Probability of μ^--meson stripping when $(\mu\mathrm{He})^+$ mesic atoms are stopped in matter

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The probabilities are calculated of the stripping of μ^- mesons from $(\mu\mathrm{He})^+$ mesic atoms produced in μ-catalysis of fusion reactions in the mesic molecules $dt\mu$, $tt\mu$, and $dd\mu$ are stopped in H_2, C, Al, and Au. The effective coefficients $\tilde{\omega}$ of the sticking of the μ^- meson to He^{++}, with allowance for the stripping of μ^-, are respectively $\tilde{\omega}_s = 0.85\times10^{-2}$, $0.05 \leq \tilde{\omega}_t \leq 0.18$, and $\tilde{\omega}_d = 7.8\times10^{-2}$ for the reactions $(dt\mu)^+ \to^{\omega s} (\mu^4\mathrm{He})^+ + n + 17.59$ MeV, $(tt\mu)^+ \to^{\omega t} (\mu^4\mathrm{He})^+ + 2n + 11.3$ MeV, and $(dd\mu)^+ \to^{\omega d} (\mu^3\mathrm{He})^+ + n + 3.27$ MeV.

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1. INTRODUCTION

When μ^- mesons are slowed down and stopped in a mixture of hydrogen isotopes, various mesic-atom and mesic-molecular processes take place.[1-3] Of particular interest is the phenomenon of muon catalysis in a mixture of deuterium and tritium, investigation of which was recently initiated experimentally[4] and theoretically.[5-7]

To ascertain the possibility of practical utilization of μ catalysis[8] we must know the sticking coefficients ω_s, ω_t, ω_d, and ω_d' of the μ^- mesons to the helium He^{++} nuclei produced as a result of fusion of the nuclei in mesic molecules:

$$(dt\mu)^+ \xrightarrow{\omega_s} (\mu^4\,\mathrm{He})^+ + n + 17.59 \text{ MeV}, \tag{1a}$$

$$(tt\mu)^+ \xrightarrow{\omega_t} (\mu^4\,\mathrm{He})^+ + 2n + 11.33 \text{ MeV}, \tag{1b}$$

$$(dd\mu)^+ \xrightarrow{\omega_d} (\mu^3\,\mathrm{He})^+ + n + 3.27 \text{ MeV}, \tag{1c}$$

$$(dd\mu)^+ \xrightarrow{\omega_d'} t\mu + p + 4.03 \text{ MeV}. \tag{1d}$$

The produced μ-mesic atoms have an appreciable initial energy, $0 < E_0 \leq 3.8$ MeV, and can lose mesons in the reactions

$$(\mu\mathrm{He})^+ + d \xrightarrow{\sigma_i} \mathrm{He}^{++} + d + \mu^-, \tag{2a}$$

$$(\mu\mathrm{He})^+ + d \xrightarrow{\sigma_c} \mathrm{He}^{++} + d\mu, \tag{2b}$$

and this leads to a decrease of the resultant sticking coefficients in reactions (1). The cross sections $\sigma_i(E)$ and $\sigma_c(E)$ of the ionization reaction (2a) and of the charge-exchange reaction (2b) depend on the energy of the mesic atom $(\mu\mathrm{He})^+$. This energy decreases in the course of deceleration mainly on account of ionization losses with cross section $\sigma_t(E)$:

$$(\mu\mathrm{He})^+ + D_2 \to (\mu\mathrm{He})^+ + D_2^+ + e. \tag{3}$$

As a result of the joint action of processes (2) and (3), by the instant that the mesic atom $(\mu\mathrm{He})^+$ is stopped the μ^- meson has only a finite probability $\gamma(E_0) < 1$ of remaining bound to the helium nucleus. The effective sticking coefficient $\tilde{\omega}$ is determined in the case of the reactions (1a), (1c), and (1d) by the relation

$$\tilde{\omega} = \omega\gamma(E_0). \tag{4}$$

The purpose of the present paper is to calculate the values of ω, $\gamma(E)$, and $\tilde{\omega}$, on which the multiplicity of the μ-catalysis chain depends significantly, i.e., the number of the dt-fusion reactions (1a) effected by a single μ^- meson.[7]

