Charge exchange of excited mesic atoms of hydrogen isotopes in triple collisions with molecules

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At high densities of deuterium-tritium mixture the probability for the occurrence of the isotope-exchange reaction $(d\mu)_n + t \to d + (t\mu)_n$ from the excited states of n mesic atoms of deuterium is high in the triple collisions of mesic atoms with the molecules of hydrogen isotopes. This reaction should be taken into account in describing the kinetics of muon catalysis.

1. Men'shikov and Ponomarev[1] have shown that the quasiresonant charge exchange

$$(d\mu)_n + t \to d + (t\mu)_n \tag{1}$$

has an appreciable effect on the kinetics of muon catalysis in the mixture $D_2 + T_2$ upon a collision of mesic atoms $(d\mu)_n$ in the excited $n = 2$–5 states with tritium nuclei. The rates of reactions (1), $\lambda_{ex} = \lambda^0_{exp} C_t \varphi$, increase linearly with increasing density of the mixture, φ, and with increasing tritium concentration C_t.[2] The same φ dependence characteristic of the rates of resonant production of the mesic molecules $dd\mu$ and $dt\mu$.[3,5] Experimental data obtained recently[6] show, however, that some characteristics of the kinetics of muon catalysis may depend on φ and C_t in a nonlinear manner.

2. In this letter we consider the charge-exchange reaction (1) in triple collisions of the type

$$(d\mu)_n + AT + M \to (t\mu)_n + DA + M^*, \tag{2}$$

where AT is a molecule that contains the tritium atom (T_2, DT, HT), and M and M^* is a hydrogen-isotope molecule in the mixture ($H_2 + D_2 + T_2$) in the initial and final state, respectively. Since the mesic atom $(d\mu)_n$ has a nonzero dipole moment $d_n = 3n\Delta/2m\mu$ (in units of $e = \hbar = m_e = 1$), where $\Delta = n_1 - n_2$; n_1, n_2, and m are the parabolic quantum numbers of the $d\mu$ atom; and $m_\mu \approx 207 m_e$ is the muon mass, the energy required to attract the mesic atom $(d\mu)_n$, $U = \mathbf{d}_n \boldsymbol{\epsilon}$, by the field $\epsilon(R)$ of an AT molecule in the state $n_1 < n_2$ is rather large ($U \sim 1$ eV even at $R \sim 1$, i.e., at distances on the order of atomic separation).

The reaction (2) occurs in two stages: A short-lived intermediate complex $[(d\mu)_n AT]$ with a large cross section ($\sigma \sim 10^{-16}$ cm^2) is produced first.[2] At low densities φ, the probability of reaction (1) in this complex is $W_{ex} \sim 0.1$ and the probability that this complex will again break up into $(d\mu)_n$ and AT is $1 - W_{ex} \approx 0.9$. At high densities φ, an M molecule can draw from the complex during its existence an energy on the order of the thermal energy, $\sim \epsilon_T$, thereby hindering its breakup. The complex then undergoes reaction (1), whose probability is ≈ 1.

The volume V of the complex $[(d\mu)_n AT]$, at the boundary of which the attractive potential energy $|U(R)| \gtrsim \epsilon_T$ is greater than the energy of thermal collisions of the atoms, is

$$V \approx \pi R_1^2 \,(2R_1 + 0,7) \sim 30 - 300 \text{ a.u.} \tag{3}$$

when $n = 3$–5 and 0.01 eV $\lesssim \epsilon_T \lesssim$ 0.1 eV. Here the distance $R_1 \approx (1/2) ln(9n^2/4m_\mu \epsilon_T)$ is determined from the condition $|d_n \epsilon(R_1)| = \epsilon_T$, where $d_n \approx 3n^2/4m_\mu$ is a typical dipole moment of the $(d\mu)_n$ atom, and the electric field $\epsilon(R)$ of the hydrogen atom (or of the AT molecule) at a distance R from the $d\mu$ atom is

$$\epsilon(R) = (R^{-2} + 2R^{-1} + 2)\, e^{-2R} \approx 3e^{-2R}.$$

Upon a collision of the M molecule with this complex, the molecule can either transfer the energy ϵ_T to this complex or take the energy away from it with equal probability. In other words, the probability for the stabilization of the complex is $P_2 \approx 0.5$. (This assumption corresponds to the well-known Thomson model.[7]) Allowing for the fact that the complex forms only in one-half of the cases ($P_1 \approx 0.5$), under the condition $n_1 < n_2$ the rate of reaction (2) can be determined from the expression

$$\lambda_{ex}^{(3)} \approx \nu P_1 P_2 \sum_A W_A, \tag{4}$$

where $W_A = N_A V$ is the probability of finding an AT molecule in the volume V. For the mixture $D_2 + T_2$ the corresponding values of N_A are

$$N_{T_2} = N_0 \frac{1}{2} C_t^2 \varphi, \quad N_{DT} = N_0 C_d C_t \varphi \tag{5}$$

where $\varphi = N/N_0$ is the density of the mixture, and $N_0 = 4.25 \times 10^{22}$ cm^{-3} is the density of the nuclei per cm^3 of liquid hydrogen. The collision frequency ν of the AT and

