform into the well-known equations[2,12] for the case $q_{1s} \ll 1$. Using data on the cross sections for elastic scattering of $t\mu$ atoms,[13] we can estimate the thermalization rate: $\lambda_T \sim 2\times 10^9\varphi\ \text{s}^{-1}$. From experiments we also have the estimate $\lambda_F \approx 2\times 10^9\varphi\ \text{s}^{-1} \gg \lambda_S$, so that we have $(\lambda_F-\lambda_S)/(\lambda_T+\lambda_F) \approx \lambda_F/(\lambda_T+\lambda_F)$; the left side of this relation is always less than unity, regardless of the relation between λ_F and λ_T. Consequently, under the conditions $\lambda_F \gg \lambda_S$ and $N_F^0 \ll 1$ we have

$$\begin{aligned} &\frac{dN_n}{dt} \approx \lambda_S\exp\{-(\lambda_0+\omega_S\lambda_S)t\} + N_F^0\lambda_F\exp\{-(\lambda_T+\lambda_F)t\},\\ &X_c \approx (\omega_S+\lambda_0/\lambda_S)^{-1}. \end{aligned} \tag{9}$$

The overwhelming majority of the neutrons in reaction (5) appear in the steady state at $t \gg (\lambda_T+\lambda_F)^{-1}$, and the rate of the μ-catalysis cycle is determined by the slow

velocity λ_S, even under the condition $\lambda_F \gg \lambda_S$. This conclusion contradicts the intuition on which relation (3) is based. The reason for the erroneous conclusions which follow from it is that the important characteristics of the process (λ_c and X_c) are determined by the steady-state regime, in which we should use, instead of the initial populations N_F^0 and N_S^0, the equilibrium populations $N_S/(N_S+N_F) \approx 1$ and $N_F/(N_S+N_F) \approx N_F^0 \lambda_S/(\lambda_T+\lambda_F) \ll N_F^0 \ll 1$. This conclusion follows from Eqs. (7) at $t \gg \lambda^{-1}$ and from the definition (which does not depend on the time at $t \gg \lambda^{-1}$

$$\lambda_{dt\mu} = \frac{\lambda_F N_F + \lambda_S N_S}{N_F + N_S}, \tag{10}$$

from which we also find, in particular, our basic relation $\lambda_{dt\mu} \approx \lambda_S$.

It thus follows from the results of this analysis that the contribution of fast $t\mu$ muonic atoms to the observed rate of formation of $dt\mu$ molecules can be ignored, and the high formation rate $\lambda_{dt\mu}$ observed in the experiments of Refs. 2 and 3 at low temperatures is unambiguous evidence of a high rate λ_S of the formation of $dt\mu$ muonic molecules in reaction (1) in collisions of D_2 molecules with thermalized $t\mu$ atoms ($E \sim kT$). This conclusion substantially alters the customary approach to analyzing μ-catalysis processes at low temperatures and it leads to certain conclusions regarding the structure of the energy levels of the $dt\mu$ muonic molecule.[14]

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