2. CALCULATION OF THE STICKING COEFFICIENTS

The sticking coefficient ω of a muon with an He^{++} nucleus is defined as the probability of μ^- capture in any bound state n of the mesic atom $(\mu\mathrm{He})^+$ produced in the reactions (1). The production of $(\mu\mathrm{He})^+$ can be regarded as a transition of the μ^- from one bound state to another under the influence of an instantaneous perturbation. The probability of such a process is calculated from the formulas[9,10]

$$\omega = \sum_n \omega(n), \quad \omega(n) = |P_{fi}^{(n)}|^2,$$
$$P_{fi}^{(n)} = \int d\mathbf{r}\,\psi_n^{(f)}(\mathbf{r})\,\psi_1^{(i)}(\mathbf{r}), \tag{5}$$

where $\omega(n)$ is the probability of μ^- capturing in an emitted mesic-atom $(\mu\mathrm{He})^+$ state $n = (nlm)$ described by a wave function $\psi_n^{(f)}(\mathbf{r})$. Since the fusion reaction takes place at distances $R \approx R_N \ll 1$ between the nuclei, the initial-state wave function $\psi_1^{(i)}(r)$ of the system practically coincides with the wave function of the mesic atom $(\mu A)^+$, where A is the intermediate compound nucleus. For reaction (1a), in particular, it is usually assumed that

$$\psi_1^{(i)}(\mathbf{r}) = \psi_{1s\sigma}(\mathbf{r}) = (\pi a_5^3)^{-1/2} e^{-r/a_5}, \tag{6}$$

where

$$a_5 = \frac{\hbar^2}{Z_i m_5 e^2}, \quad m_5^{-1} = m_\mu^{-1} + M_5^{-1}, \quad Z_i = 2,$$

m_μ and M_5 are the masses of the muon and of ^{5}He, i.e., the initial state of the system is, with good accuracy, the ground state $1 = (100)$ of the mesic atom[4)] $(\mu^5\mathrm{He})^+$.

The final-state wave function of the system is of the form

$$\psi_n^{(f)} = \psi_n(\mathbf{r}) \exp(-i\mathbf{q}_c\mathbf{r}_c), \tag{7}$$

where

$$\mathbf{r}_c = \frac{m_\mu \mathbf{r}_\mu + M_4 \mathbf{R}_4}{m_\mu + M_4} = \frac{m_\mu}{m_\mu + M_4}\mathbf{r} + \mathbf{R}_4, \quad q_c = \left[\frac{2m_n(m_\mu + M_4)}{m_\mu + M_5}\Delta E\right]^{1/2} \tag{7a}$$

are the mass-center coordinates of the $(\mu\mathrm{He})^+$ produced

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in reactions (1) and its momentum; $\mathbf{r}_\mu$ and $\mathbf{R}_4$ are the coordinates of the muon and of the $^4He^{++}$ nucleus, $\mathbf{r} = \mathbf{r}_\mu - \mathbf{R}_4$; m_μ, m_n, M_4, and M_5 are respectively the masses of the muon, neutron $^4He^{++}$, and $^5He^{++}$; ΔE is the energy released in the reactions (1).

Using relations (7a), leaving out the variable $\mathbf{R}_4$, i.e., retaining only the variables that characterize the internal state of the mesic atom and its motion as a whole, we obtain

$$\psi_n^{(f)} = \psi_n(\mathbf{r})e^{-iq\mathbf{r}}, \quad q = m_\mu v = m_\mu\left\{\frac{2m_n\Delta E}{(m_n+M_4)(m_\mu+M_5)}\right\}^{1/2}, \tag{7b}$$

where v is the velocity of the mesic atom $(\mu^4He)^+$ relative to the mass center of the mesic molecule, and $\psi_n(\mathbf{r})$ is the wave function of the mesic atom $(\mu^4He)^+$ in the state n.