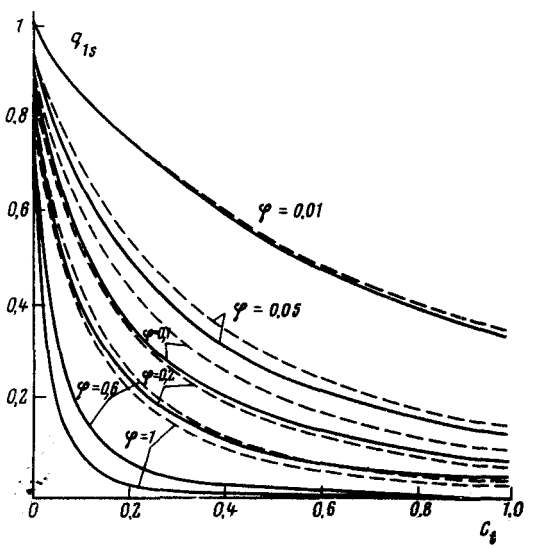

FIG. 1. The functional dependence q_{1s} (C_t) for fixed values of φ. The dashed curve represents the functional dependence without consideration of reaction (2).

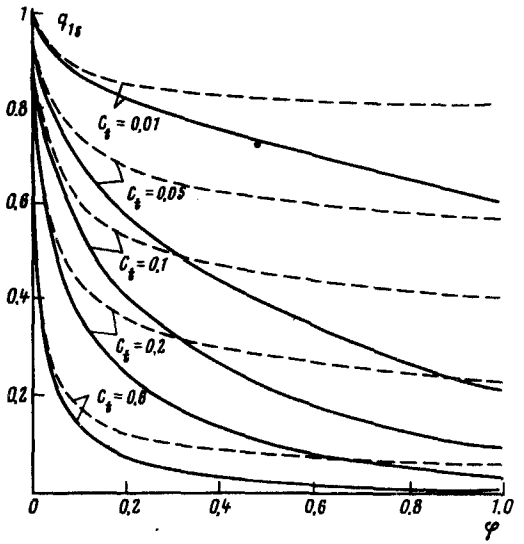

FIG. 2. The functional dependence $q_{1s}(\varphi)$ for fixed values of C_t.

M molecules can be estimated from the model for the rigid spheres with a radius $R_2 \approx 0{,}6 ln(U_0/\epsilon_T)$, ($U_0 \approx 250$ eV) which is equal to the collision diameter of the molecules at the collision energy ϵ_T. In this approximation ($m^{-1} = m_{AT}^{-1} + m_M^{-1}$) we have

$$\nu = \pi R_2^2 (2\epsilon_T / m)^{1/2} N_0 \varphi \approx 3,6 \times 10^{12} R_2^2 \varphi \sqrt{\epsilon_T \text{ (eV)}}. \tag{6}$$

From (3)–(5) the rate of reaction (2) is estimated to be

$$\lambda_{ex}^{(3)} = \tilde{\lambda}_{ex}^{0} C_t (2 - C_t) \varphi^2 ,$$

$$\tilde{\lambda}_{ex} \approx 10^{10} (R_1 R_2)^2 (2R_1 + 0,7) \sqrt{\epsilon_T \text{ (eV)}} \text{ s}^{-1} . \tag{7}$$

For $n = 4$ and $\epsilon_T = 3 \times 10^{-3}$ eV we find $\tilde{\lambda}_{ex}^{0} \approx 2.8 \times 10^{12}$ s^{-1} and for $\epsilon_T = 0.05$ eV we find $\tilde{\lambda}_{ex}^{0} \approx 1.6 \times 10^{12}$ s^{-1}.

3. At $\varphi \sim 1$ the rate (6) of reaction (2) is comparable to the rates $\lambda_{ex} \approx 10^{12} C_t \varphi$ s^{-1} of the isotopic exchange of muons in the pair collisions in (1). Figures 1 and 2 show the populations (q_{1s}) of the 1s state of the $d\mu$ mesic atom plotted as functions of C_t and φ. These plots are similar to those shown in Ref. 1. We easily see that at large φ the appreciable effect of reaction (2) must be taken into account in evaluating experimental data.[6] It is conceivable that the dependence of the sticking coefficient ω_s in the reaction $dt\mu \to \mu^4\text{He} + n$ on the product $C_t\varphi$ will turn out to be fictitous[6] if reaction (2) and the reaction involving a quasiresonant production of $dt\mu$ mesic molecules in triple collisions[8] are ignored.

We should mention in conclusion that reaction (2), like reaction (1), can be studied by using as an example the charge-exchange reaction[1]

$$(p\,\pi)_n + d \to p + (d\,\pi)_n \ ,$$

from which we can estimate the rates of reaction (2).

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