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MUON TRANSFER FROM MUONIC ATOMS OF HYDROGEN ISOTOPES TO He NUCLEI.

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Performed before 1970, experimental investigations into process of muon transfer from mu-atoms of hydrogen isotopes in their ground states to nuclei of elements with Z > 1

$$H\mu + Z \rightarrow Z\mu + H;\ (H \equiv p,\ d,\ t), \qquad (1)$$

indicated that at admixture concentrations $C_Z \sim 10^{-5} - 10^{-3}$ muons are transferred to atoms of all elements studied except He, for which it is suppressed by several orders of magnitude [1-3]. The reason [4, 5] is that there are no intersections and pseudointersections between the molecular term $2p\sigma$, which corresponds to a system like $H\mu$ + He, and the term of the system $He\mu$ + H.

As to muon transfer from excited mu-atoms of hydrogen isotopes to He nuclei, no theoretical calculation were published, and only one experimental paper [6] appeared reporting estimated rate of the muon transfer from excited $d\mu$-atoms $(d\mu)^* + {}^4He \rightarrow {}^4He\mu + d$ to be $(\lambda^d_{{}^4He})^* \geqslant 10^{11}\ s^{-1}$. It is also known that there exists π^--meson transfer from excited $p\pi^-$-atoms to He nuclei [7].

In 1977 an experiment [8] was carried out at Dubna to look for possible muon transfer from $p\mu$-atoms in excited states to ${}^4He$ nuclei $((p\mu)^* + {}^4He \rightarrow {}^4He\mu + p)$. The transfer rate $(\lambda^p_{{}^4He})^*$ was determined by analysing yields of muon decay electrons and meso-X-ray γ-quanta of $Xe\mu$-atoms with energy $E_\gamma \sim 3.8$ MeV (resulting from muon transfer from $p\mu$-atoms to xenon nuclei used as an admixture with $C_{Xe} \sim 10^{-5}$). These yields were measured in exposures with pure hydrogen, H_2+Xe and H_2+Xe+${}^4He$ mixtures.

The experiment [8] was carried out at a set-up schematically shown in Fig. 1. There were three measurement series with different initial pressures of hydrogen and relative concentrations of helium ($C_{He} = n_{He}/n_H$, where n_{He} and n_H are the numbers of helium and hydrogen atoms in cm^3). The initial hydrogen pressure varied from 16.5 to 24.6 atm, and ${}^4He$ concentration from 0.05 to 1.03. After processing of the experimental data it was found that $(\lambda^{p}_{^4He})^*$ is large and close in value to $(\lambda^{d}_{^4He})^*$ obtained in [6].

In 1980 a group of theorists from LINP and JINR assumed another mechanism of muon transfer from mu-atoms of hydrogen isotopes in the ground state to He nuclei. This is a molecular charge exchange mechanism [9].

The principle of the mechanism is as follows. Collisions between hydrogen mu-atoms and He nuclei result in intermediate complexes, which are muon molecules $(HeH\mu)$ in the excited state

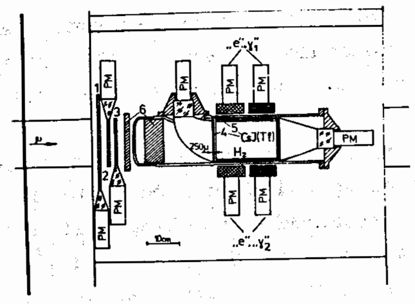

Fig. 1. Lay-out of the registration equipment in the muon beam: 1-3 — monitoring scintillation detectors; 4, 5— CsI(Tl) scintillators; 6—stopping filter; "e","γ"— detectors for electrons and γ-quanta, respectively.

$2p\sigma$, and the released binding energy of the muon molecule is carried away by a conversion electron

$$H\mu + He \rightarrow [(HeH\mu)^* e^-]^+ + e^-, \quad (H \equiv p,d,t). \qquad (2a)$$

Then the muon molecule goes from the excited state $2p\sigma$ to the ground state $1s\sigma$ either with electron conversion

$$[(HeH\mu)^* e^-]^+ \rightarrow (HeH\mu)^{++} + e^- \qquad (2b)$$

or with γ-quantum emission

$$[(HeH\mu)^* e^-]^+ \rightarrow [(HeH\mu)^{++} e^-] + \gamma \quad (6.85\ \text{keV}). \qquad (2c)$$

Since there are no bound states in the term $1s\sigma$ of the $(HeH\mu)^{++}$ system, it dissociates into a hydrogen isotope nucleus and a helium mu-atom

$$(HeH\mu)^{++} \rightarrow (He\mu)^+ + H. \qquad (2d)$$

Consideration of the mechanism [9] yielded a conclusion that the muon transfer rate from the ground state of $p\mu(d\mu,\ t\mu)$-atoms exceeds its earlier calculated and measured values ($\sim 10^8\ c^{-1}$).