Using (5), (6), and (7b) we obtain

$$\omega(1s\sigma) = \frac{(2a_1)^6}{a_i^3 a_f^3}[1+(qa_1)^2]^{-4},$$

$$\omega(2s\sigma) = \frac{(2a_2)^6}{8a_i^3 a_f^3}[1+(qa_2)^2]^{-4}\left[1-\frac{a_2}{2a_f}\frac{3-(qa_2)^2}{1+(qa_2)^2}\right]^2, \tag{8}$$

$$\omega(3s\sigma) = \frac{(2a_3)^6}{27a_i^3 a_f^3}[1+(qa_3)^2]^{-4}\left\{1-\frac{2a_3}{3a_f}\frac{3-(qa_3)^2}{1+(qa_3)^2}+\frac{8a_3^2}{9a_f^2}\frac{1-(qa_3)^2}{[1+(qa_3)^2]^2}\right\}^2$$

$$\omega(2p\sigma) = \frac{(2a_2)^6}{2a_i^3 a_f^3}\frac{(qa_2)^4}{(qa_f)^2}[1+(qa_2)^2]^{-6},$$

where

$$a_i = \hbar^2/Z_i m_i e^2, \quad m_i^{-1} = m_\mu^{-1} + M_i^{-1},$$
$$a_f = \hbar^2/Z_f m_f e^2, \quad a_n^{-1} = a_i^{-1} + (na_f)^{-1}.$$

For transitions from the ground state $1 = (1s\sigma)$ to the final states $n = (ns\sigma)$, $n \gg 1$, the following estimate holds:

$$P_{fi}^{(n)} \approx \frac{(2a_n)^6}{n^3 a_i^3 a_f^3}[1+(qa_n)^2]^{-4} \approx \frac{(4n)^3}{(n+1)^6}\left[1+\left(\frac{v}{v_0}\right)^2\left(\frac{n}{n+1}\right)^2\right]^{-4}. \tag{9}$$

Tables I and II show the values of a_i, a_f, $q = v/v_0$, $\omega(n)$ and the value of $\omega = \Sigma_n\omega(n)$ for the reactions (1). It is seen from the tables that approximately 15 and 5% of the fraction of μ^- mesons captured in the state $1s\sigma$ of the mesic atom $(\mu He)^+$ are captured respectively in the states $2s\sigma$ and $3s\sigma$.

3. KINETICS OF THE SLOWING DOWN OF $(\mu He)^+$ AND OF THE STRIPPING OF μ^-

The probability of stripping of μ^- in collisions of $(\mu He)^+$ with nuclei of matter depends on the ratio of the cross sections $\sigma_s = \sigma_i + \sigma_c$ and σ_t of reactions (2) and (3). To calculate the joint probability of μ^- stripping when the $(\mu He)^+$ slows down from an initial energy E_0 to a final $E_1 \approx 0.1$ MeV (when the stripping probability becomes negligible), we write down the balance equation for the collision density $q(E)$ of the $(\mu He)^+$ mesic atoms with the atomic nuclei of the medium per unit time in the energy interval dE (Refs. 12 and 13)

TABLE I. Mesic-atom parameters that determine the muon sticking process.*

Reaction	a_i	a_f	$q=v/v_0$	a_1	a_2	a_3
$(dt\mu)^+ \to (\mu^4He)^+ + n$	0.511	0.514	5.83	0.256	0.342	0.384
$(tt\mu)^+ \to (\mu^4He)^+ + 2n$	0.509	0.514	6.04	0.256	0.341	0.383
$(dd\mu)^+ \to (\mu^3He)^+ + n$	0.514	0.519	3.21	0.258	0.344	0.387
$(dd\mu)^+ \to t\mu + n$	0,514	1,038	3.57	0.344	0.412	0.441

*In mesic-atom units $e = \hbar = m_\mu = 1$.

