DIRECT MUON TRANSFER FROM MUONIC HYDROGEN TO HELIUM

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1. Muon transfer from muonic hydrogen to helium nucleus is important for the study of the muon catalyzed fusion in $d-t$ mixture which contains helium as a result of the natural tritium decay and of fusion reactions. The rate of the reaction is not high ($\sim 10^6 s^{-1}$) since heavy nuclei should accelerate up to rather large energy ($\sim$ 6 keV) for the short time of the muon transition which decreases considerably the reaction probability. Here we consider direct radiative process

$$(p\mu)_{1s} + He^{++} \rightarrow (He^{++}\mu)_{1s} + p + \gamma \tag{1}$$

and direct Auger process in which He^+ replaces He^{++} in the left hand side of (1) and the electron replaces the photon. Photon (or electron) emission leads to the additional smallness of the charge exchange rate due to the weakness of the electromagnetic interaction. Nevertheless the process (1) can compete with the nonradiative transfer because the most of the energy goes away with the light particle, which leads to the adiabatic motion of nuclei, like in the case of the terms crossing.

We obtained [1] for the photon spectrum (in units $\hbar = e = m = 1$, $m^{-1} = m_\mu^{-1} + M_H^{-1}$) :

$$\frac{d\lambda_\gamma}{d\omega} = \frac{16}{3} N (\alpha\omega)^3 \frac{J^2_{k'k}}{\varepsilon k'}. \tag{2}$$

Here ω — photon energy, $\alpha = 1/137$, $\varepsilon(\varepsilon')$ and $k(k')$ — energy and momentum of the relative motion of nuclei in the initial (final) state. Integral J is the matrix element of the dipole transition between the initial and final states of the $(p\mu He^{++})$ system.

The rates of the process (1) turned out to be $\sim 10^6 s^{-1}$. One should note that although this rate is not large, the process can be important for charge exchange on helium nucleus where the molecular charge exchange does not work, as well as for the most cases of the charge exchange on the He^+ ion where the electron binding energy is higher than the binding energy of the mesic molecule. Photon spectra for the $d\mu He$ case are shown in Fig.1.

The rates of the direct Auger charge exchange are 3-4 times lower than radiative ones. The electron spectra are similar to those of the photon.

2. We investigated the process of the direct muon transfer from the excited muonic hydrogen to helium

$$(H\mu)^*_n + He \rightarrow (He\,\mu)^*_{n'} + H \tag{3}$$

for $n = 2, 3, 4$ and 5 [2]. We used the quasiclassical approximation and considered the motion of the mesic atom along the classical trajectory with the impact parameter ϱ. Transition probability is known to be large mainly in a region of quasicrossing of terms corresponding to initial and final states of the system and can be expressed via the Massey parameter

$$\delta(\varrho) \;=\; \left|\mathrm{Im}\int_C p(R)\,dR\right|, \tag{4}$$

where $p(R) = [2M(\varepsilon - u(R) - \varepsilon\varrho^2/R^2)]^{1/2}$ — radial momentum, $\varepsilon = M\,v^2/2$ — relative energy of colliding particles, C — integration contour, beginning and ending at the real axis and going around the complex crossing point of the terms R_c. The transition probability is