In this connection the Dubna group carried out full joint analysis [10] of experimentally found [8] yields and time distributions of electrons and meso-X-ray γ-quanta from $Xe\mu$-atoms under the assumption that there is muon transfer from the ground state of $p\mu$-atoms to ^4He nuclei. The analysis showed that the rate of muon transfer from $p\mu$-atoms (in the ground state) to ^4He nuclei was $\lambda^{p}_{^4He} = (0.36\pm0.10)\times10^8\ s^{-1}$ agreeing with the calculated value of $\lambda^{p}_{^4He}$ [9].

Thus, a theoretically predicted [9] new phenomenon of molecular charge exchange of ground-state mu-atoms of hydrogen isotopes on He nuclei was experimentally found in Dubna. The relation between the quantity $W = W_H W_\theta$ and the concentration of ^4He was also found in that experiment (W_H is the probability of muon capture by the hydrogen atom in the $H_2+{}^4He$ mixture, W_θ is the probability that a $p\mu$-atom formed in the excited state will change to the ground state). Figure 2 shows the dependence of W on C_{He}.

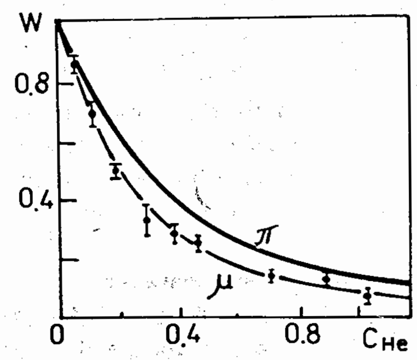

Fig. 2. Dependence of W on the relative atomic concentration of ^4He. μ, Π are results of [9] and [6] respectively.

After the above phenomenon [10] and muon transfer from excited states of mesohydrogen [6, 8] were found, interest in studying these processes has greatly increased, mainly for the following reasons.

a) Knowing parameters of muon transfer from mu-atoms of hydrogen isotopes both in ground and excited states, one can correctly interpret measurements of characteristics of muon-catalyzed nuclear fusion (μCF) in the D_2+T_2 mixture and estimate frequency and necessity of removing helium from the D_2+T_2 mixture exposed to a muon beam. b) It is necessary to describe cascade transition kinetics for mu-atoms of hydrogen isotopes in mixtures of hydrogen isotopes and helium.

Studying μCF in pure deuterium with a high-pressure ionization chamber, the scientists of LINP (Gatchina) carried out experiments [11] to measure rates of muon transfer from dμ-atoms to ^{3}He and ^{4}He nuclei ($\lambda^d_{^3He}$ and $\lambda^d_{^4He}$). Measurement of these quantities was based on the method used by the authors to study muon catalysis in deuterium [12, 13]. The deuterium-to-helium muon transfer rate was defined as a change in the slope of the time distribution of the first recorded dd-fusion events after adding a certain amount of helium to deuterium. The concentration of ^{4}He (^{3}He) in deuterium was 1.8%. The rate values resulted from the analysis of the experimental data were $\lambda^d_{^4He} = (3.68\pm0.18)\times10^8$ s^{-1} and $\lambda^d_{^3He} = (1.27\pm0.11)\times10^8$ s^{-1} (the values are reduced to the liquid hydrogen density). The results are in fairly good agreement with the calculations [9, 14, 15] performed in a simple approach within the frozen core model with allowance for electron shielding and with averaging over the Maxwell distribution of dμ-atom rates (see Table 1).