TABLE II. Values of $\omega(n)$, ω, $\tilde{\omega}$, and $\gamma(E_0)$ for reactions (1).

Reaction	E_0, MeV	$\omega(1s)$, 10^{-2}	$\omega(2s)$, 10^{-2}	$\omega(3s)$, 10^{-2}	$\omega(2p)$, 10^{-2}	ω, 10^{-2}	$\gamma(E_0)$	$\tilde{\omega}$
$(dt\mu)^+ \to (\mu^4He)^+ + n$	3,46	0.92	0,13	0,04	0.03	1.12	0.77	$0.86 \cdot 10^{-2}$
$(tt\mu)^+ \to (\mu^4He)^+ + 2n$	$\leqslant$3,73	–	–	–	–	–	–	$0.05 \leqslant \tilde{\omega} \leqslant 0,18$
$(dd\mu)^+ \to (\mu^3He)^+ + n$	0.797	12 28	1,54	0,46	1.25	15,53	0,95	0,15
$(dd\mu)^+ \to t\mu + p$	0.982	1.77	0.23	0,07	0.04	2.11	0	0

Note. Here $\omega = \sum_{n=1}^3 \omega(n)$ and $\tilde{\omega} = \omega\gamma(E_c)$. In the calculation of $\tilde{\omega}$ it is assumed at the $(\mu He)^+$ mesic atoms produced in nl states go over rapidly in the collisions into the state $1s$. In the case of reaction (1d) we have $\gamma(E_0) \approx 0$, since the deceleration losses $\varkappa(E)$ for the produced neutral $t\mu$ atom are negligibly small. When account is taken of the equal probability of the channels (1c) and (1d) we have $\tilde{\omega}_d = 0.078$. The contributions of the ns states with $n \geqslant 4$ for the reactions (1a) and (1c) are respectively $<10^{-4}$ and $<10^{-2}$.

$$\frac{\sigma_s}{\sigma_t}q(E) + \frac{d}{dE}S(E) = Q\delta(E-E_0). \tag{10}$$

Here $q(E) = N\sigma_t vF(E)$, $F(E)$ is the mesic-atomic density per energy interval dE, σ_s is the summary cross section of the reactions (2), σ_t is the total cross section of the reaction (3), v is the relative velocity of the collisions, N is the density of the atoms of the medium, Q is the number of $(\mu He)^+$ mesic atoms produced at the initial energy E_0, and $S(E)$ the current of the mesic atoms $(\mu He)^+$ through the energy surface in phase space.

Assuming an average energy $\langle\Delta E\rangle < 0$ transferred to the $(\mu He)^+$ atom in each collision much lower than its kinetic energy E, the following equation[12,13] is valid for the current $S(E)$

$$S(E) = -\langle\Delta E\rangle q(E). \tag{10a}$$

This equation does not take into account the higher moments in the expansion of $S(E)$ in the energy transfer $\langle\Delta E\rangle$. Since $|\langle\Delta E\rangle| \sim 2I_0 \approx 30$ eV, where I_0 is the average ionization potential of the atoms of the medium and $E \sim 1$ MeV, the assumed continuity of the energy loss is fully justified. Taking (10a) into account, we reduce (10) to an equation of the Fokker-Planck type:

$$-\frac{\sigma_s(E)}{\varkappa(E)}S(E) + \frac{d}{dE}S(E) = Q\delta(E-E_0), \tag{11}$$

where $\varkappa(E) = -\langle\Delta E\rangle\sigma_t(E)$ is the stopping ability of the substance. The solution of this equation is

$$S(E) = -Qe^{-\nu(E)}\Theta(E_0-E), \quad \Theta(x) = \begin{cases}1 & \text{if } x>0\\ 0 & \text{if } x<0\end{cases},$$
$$\nu(E) = \int_E^{E_0}\delta(E')dE', \quad \delta(E) = \frac{\sigma_s(E)}{\varkappa(E)}. \tag{12}$$