$$w(\varrho) \;=\; 2\,\exp(-2\delta)\,[1 - \exp(-2\delta)]. \tag{5}$$

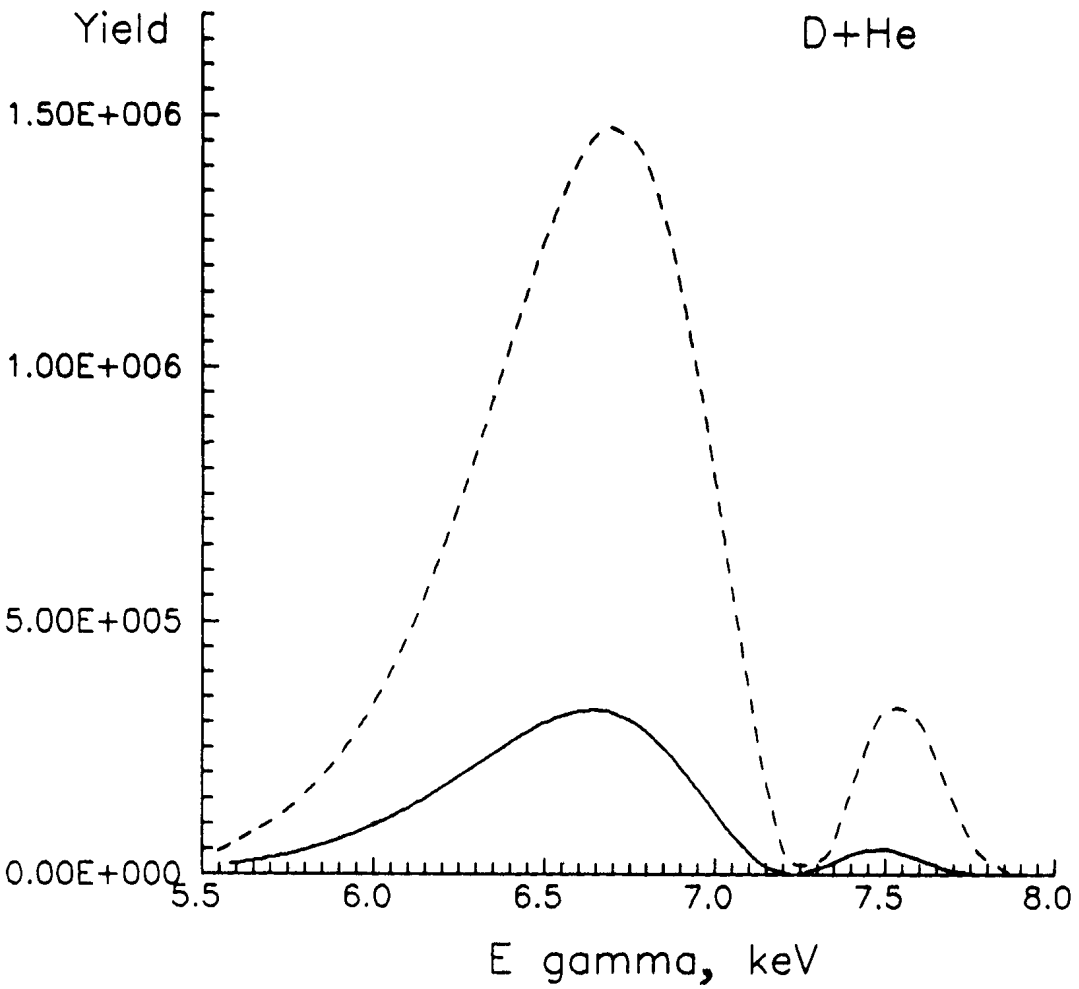

Fig.1. Photon spectra for the direct radiative muon transfer from $d\mu$ to ^3He (dashed line) and to ^4He (solid line)