At KEK (Japan) experiments [16, 17] were carried out to measure rates of muon transfer from dμ-atoms to ^{4}He nuclei. The rate $\lambda^d_{^4He}$ was determined by measuring the yield and time distribution of γ-quanta appearing at the radiative transition of

the excited mu-molecular complex $[(\mu^- d\,^4He)]$ to the unbound ground state of a system consisting of a ^{4}Heμ ion and a deuteron (process (2c)). Registration of 6.85-keV γ-quanta is direct experimental evidence for existence of the predicted mechanism [9] for molecular charge exchange of mu-atoms of hydrogen isotopes on He nuclei. The experiments [16, 17] were carried out with the same set-up and registration equipment as the experiment on investigation of muon-catalyzed fusion in the D_2+T_2 mixture [18]. To determine $\lambda^d_{^4He}$, the time distributions and yield obtained for γ-quanta (E_γ = 6.85 keV) were approximated by the following expressions:

$$\frac{dN_\gamma}{dt} = N_\mu \alpha \varepsilon_\gamma \lambda^d_{^4He} \varphi C_{He} e^{-\lambda t}; \qquad (3)$$

$$N_\gamma = N_\mu \alpha \varepsilon_\gamma \lambda^d_{^4He} \varphi C_{He}/\lambda; \qquad (4)$$

$$\lambda = \lambda_0 + \lambda^d_{^4He} \varphi C_{He}; \quad \alpha = \lambda_\gamma/(\lambda_\gamma+\lambda_e) \; , \qquad (5)$$

where N_μ is the number of muon stops in the $D_2+{}^4He$ mixture, ε_γ is Si(Li)-detector registration efficiency for 6.85-keV γ-quanta, α is the radiation de-excitation probability for the $(He\mu d)^{++}$ complex, λ_γ, λ_e are the rates of transitions (2c) and (2b), respectively, C_{He} is the relative atomic concentration of ^{4}He in $D_2+{}^4He$, φ is the $D_2+{}^4He$ density reduced to the liquid hydrogen density (n_0 = = 4.25×10^{22} cm^{-3}), $\lambda_0 = 0.455\times10^6$ s^{-1} is the free muon decay rate.

The rate of muon transfer from dμ-atoms to ^{4}He nuclei at T = = 20 K was found to be $\lambda^d_{^4He} = (13.1\pm1.2)\times10^8$ s^{-1}. The rate obtained for muon transfer from deuterium to helium is in fairly good agreement with the calculations [15] performed in a simple approach with allowance for electron shielding (see Table 1).

In Los Alamos the analysis of the experimental data [19, 20] on μCF in D_2+T_2 allowed information on rates of muon transfer from

Table 1. Experimental and theoretical rates of muon transfer from mu-atoms of hydrogen isotopes to He nuclei.

Quantity	Experimental conditions			Rate (10^8 s^{-1})	
	T, K	φ	C_{He}, %	Experiment	Theory [15]
$\lambda^p_{^4He}$	300	0,04-0,05	25;48	0,36±0,1 [10]	
		0,025-0,066	16-68		
		0,03-0,04	4,7-22	0,88±0,09 [22]	0,35*
		0,02	17;34		
		0,006	25	0,032±0,013 [21]	
$\lambda^d_{^4He}$	20	1,2	0,043	13,1±1,2 [16]	11,3*
	300	0,1	1,8	3,68±0,18 [11]	3,22*
		0,84	0,05÷1,0	2,75±0,22 [23]	2,96**
		0,008	4,8	≤0,1 [6]	
$\lambda^d_{^3He}$	300	0,1	1,8	1,27±0,11 [11]	1,43*
		0,45;0,6	0,04	2±1 [19,20]	1,3**
$\lambda^t_{^3He}$	300	0,45;0,6	0,04	15,0±2,5 [19,20]	8,7*

*, ** indicate calculations in the simple approach within the frozen core and unfrozen core models with allowance for electron shielding and with averaging over the Maxwell distribution of dμ-atom rates

dμ- and tμ-atoms to ^{3}He nuclei in the temperature range from 50 K to 400 K. There is substantial discrepancy between the experimental value of $\lambda^t_{^3He}$ and the calculations performed in a

simple approach and one-channel approximation with and without electron shielding [15] (see Table 1).