The probability P_s of stripping the μ^- meson from the $(\mu He)^+$ mesic atom when the latter is slowed down from an initial energy E_0 to an energy E_1 is, by definition,

$$P_s = P_s(E_0, E_1) = \frac{1}{Q}\int_{E_1}^{E_0} N\sigma_s vF(E)dE = -\frac{1}{Q}\int_{E_1}^{E_0}\delta(E)S(E)dE$$
$$= 1 + \frac{1}{Q}S(E_1) = 1 - e^{-\nu(E_1)}. \tag{13}$$

[The last two equalities follow from (10) and (12).] The probability $\gamma(E_0)$ that the μ^- meson will remain bound in the $(\mu He)^+$ mesic atom when the latter is slowed down from an initial energy E_0 to an energy $E_1 \approx 0.1$ MeV is

$$\gamma(E_0)=1-P_s=\exp\left\{-\int_{E_1}^{E_0}\delta(E)\,dE\right\}. \tag{14}$$

The quantity $\gamma(E_0)$ can be estimated by using for $\sigma_i(E)$ and $\varkappa(E)$ the Bethe formulas[14] obtained in the Born approximation, i.e., at $v \gg Z_i v_0$, where $v_0=\alpha c$:

$$\sigma_i(E)=4\pi\left(\frac{m_e a_0}{m_\mu Z_i}\right)^2\left(\frac{v_0}{v}\right)^2\cdot 0.285\ln\left\{\left(\frac{v}{Z_i v_0}\right)^2\frac{1}{0.012}\right\},$$
$$\varkappa(E)=8\pi a_0^2\left(\frac{v_0}{v}\right)^2 I_0\ln\left\{\left(\frac{v}{v_0}\right)^2\frac{1}{0.275}\right\} \tag{15}$$

where v is the velocity of the $(\mu He)^+$ mesic atom with energy E, a_0 is the Bohr radius, and $Z_i=2$ is the charge of the He^{++} nucleus. Assuming that $\sigma_i(E)\approx\sigma_s(E)$, it follows from (15) that the function

$$\delta(E)\approx\frac{\sigma_i(E)}{\varkappa(E)}=\frac{0{,}143}{Z_i^2 I_0}\left(\frac{m_e}{m_\mu}\right)^2\frac{\ln[(v/v_0)^2/0.048]}{\ln[(v/v_0)^2/0.275]} \tag{16}$$

depends little on the velocity v of the $(\mu He)^+$ mesic atom. For the reaction (1a), calculation with Eqs. (16) and (14) yields $\gamma(E_0)=0.71$ at[5)] $E_0=3.5$ MeV.

The initial $(\mu He)^+$ velocities, however, are only 2–3 times larger than $v_s=Z_i v_0$. At these and smaller v, deviations from (15) appear, and to calculate $\gamma(E_0)$ we must invoke more accurate data on the cross sections $\sigma_s(E)$ and $\varkappa(E)$.

4. IONIZATION AND CHARGE-EXCHANGE CROSS SECTIONS AND IONIZATION LOSSES OF $(\mu He)^+$ MESIC ATOMS

Atomic analogs of the cross sections for processes (2), with the μ^- meson replaced by an electron, have been measured in recent years.[15–18] The results of these experiments, recalculated for the case of the reactions (2), are shown in Fig. 1 together with measured[19,20] cross sections for the ionization of He^+ by electron impact. The latter cross sections, at collision energies $E \gtrsim 4$ MeV, should be comparable with the cross sections for the processes (2a).

