Formation of mesic molecules in the scattering of metastable muonic hydrogen in helium

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(Submitted 26 August 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 10, 377–379 (25 November 1987)

Calculations are carried out for the rates of production of mesic molecules in the scattering of mesic atoms of hydrogen isotopes in the metastable 2*s* state by helium nuclei with allowance for the electron shell of the target atoms. The electron screening in this process is shown to be small.

The charge exchange of excited mesic atoms of hydrogen isotopes by nuclei of heavier hydrogen isotopes and by nuclei of other elements influences the kinetics of processes occurring in hydrogenous mixtures. It was shown in Refs. 1–3 that quasiresonant charge exchange of mesic deuterium by tritium nuclei is appreciable in the analysis of the kinetics of muonic catalysis in the $D_2 + T_2$ mixture. Helium from the fusion of nuclei of the hydrogen isotopes in a mesic molecule and from tritium decay is also accumulated in this mixture. If the capture of a muon from the excited mesic deuterium by tritium atoms increases the number of cycles per muon of the muonic catalysis, the charge exchange of mesic atoms of the hydrogen isotopes by the helium nuclei will decrease their number.

The charge exchange of muonic hydrogen in the metastable 2*s* state by helium nuclei was analyzed by Kravtsov and Popov.[4] They showed that the charge exchange may reach $10^9\ s^{-1}$, a level comparable to the rate at which this state becomes deexcited in the collisions due to "virtual" Stark mixing of the 2*s* and 2*p* states at room temperature.

The screening of helium atoms by atomic electrons was ignored by Kravtsov and Popov[4] in their calculation of the charge-exchange rates. We have taken this effect into account. The effect of the atomic shell on the charge-exchange rate is appreciable in the quasiresonant charge exchange of mesic deuterium by tritium atoms,[1–3] because of the large nuclear separation R, which is responsible for the muon capture and which increases with increasing principal quantum number n of the muonic hydrogen.

The capture of a muon from muonic hydrogen in the 2*s* state by helium in the absence of crossing of the molecular terms corresponding to the initial and final states of the reaction can occur only through a molecular charge-exchange mechanism:

$$(H\mu)^*_{2s} + \mathrm{He} \to (H\mu)^*_{2s}\,\mathrm{He} \to \mathrm{He}\mu + H \tag{1}$$

($H=p,\ d,\ t$) with characteristic $R \sim 20a_\mu$ (Ref. 4) (a_μ is the Bohr radius of the muonic hydrogen).

The binding energies of mesic molecules and the wave functions of the initial and final states in reaction (1) are found numerically in an effective single-channel approximation. The interaction with the electron shell of the helium atom in this case is taken

TABLE I. Values of $\tilde{\lambda}_m^{nres}(10^8\ s^{-1})$ calculated without allowance for screening.

T(K)	$(p\mu)^*_{2s} + {}^3He$	$(p\mu)^*_{2s} + {}^4He$	$(d\mu)^*_{2s} + {}^3He$	$(d\mu)^*_{2s} + {}^4He$	$(t\mu)^*_{2s} + {}^3He$	$(t\mu)^*_{2s} + {}^4He$
20	10.0	5.47	13.3	6.32	8.29	3.58
50	7.33	4.07	9.75	4.62	6.08	2.62
100	5.47	3.07	7.29	3.45	4.54	1.96
400	2.85	1.61	3.80	1.80	2.37	1.02
800	2.03	1.15	2.70	1.28	1.68	0.73
1000	1.82	1.03	2.41	1.15	1.51	0.65

into account in first-order perturbation theory,[5] so that at $R \sim 20a_\mu$ the effective interaction potential is determined by the $5g\sigma$ term[4] at $R \gg a_\mu$ it has the form $V(R) = d_n \epsilon(R)$, where $d_n = 3n\Delta/2m_\mu$ is the dipole moment of the excited muonic hydrogen (in units of $e = \hbar = m_e = 1$), $\Delta = n_1 - n_2$, n_1, and n_2 are the parabolic quantum numbers of the mesic atom ($n = 2$, $\Delta = -1$), m_μ is the muon mass, and $\epsilon(R)$ is the electric field strength of the helium atom. Using, as in Ref. 5, the expression for the atomic potential from Ref. 6, we find

$$\epsilon(R) = -\frac{d}{dR} V_a(R) = \frac{z}{R^2} \sum_{i=1}^{p} \gamma_i \left(1 + \lambda_i \frac{R}{a_e}\right) \exp(-\lambda_i R/a_e) \tag{2}$$

(a_e is the Bohr radius), where the parameters γ_i and λ_i for $z = 2$ are given in Ref. 6. As was shown in Ref. 4, the charge-exchange of muonic hydrogen in the metastable $2s$

TABLE II. Values of $\tilde{\lambda}_m^{nres}(10^8\ s^{-1})$ calculated with allowance for screening.

T(K)	$(p\mu)^*_{2s} + {}^3He$	$(p\mu)^*_{2s} + {}^4He$	$(d\mu)^*_{2s} + {}^3He$	$(d\mu)^*_{2s} + {}^4He$	$(t\mu)^*_{2s} + {}^3He$	$(t\mu)^*_{2s} + {}^4He$
20	9.32	2.70	14.0	5.28	6.50	4.59
50	7.12	2.42	10.2	4.02	5.24	3.19
100	5.42	2.12	7.49	3.09	4.17	2.28
400	2.82	1.38	3.73	1.68	2.35	1.11
800	1.98	1.05	2.61	1.22	1.70	0.77
1000	1.77	0.95	2.35	1.09	1.53	0.68

TABLE III. Maximum values of λ_m^{res} (10^8 s^{-1}) calculated with and without allowance for screening.

	$(p\mu)_{2s}^* + {}^3He$	$(p\mu)_{2s}^* + {}^4He$	$(d\mu)_{2s}^* + {}^3He$	$(d\mu)_{2s}^* + {}^4He$	$(t\mu)_{2s}^* + {}^3He$	$(t\mu)_{2s}^* + {}^4He$
Without screening	3.06	0.148	0.083	0.107	1.15	3.40
With screening	2.53	0.142	0.081	0.102	1.04	2.57

state can occur through the nonresonant mechanism for the production of mesic molecules (3) and by means of resonant reaction (4):

$$(H\mu)_{2s}^* + He \nearrow [(H\mu)_{2s}^* He^{2+})e]^+ + e \quad (3)$$

$$(H\mu)_{2s}^* + He \searrow [((H\mu)_{2s}^* He^{2+})2e]^* \quad (4)$$

Our calculations of the nonresonant production rates of mesic moelcules, $\tilde{\lambda}_m^{nres}$, averaged over the Maxwellian velocity distribution of mesic atoms at the temperature $T(K)$, are given in Table I without allowance for screening and in Table II with allowance for screening. With regard to the resonant production of mesic molecules, Table III gives data for the maximum values of λ_m^{res}, which were obtained with and without allowance for screening. It follows from the data of Tables I–III that the effect of screening on the charge-exchange rate of muonic hydrogen in the metastable $2s$ state in helium is small.

In the study of the charge exchange of muonic hydrogen in the excited state the direct charge exchange from the highly excited states with $n > 2$ is expected to be of great importance, as suggested by the experimental data on the capture of a muon from mesic protium by ^4He nuclei.[7]

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Translated by S. J. Amoretty