In 1988-1989 two groups carry out experiments [21, 22] on measurement of muon transfer rates from pμ-atoms to ^{4}He nuclei at PSI (Switzerland). In [21] the transfer rate was determined by analysing γ-quantum yield in transition of the $(He\mu d)^{++}$ complex from the state 2pσ to the state 1sσ (E_γ = 6.85 keV) measured in the H_2(2.5 atm) + ^{4}He(2.5 atm). In [22] the value of $\lambda^p_{^4H}$ was found by analysing time distributions of γ-quanta with the above energy in the triple mixtures H_2 + 50.7% ^{4}He + 943 ppm Ar (mixture pressure was P = 14.8 atm), H_2 + 34.4% ^{4}He + 649 ppm Ar (P = 14.8 atm). The results of these investigations are given in Table 1.

In 1990 an experiment [23] was carried out in Dubna to measure the rate of muon transfer from dμ-atoms to ^{4}He nuclei in a deuterium-helium mixture at a pressure of 1350 atm. The transfer parameters were measured by analysing yields and time distributions of successively registered dd-fusion neutrons induced by one muon [24]:

$$\lambda^d_{^4He} = [(\lambda_2-\lambda_1)-(1-W)\varphi\lambda_{dd\mu}+(1-W)(\lambda_1-\lambda_0)]/C_{He}\varphi; \qquad (6)$$

$$\lambda_1 = \lambda_0+(\varepsilon_n+\omega_d-\varepsilon_n\omega_d)\beta\varphi\lambda_{dd\mu}; \qquad (7)$$

$$\lambda_2 = \lambda_0+(\varepsilon_n+\omega_d-\varepsilon_n\omega_d)W\beta\varphi\lambda_{dd\mu}+(1-W)\varphi\lambda_{dd\mu}+C_{He}\varphi\lambda^d_{^4He}; \qquad (8)$$

$$\eta_1^{D/He} = (N^1_n/N_e)^{D/He}; \quad \eta^D_1 = (N^1_n/N_e)^D; \qquad (9)$$

$$W = W_D W_0 = \eta_1^{D/He}\lambda_2/\eta^D_1\lambda_1; \qquad (10)$$

$$\left[\frac{dN^1_n}{dt}\right]^D = \varepsilon_n\beta\varphi\lambda_{dd\mu}e^{-\lambda_1 t}; \qquad (11)$$

$$\left[\frac{dN_n^1}{dt}\right]^{D/He} = W\varepsilon_n \beta\varphi\lambda_{dd\mu}e^{-\lambda_2 t}; \qquad (12)$$

where $(N_e)^{D,D/He}$, $(N_n^1)^{D,D/He}$ are the numbers of muon decay electrons and first registered neutrons measured in pure deuterium and $D_2+{}^4He$ respectively; φ is the $D_2+{}^4He$ density with respect to the liquid hydrogen density; W_D is the probability of muon capture by the deuterium atom in the $D_2+{}^4He$ mixture; W_θ is the probability that a dμ-atom formed in the excited state will change to the ground state; η_1^D, $\eta_1^{D/He}$ are the yields of the first registered neutrons (per muon stopped in the target) in experiments with pure deuterium and $D_2+{}^4He$ respectively; λ_1, λ_2 are slopes of time distributions of the first registered neutrons in exposures with D_2 and $D_2+{}^4He$; ε_n is the neutron registration efficiency of the experimental set-up; ω_d is the probability of muon sticking to the ${}^3He$ nucleus resulted from the dd-fusion reaction (ω_d = 0.122±0.003 [12]); β is the relative probability of dd-fusion with production of a neutron (β = = 0.58 [12]); $\lambda_{dd\mu}$ is the rate for formation of ddμ-molecules [12,25]; C_{He} is the helium concentration. A scheme of mu-atomic and mu-molecular processes in the $D_2+{}^4He$ mixture is given in Fig.3. The experimental lay-out is shown in Fig. 4. The helium concentration ranged from 5×10^{-4} to 10^{-2}. As an example, in Fig. 5 there are time distributions of the first registered neutrons measured in the experiments with pure deuterium and with $D_2+{}^4He$ (C_{He} = 0.31%). Values of W_θ were determined for each exposure with $D_2+{}^4He$ by substituting the values of η_1^D, $\eta_1^{D/He}$, λ_1, λ_2 to expression (11). The processing of all the data resulted in

$$\lambda^d_{{}^4He} = (2.75\pm0.22)\times10^8\ s^{-1}.$$

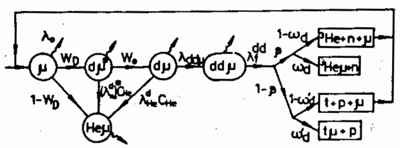

Fig. 3. Scheme of mu-atomic and mu-molecular processes in the $D_2+{}^4He$ mixture.