Figure 1 shows also a theoretical $\sigma_s(E)$ plot calculated by the tight-binding method developed in Refs. 21–25. In this approach the ionization and charge-exchange cross sections σ_i and σ_c for the processes

$$(\mu He)^+ + Z \xrightarrow{\sigma_i} He^{++}+Z+\mu^- \tag{17a}$$
$$(\mu He)^+ + Z \xrightarrow{\sigma_c} He^{++}+\mu Z \tag{17b}$$

can be represented in universal form

$$\sigma_i=\pi a_m^2 ZF(x_i),\quad x_i=(v/v_0)^2Z^{-1} \tag{18a}$$
$$\sigma_c=\pi a_m^2 Z^2\Phi(x_c),\quad x_c=(v/v_0)^2Z^{-1/2}, \tag{18b}$$

where $a_m=a_\mu(1+m_\mu/M_{He})=2.63\times10^{-11}$ cm, v is the relative velocity, and $v_0=\alpha c$.

Plots of $F(x_i)$ and $\Phi(x_c)$ vs. the variables x_i and x_c are shown in Fig. 2. At $x_i=2.79$, the function $F(2.79)=0.19$ reaches a maximum, and at $x_i \gg 1$ it takes the Born asymptotic form

$$F(x_i)\approx Z(v_0/v)^2\ln[Z^{-1}(v/v_0)^2+3]. \tag{19}$$

The cross section $\sigma_s=\sigma_i+\sigma_c$, plotted in accord with (18) and shown in Fig. 1, agrees well with the measured values, as well as results of calculations by the formulas of Ref. 26 at $E \gtrsim 1$ MeV.

The ionization losses of a $(\mu He)^+$ mesic atom and of a proton moving with equal velocity v are equal. We can therefore use in our case the experimental data[27–29] on the ionization loss of a proton at energies $0.2 \le E_p \le 1$ MeV.

The ionization-loss plots $\varkappa(E)$ together with the cross sections $\sigma_i(E)$ and $\sigma_c(E)$ and the function $\delta(E)$ are shown in Figs. 3 and 4 for $(\mu He)^+$ moving in hydrogen, carbon, aluminum, and gold.

5. CALCULATION OF THE PROBABILITY OF μ^--MESON STRIPPING IN $(\mu He)^+$ COLLISIONS

The values of $\gamma(E_0)$ calculated from (14) are listed in Table II together with the effective sticking coefficients $\tilde{\omega}$ determined from (4).

For the mesic atoms $(\mu^4He)^+$ produced in reaction (1a), the values of $\tilde{\omega}$ calculated from (4), (14), and (18) for deceleration in carbon, aluminum, and gold are

$$\tilde{\omega}(C)\approx0{,}11\cdot10^{-2},\quad \tilde{\omega}(Al)\approx0{,}34\cdot10^{-5},\quad \tilde{\omega}(Au)\approx0.77\cdot10^{-10},$$

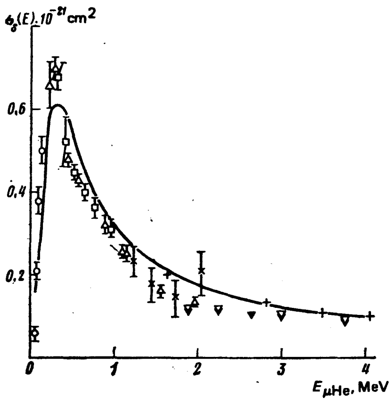

FIG. 1. Experimental and theoretical values of the cross section $\sigma_s(E)=\sigma_i(E)+\sigma_c(E)$ [reactions (2a) and (2b)] for stripping a μ^- in collisions of $(\mu He)^+$ with hydrogen nuclei. Experimental points: ×) Ref. 15, △) Ref. 16, □) Ref. 17, ○) Ref. 18, ▽) Ref. 19, and ▼) Ref. 20, obtained by measuring the cross section for He^+ ionization by electron impact. +) Theoretical calculation[26] of the cross section $\sigma_i(E)$; the curve was plotted from the data of Refs. 21–25 with the aid of the functions (18).