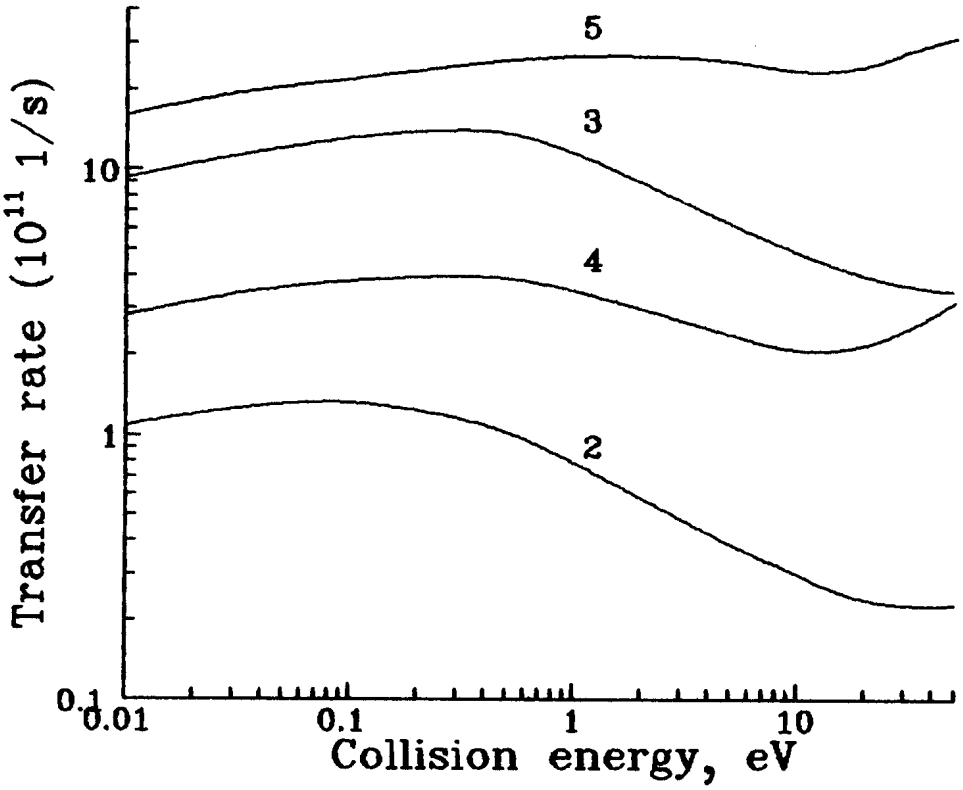

Fig.2. Energy dependence of the rates of the muon transfer from the $(p\mu)_n$ to the ^4He–atom. The values n are shown at the curves

While calculating the cross section of the process (3) for $n = 2$ and 3 we used the branch points of the Q — series [2]. For higher states ($n \geq 4$) the process of calculating of R_Q (and even the calculating of the terms for real large R corresponding to the transition point) becomes very laborious and time consuming, what makes the calculation impossible with computers we have. For this reason we used the quasiclassical approximation for the terms of the two-center problem [3] to calculate the necessary terms at real R. This allowed us to use the Landau–Zener formula when calculating the Massey parameter. Only attractive terms were considered, which gave the largest contribution to the cross section due to the 'focusing' of the particles. The effect of screening of the charge of helium nucleus by atomic electrons was taken into account.

For $n \geq 4$ the Massey parameters (and hence the transition probabilities (5)) become very small. For this reason to calculate charge exchange cross section for $n \geq 4$ one should consider also a two-step process $(eZ_1) \rightarrow (eZ_2) \rightarrow (eZ_2)'$. In this case the first (right–hand) crossing is passed by the system diabatically, that is with the probability $w_1 \simeq 100\%$ (at least for $n > 4$). The cross sections for muon transfer on the nucleus behave at low energies as $\sim 1/\varepsilon$ and the corresponding reaction rates $\lambda \sim 1/\sqrt{\varepsilon}$. It is natural because for the potential $u(R) \sim -\alpha/R^2$ the square of the maximum impact parameter $\varrho_{max}^2 = \alpha/\varepsilon + R_0^2$ which gives for the cross section (for $w(\varrho) \simeq 0.5$)

$$\sigma \simeq \frac{\pi}{2}\left(\frac{\alpha}{\varepsilon} + R_0^2\right) \tag{6}$$

When the screening is switched on, ϱ_{max} decreases sharply at low energy and the energy

dependence of λ becomes much more flat. Fig.2 shows the energy dependence of the transfer rates for $p\mu^4He$ case.

REFERENCES

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