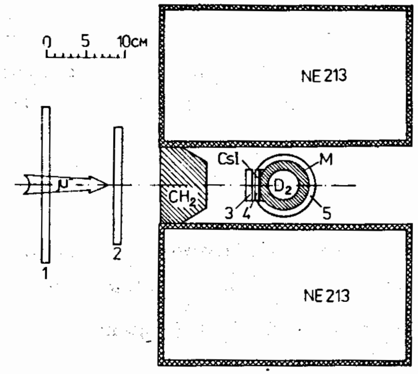

Fig. 4. Experimental lay-out: 1-5 — scintillation detectors; CH_2 — stopping filter; M — target; NE-213 — neutron detectors.

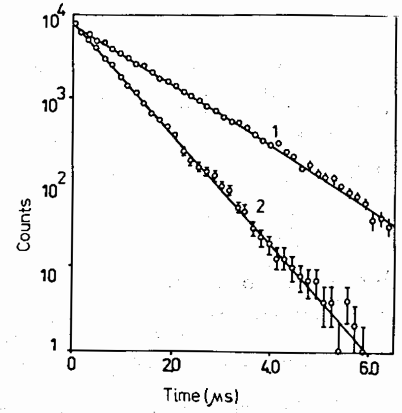

Fig.5. Time distribution of the first registered neutrons from the dd-fusion reaction: 1-experiment with pure deuterium; 2 - experiment with $D_2+{}^4He$ (C_{He}= 0.31%); solid lines show the fitting.

The boundary values of W_θ corresponding to the minimum and maximum ${}^4He$ concentrations were found at a 90% confidence level:

$$W_\theta(C_{He}=0.5\cdot10^{-3}) \geqslant 0.96, \qquad W_\theta(C_{He}=10^{-2}) \geqslant 0.90$$

The values derived for $\lambda^d_{{}^4He}$ and W_θ are in agreement with the results of calculations [15] and [26, 27] respectively.

Table 1 lists the results of all experimental measurements of muon transfer rates from mu-atoms of hydrogen isotopes to He nuclei carried out by now.

Comparison of the experimental results obtained allow the following conclusions.

$H_2+{}^4He$ mixture

1. The difference between the results of [10] $(3.6\pm0.1)\times10^7\ s^{-1}$) and [21] $(0.32\pm0.13)\times10^7\ s^{-1}$) can be explained now. Since there is a predissociation channel for the $(He\mu d)^{++}$ complex in the excited state $2p\sigma$

$$(H\mu He)^* \rightarrow He\mu + H, \qquad (13)$$

(considered in detail in [28-30]), one must introduce a correction γ to the value of $(\lambda^p_{^4He})'$ obtained in [21]. This correction is derived from the analysis of the yield of 6.85-keV γ-quanta

$$\gamma = \lambda_\gamma/(\lambda_\gamma+\lambda_e+\lambda_p) \approx 0{,}07, \qquad (14)$$

where λ_p is the rate of process (13); λ_γ, $\lambda_e = 0.15\lambda_\gamma$ are the rates of processes (2c) and (2b) respectively (λ_p, λ_γ, λ_e are calculated in [28-30]). Since the authors of [21] determined $\lambda^p_{^4He}$ with $\alpha = \lambda_\gamma/(\lambda_\gamma+\lambda_e) = 0.85$ (without allowance for the predissociation channel), one can get a correct value of $\lambda^p_{^4He}$ from expression (4):

$$\lambda^p_{^4He} \approx \frac{0{,}85}{\gamma}(\lambda^p_{^4He})' = (0{,}39\pm0{,}16)\times10^8\ s^{-1}.$$

This value is seen to be in good agreement with the result of [10]. As to the discrepancy between [10] and [22], its nature has not been clarified by now.

$D_2+{}^4He$ mixture

1. The difference between the $\lambda^d_{^4He}$ values derived in [16, 17] from analysis of the time distribution of 6.85-keV γ-quanta ($\lambda^d_{^4He}$ = $= (13.1\pm1.2)\times10^8\ s^{-1}$) and of their yield $((\lambda^d_{^4He})' = 6.7\pm1.3)\times10^8$

s^{-1}) is also eliminated by the correction $\gamma = 0.49$ [28-30] to $(\lambda^d_{^4He})'$.