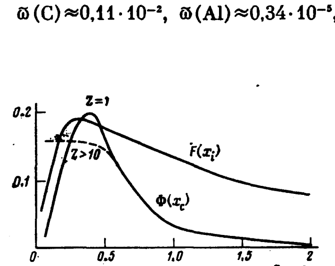

FIG. 2. The functions $F(x_i)$ and $\Phi(x_c)$ defined by relation (18): $x_i=E_{\mu He}[\text{MeV}]/\varepsilon_0 Z$, $x_c=E_{\mu He}[\text{MeV}]/\varepsilon_0 Z^{1/2}$, $\varepsilon_0=(m_\mu+m_{He})v_0^2/2=0.108$ MeV.

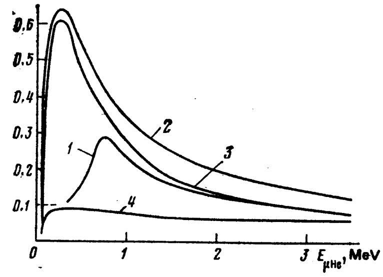

FIG. 3. Theoretical plots of $\sigma_i(E)$ (in units of 10^{-21} cm^2), (curve 1), $\sigma_s(E)$ (10^{-21} cm^2), (curve 3) and $\delta(E)$ (1/MeV), (curve 4) for reactions (2), plotted in accord with formulas (18) and (12). The function $\varkappa(E)$ (10^{-20} MeV $\cdot$ cm^2) (curve 2) was plotted from the data of Refs. 27–29.

i.e., almost complete stripping of μ^- takes place when $(\mu He)^+$ is slowed down in these substances.

Reaction (1b) calls for a special analysis, since the μ^4He mesic atoms are produced in this reaction with differing initial energies $0 < E_0 < E_{max} = 3.77$ MeV. In this case the effective sticking coefficient is calculated from the formula

$$\omega_t = \int_0^{E_{max}} \omega_t(E_0)\gamma(E_0)\rho(E_0)\,dE_0, \tag{20}$$

where $\rho(E_0)$ is the probability that the mesic atom $(\mu^4He)^+$ is produced with an initial kinetic energy E_0, $\omega_t(E_0)$ is the probability that the μ^- is initially captured on an $(\mu He)^+$ orbit at the given kinetic energy E_0 of the mesic atom, and $\gamma(E_0)$ is the probability that the $(\mu He)^+$ will "survive" during the time of the deceleration from the initial energy E_0 to total stopping.

The form of the $\rho(E)$ spectrum depends substantially

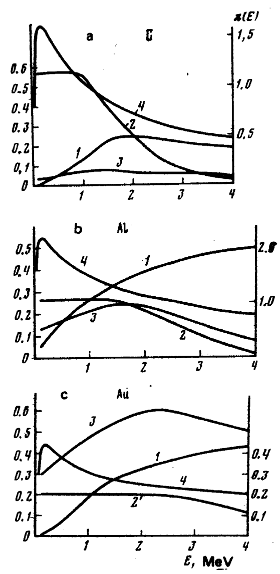

FIG. 4. Theoretical plots of $\sigma_i(E)$ (10^{-20} cm^2) (curve 1), $\sigma_c(E)$ (curve 2), and $\delta(E)$ (10 MeV^{-1}) (curve 3) for the processes (17) in carbon (a), aluminum (b) and gold (c). Plots of $\varkappa(E)$ (10^{-20} MeV $\cdot$ cm^2) (curve 4) in accord with the data of Refs. 27–29. In the case of gold, $Z = Z_{eff} = 30$, $\sigma_c = \sigma_c(E)$ (10^{-18} cm^2); for aluminum, $Z = 13$, $\sigma_c = \sigma_c(E)$ (10^{-19} cm^2); for carbon, $Z = 6$, $\sigma_c = \sigma_c(E)$ (10^{-20} cm^2).

on the interaction of the particles in the final state of reaction (1b). If there are no correlations between their momenta, then the function is determined by the expression for the phase space of the reaction (1b)

$$\rho(E) = \frac{2}{\pi}\left(\frac{2}{E_{max}}\right)^2 [E(E_{max}-E)]^{1/2} \tag{21}$$

and takes the form of curve 1 of Fig. 5.