2. The difference between the data of [10] $\lambda^d_{^4He} = (2.75\pm0.22)$ $\times10^8\ s^{-1}$) and [11] ($\lambda^d_{^4H} = (3.68\pm0.18)\times10^8\ s^{-1}$) cannot be explained at present.

3. There is an explanation for the value of the ratio R_γ = $Y_\gamma^{D_2+{}^3He}/Y_\gamma^{D_2+{}^4He} = 0.082$ found in [31] from analysis of the experimental data with allowance for the predissociation mechanism [28-30] ($Y_\gamma^{D_2+{}^3He}$, $Y_\gamma^{D_2+{}^4He}$ are the yields of 6.85-keV γ-quanta in experiments with $D_2+{}^3He$ and $D_2+{}^4He$ respectively). With the calculated values of λ_p, λ_γ, λ_e [28-30], the calculated value of R_γ is about 0.10.

$T_2+{}^3He$ mixture

To compare calculation results with indirectly obtained experimental $\lambda^t_{^3He}$ correctly, one must analyse the experimental data [19, 20] with allowance for muon transfer from excited $t\mu$-atoms to ^3He.

All the results listed in Table 1 are the rates of muon transfer from $p\mu$-, $d\mu$- and $t\mu$-atoms in the ground state to ^3He and ^4He nuclei.

As mentioned above, particular attention should be given to the points related to kinetics of excited mesohydrogen in mixtures of hydrogen isotopes and helium. It is difficult to distinguish experimentally between the process of muon capture by the hydrogen isotope atoms (formation of muon atoms of hydrogen isotopes) in mixtures like H_2+ He, D_2+ He, T_2+ He and the process of their subsequent charge exchange in excited states on He nuclei. There is practically no experimental data on these processes, while theoretical information is incomplete, ambiguous, and thus should be specified and refined. A characteristic of the processes of muon capture and muon transfer from excited states of mesohydrogen to He nuclei is the quantity $W = = W_H W_\theta$. The quantity $W_\theta \equiv q_{1s}^{He}$, which characterises population of the mesohydrogen ground state with allowance for muon transfer from an excited mesoatom to helium, depends on the target density, helium concentration and, generally speaking, on the energy of the excited mesoatom. In [26] a cascade of excited mesohydrogen in a mixture of hydrogen isotopes and helium was considered and a method was proposed for determining the rate of muon transfer from excited mesohydrogen to helium and the probability of muon capture by the hydrogen isotopes.

The authors of [32] employed this technique [26] to analyse the data from the experiment [8] and determine the rate of muon transfer from excited pμ-atoms to ^{4}He nuclei. Using the values of $W = W_H W_\theta$ [8] found for different pressures and ^{4}He concentrations in the hydrogen-helium mixture and the calculated values of W_H ($W_H = 1/(1 + AC_{He})$; $A = 1.7\pm0.2$ is the ratio of stopping capabilities of He and H atoms averaged over the data of [7, 33, 34]), the authors of [32] determined W_θ values for the conditions of each of 9 exposures in the experiment [8]. On approximating the values obtained for $W_\theta \equiv q_{1s}^{He}$ by the expression [32], which reflects dependence of the pμ-atom ground state population on the ^{4}He concentration, H_2+^4He density and partial rates $\lambda_{He}^{(n)}$ of muon transfer from excited states with $2 \leqslant n \leqslant 5$ (initial population of the n = 5 state was taken to be 1 because Auger de-excitation rates of mesohydrogen in states with n > 5 considerably exceed muon transfer rates to helium), the authors of [32] estimated $\lambda_{^4He}^{(n)}$ to be

$$\lambda_{^4He}^{(3)} = (2\pm7)\times10^{10}\ s^{-1};\ \lambda_{^4He}^{(4)} = (16\pm13)\times10^{11}\ s^{-1};$$

$$\lambda_{^4He}^{(5)} = (75\pm60)\times10^{11}\ s^{-1}$$

Such large errors in determination of the sought-for quantities

mainly arise from statistical errors in measurements [8]. It should be mentioned that the following assumptions were made in [32] for consideration of the pμ-atom cascade scheme:

1) the rate of muon transfer from states with a certain n and different orbital quantum numbers l is the same;

2) there is no difference in external Auger effect cross sections for ^{4}He and H atoms;

3) the rate of muon transfer from excited states of pμ-atoms does not depend on their energy;

4) concerning n = 2 states, allowance was made only mesohydrogen charge exchange on ^{4}He nuclei from the state 2s corresponding to attraction of a pμ-atom and a ^{4}He nucleus.

Insensitivity of q_{1s}^{He} to $\lambda_{He}^{(2s)}$ under the experimental conditions [8] is due to small initial population of the 2s-state and a small absolute value of $\lambda_{He}^{(2s)}$. Having analysed all the available data, we formulate the programme for further study of kinetics of mu-atomic and mu-molecular processes in mixtures of hydrogen isotopes and helium.

1. Experiments with D_2+He (φ = 0.05-1.0, C_{He} = 10^{-4}-5×10^{-2}) and T_2+He ($\varphi \leqslant 0.2$, $C_{He} = 10^{-4}$-5×10^{-2}) mixtures will allow one to determine q_{1s}^{He} with high precision, to refine the calculated values of muon transfer rates from excited states of dμ- and tμ-atoms to He nuclei and to define more exactly the scheme of cascade transitions in mu-atoms of hydrogen isotopes.

2. Using the given cascade scheme and carrying out experiments with D_2+He and T_2+He at higher He concentrations, one can find the probability of muon capture by the deuterium and tritium with a fairly good accuracy, which entails determination of A to an accuracy of 2-4%.

3. Experiments with D_2+He and T_2+He at smaller densities $\varphi \leqslant 10^{-5}$ and higher He concentrations will allow one to determine muon transfer rates from dμ- and tμ-atoms in the 2s-state and to get information on energy distribution of mu-atoms in 2s- and 2p-states. Using the theoretical dependence of $\lambda_{He}^{(n)}$ on the energy of mu-atoms of hydrogen isotopes and experimentally obtained

values of q_{1s}^{He}, one can get information on energy distribution of hydrogen mu-atoms during their de-excitation.

4. Using the experimentally found rates of muon transfer from $d\mu$- and $t\mu$-atoms in excited states to He nuclei and the refined algorithm for calculation of these rates, one can calculate the rates of muon transfer from $p\mu$-atoms to helium nuclei.

5. Carrying out experiments with widely varying densities and He concentrations and analysing the data with calculated values of $\lambda_{He}^{(n)}$, one can find the probability of muon capture by the hydrogen and the value of A.

6. Comparison of A values found in experiments with H_2+He, D_2+He and T_2+He will allow an answer to the question if there exists isotopic dependence of the probability of muon capture by the hydrogen isotope atoms.

7. At least two series of experiments (for the same φ and C_{He}) with the H_2+He, D_2+He and T_2+He gas mixtures must be carried out at different temperatures to confirm temperature dependence of the muon transfer rate from mu-atoms of hydrogen isotopes in the ground state to He nuclei.

8. To get more exact information on $\lambda_{He}^{(2s)}$ and on energy distribution of mu-atoms of hydrogen isotopes in the n = 2 states, one must experimentally measure K-line intensities of delayed meso-X-radiation from mesohydrogen (radiative transition $2p \rightarrow 2s$ following the Stark transition $2s \rightarrow 2p$) and mesohelium. These experiments should be carried out at small densities of the hydrogen-helium mixture ($\varphi \leqslant 10^{-5}$) and fairly large He concentrations ($C_{He} \geqslant 0.5$).

9. Investigations with the H_2+He, D_2+He and T_2+He mixtures at different temperatures ($20\ K \leqslant T \leqslant 5000\ K$), densities and He concentrations will probably allow one to get information on contributions of resonant and nonresonant mechanisms to molecular charge exchange of hydrogen isotope mesoatoms on helium nuclei.