In many investigations, e.g., in Ref. 30, the presence of an interaction between the outgoing neutrons was established. This interaction is characterized by a neutron-neutron scattering length $a_{nn} \approx -15$ fm. The $(\mu^4He)^+$ spectrum is then distorted as shown by curve 2 of Fig. 5.

Other papers (see, e.g., Ref. 31) indicate the presence of strong n^4He correlations. This leads to deformation of the spectrum $\rho(E)$ shown by curve 3 of Fig. 5.

The value of $\bar{\omega}_t$ depends strongly on the assumptions made concerning the function $\rho(E)$. Its values are: $\bar{\omega}_t = 0.10$ (in the absence of correlations), $\bar{\omega}_t = 0.05$ (nn correlation), and $\bar{\omega}_t = 0.18$ (n^4He correlation). The final choice between these possibilities can be made only after experimentally studying the spectrum of the $^4He^{++}$ recoil nuclei in reaction (1b).

6. CONCLUSION

The calculation results show that the μ^--meson stripping processes (2) decrease noticeably the initial sticking coefficients ω in reactions (1), and this effect must be taken into account when considering the kinetics of the μ-catalysis processes in a deuterium-tritium mixture.

The numerical value $P_s = 0.23$ for the probability of stripping a μ^- meson from $(\mu He)^+$ produced in reaction (1a) agrees with the value $P_s = 0.22$ cited by Jackson.[32] This agreement, however, is accidental, since Jackson used incorrect values for the (2a) ionization cross section, and took no account at all of the transfer process (2b).

The accuracy of the presented calculations is limited by the knowledge of the cross sections of processes (2) and amounts to ~10%. We did not take into account here the increase of the stripping probability P_s because of the two-step process

$$(\mu He)_{1s}{}^+ + d \to (\mu He)_{nl}{}^+ + d \to He^{++} + d + \mu^-, \tag{22}$$

nor because of the stripping of μ^- from ns states of the

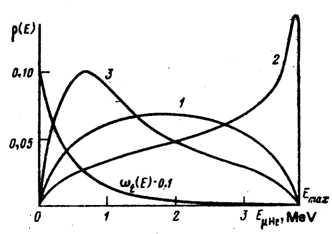

FIG. 5. Energy distribution of $\rho(E)$ of $(\mu^4He)^+$ mesic atoms produced in the reaction (1b): 1) statistical distribution, 2) with allowance for nn correlations, 3) with allowance for n^4He correlations.

mesic atoms $(\mu He)^{+}_{ns}$ initially produced in reactions (1). Rough estimates indicate that these processes increase P_s by not more than 5%.

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4)Actually

$$\psi^{(i)}(\mathbf{r}) = \lim_{R\to 0} \Psi(\mathbf{r}, \mathbf{R}) = \sum_{nlm} C_{nlm}\psi_{nlm}(\mathbf{r})$$

where $\Psi(\mathbf{r}, \mathbf{R})$ is the wave function of the mesic molecule.[11] This assumption means that $C_{nlm}/C_{100} \ll 1$, i.e., the nonadiabatic corrections to the zeroth approximation are small. Numerical calculations confirm this assumption. We note also that $\omega(n)$ depends quite strongly on the effective mass m_5 and that this effect must be taken into account.

5)A rough estimate for $\gamma(E_0)$ can be obtained by assuming the probability of stripping the μ^- in one collision is approximately equal to the ratio of the geometric dimensions $(\mu He)^+$ and H, namely, $\sigma_s/\sigma_t \approx (m_e/Z_i m_\mu)^2$, and the number of collisions is $\approx E_0/2I_0$. In this case we have for reaction (1a)

$$\nu \approx \frac{E_0}{2I_0}\left(\frac{m_e}{2m_\mu}\right)^2 \approx 0.68, \quad \gamma(E_0) \approx 0.5.$$

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