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REFERENCES

1. M.Shiff. Nuovo Cim., 1961, v.22, p.66.
2. O.A.Zaimidoroga et al.Zh.Eksp.Teor.Fiz.,1963,v.44,p.1852.
3. A.Bertin et al. Nuovo Cim., 1967, v.52A, p.1274.
4. Ya.B.Zeldovich,S.S.Gershtein.Uspekhi Fiz.Nauk, 1960, v.71, p.581.
5. A.V.Matveenko,L.I.Ponomarev.Zh.Eksp.Teor.Fiz.,1972, v.63, p.48.
6. A.Bertin et al. Lett. Nuovo Cim., 1977, v.18, p.3817.
7. V.I.Petrukhin,V.M.Suvorov.Zh.Eksp.Teor.Fiz.,1976, v.70, p.1145.
8. V.M.Bystritsky et al.Mesons in matter. Proc. of the Int.Symp. on Meson Chemistry and Mesomolecular Processes in Matter. D1,2,14-10908, Dubna, 1977, p.220.
9. Yu.A.Aristov et al.Yad.Fiz.,1981, v.33, p.1066.
10. V.M.Bystritsky et al.Zh.Eksp.Teor.Fiz., 1983, v.84, p.1257.
11. D.V.Balin et al.Pis'ma Zh.Eksp.Teor.Fiz., 1985, v.42, p.236.
12. D.V.Balin et al.Pis'ma Zh.Eksp.Teor.Fiz., 1984, v.40, p.318. D.V.Balin et al. Phys.Lett.B, 1984, v.141, p.1737.
13. A.A.Vorobyov. MCF, 1988, v.2, p.17.
14. A.V.Kravtsov et al. J.Phys.B: At.Mol.Phys., 1986, v.19, p.2579.
15. V.K.Ivanov et al.Zh.Eksp.Teor.Fiz., 1986, v.91, p.358.
16. T.Matsuzaki et al. MCF, 1988, v.2, p.217.
17. T.Matsuzaki et al. AIP, 1989, v.181, p.23.
18. K.Nagamine et al. MCF, 1987, v.1, p.137.
19. S.E.Jones et al. Phys.Rev.Lett., 1986, v.56, p.588.
20. A.J.Caffrey et al. MCF, 1987, v.1, p.53.
21. H.P.von Arb et al. MCF, 1989, v.4, p.61.
22. R.Jacot-Guillarmod et al. Phys.Rev.A, 1988, v.38, p.6151.
23. V.M.Bystritsky et al.Zh.Eksp.Teor.Fiz., 1990, v.98, p.1514.
24. V.M.Bystritsky, V.A.Stolupin.Yad.Fiz., 1991, v.53, p.1005.
25. V.M.Bystritsky et al. AIP, 1988, v.181, p.17.
26. V.M.Bystritsky et al.Zh.Eksp.Teor.Fiz., 1990, v.96, p.73.
27. A.V.Kravtsov et al. Phys.Lett.A, 1988, v.132, p.124.
28. S.S.Gershtein and V.V.Gusev. Preprint IHEP, 92-129, Protvino, 1992.

29. A.V.Kravtsov et al. Preprint PNPI, No. 1819, S.Petersburg, 1992.
30. Y.Kino and M.Kamimura. Preprint (Int. Workshop on Muon Catalyzed Fusion, μCF-92, Uppsala, June 28 - July 3, 1992).
31. R.Nagamine.Proc.Inter.Conf.on Particle Nucl.Phys.,1991;UT-MSL Newsletter, No. 10, 1991, 22.
32. V.M.Bystritsky et al. Kerntechnik, 1993, v.58, p.185.
33. F.Kottmann: Mesons in Matter. Proc.Int.Symp. on Meson Chemistry and Mesomolecular Processes in Matter, Dubna, 1987, p.220.
34. V.Balashov et al. MCF, 1988. v.2, p.105.

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Быстрицкий В.М. E1-93-451
Перехват мюонов от мюонных атомов изотопов водорода
к ядрам He. Статус и предложения

Приводится обсуждение и сравнение всей совокупности результатов экспериментов по исследованию явления перехвата мюонов от μ-атомов изотопов водорода к ядрам гелия. Предложена программа дальнейших исследований данного явления с целью получения более точной и детальной информации о характеристиках μ-атомных и μ-молекулярных процессов, происходящих в смесях изотопов водорода и гелия.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Bystritsky V.M. E1-93-451
Muon Transfer from Muonic Atoms of Hydrogen Isotopes
to He Nuclei. Status and Proposals

All experimental data on muon transfer from μ-atoms of hydrogen isotopes to helium nuclei are discussed and compared. The program of further investigations is proposed so as to get more accurate and detailed information on characteristics of μ-atomic and μ-molecular processes in mixtures of hydrogen and helium isotopes.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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