Muon transfer from $d\mu$ atoms to ^4He nuclei in a deuterium-helium mixture at 1350 atmospheres

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An experiment has been performed to measure the parameters of charge exchange of $d\mu$ atoms on ^4He nuclei in a $D_2 + {}^4He$ mixture at a pressure $P = 1350$ atm. The helium concentration was varied in the range $5 \cdot 10^{-4}$ to 10^{-2}. The rate of transfer of muons from $d\mu$ atoms in the ground state to ^4He nuclei turned out to be $(2.75 \pm 0.22) \cdot 10^8 \sec^{-1}$. Lower-limit estimates were obtained for the population of the ground state of $d\mu$ atoms at minimal and maximal helium concentrations, which amounted respectively to 0.96 and 0.90.

The experimental observation[1] of the theoretically predicted[2] mechanism of molecular charge exchange of muonic atoms of the hydrogen isotopes on He nuclei,

$$\mathrm{H}\mu + \mathrm{He} \rightarrow [(\mathrm{H}\mu\,\mathrm{He})^* e^-]^+ \nearrow (\mathrm{H}\mu\,\mathrm{He})^{++} + e, \quad (1a)$$

$$\searrow (\mathrm{H}\mu\,\mathrm{He})^{+} + \gamma\,(6{,}85\ \mathrm{keV}), \quad (1b)$$

$$(\mathrm{H}\mu\ \mathrm{He}) \rightarrow \mathrm{He}\,\mu + \mathrm{H}, \quad (1c)$$

where $\mathrm{H} \equiv$ H, D, T, $\mathrm{He} \equiv {}^3He$, ^4He, and also the observation of transfer of muons from excited states of muonic atoms of the hydrogen isotopes[1,3] served as the stimulus for further more detailed study of this phenomenon.

At the present time a considerable number of experimental studies have been carried out on the transfer of muons from the hydrogen isotopes to helium. The results are given in the table. As can be seen, the experimental values found[1,7] for the rates of transfer of muons from $p\mu$ and $d\mu$ atoms to He nuclei are in agreement with the results of calculations[9] carried out in a simple approach taking into account electronic screening. In regard to the muon transfer rates $\lambda^p_{^4He}$ and $\lambda^d_{^4He}$ measured in the experiments of Refs. 3–5, they not only differ from each other but also do not agree with the results of the calculations of Ref. 9.

The purpose of the present work was to study the transfer of muons from $d\mu$ atoms to ^4He nuclei at small concentrations of helium and a pressure $P = 1350$ atm of the mixture $D_2 + {}^4He$.

METHOD OF MEASUREMENT

In Fig. 1 we show a diagram of the muon-atom and muon-molecule processes occurring in a $D_2 + {}^4He$ mixture after stopping in it of a negative muon. The method of measurement of the parameters of the muon transfer process is based on analysis of the yields and time distributions of the successively detected neutrons of dd fusion initiated by a single muon.

The expressions for the desired parameters ($\lambda^d_{^4He}$ and W) have the form [Eq. (5) was obtained in Ref. 10]

$$W = W_D W_0 = \eta_1^{D/He} \lambda_2 / \eta_1^D \lambda_1, \quad (2)$$

$$\lambda_1 = \lambda_0 + (\varepsilon_n + \omega_d - \varepsilon_n \omega_d) \beta \phi \lambda_{dd\mu}, \quad (3)$$

$$\lambda_2 = \lambda_0 + (\varepsilon_n + \omega_d - \varepsilon_n \omega_d) W \beta \phi \lambda_{dd\mu} + (1-W) \phi \lambda_{dd\mu} + C_{He} \phi \lambda^d_{^4He}, \quad (4)$$

$$\lambda_{^4He} = [(\lambda_2 - \lambda_1) - (1-W) \phi \lambda_{dd\mu} + (1-W)(\lambda_1 - \lambda_0)] / C_{He} \phi, \quad (5)$$

$$\eta_1^{D/He} = (N_n^1/N_e)^{D/He}, \quad \eta_1^D = (N_n^1/N_e)^D, \quad (6)$$

where $(N_e)^{D,D/He}$ and $(N_n^1)^{D,D/He}$ are the numbers of electrons from decay of muons and the first detected neutrons, measured respectively in experiments with pure deuterium and with a $D_2 + {}^4He$ mixture, ϕ is the density of the $D_2 + {}^4He$ mixture relative to the density of liquid hydrogen ($n_0 = 4.25 \cdot 10^{22} cm^{-3}$), W_D is the probability of direct sitdown of a muon on a D atom in a $D_2 + {}^4He$ mixture, W_0 is the probability that a $d\mu$ atom formed in an excited state reaches the ground state, η_1^D and $\eta_1^{D/He}$ are the yields of the first detected neutrons (per muon stopped in the target) respectively in experiments with pure deuterium and with a $D_2 + {}^4He$ mixture, λ_1 and λ_2 are the slopes of the time distributions of the first detected neutrons in runs with D_2 and $D_2 + {}^4He$, ε_n is the efficiency of detection of neutrons by the experimental apparatus, ω_d is the probability of sticking of a muon to a ^3He nucleus formed as the result of the dd fusion reaction ($\omega_d = 0.122 \pm 0.003$; Ref. 11), β is the relative probability of the dd fusion reaction channel with formation of a neutron ($\beta = 0.58$; Ref. 11), $\lambda_{dd\mu}$ is the rate of production of $dd\mu$ molecules, λ_0 is the rate of decay of the free muon ($\lambda_0 = 0.455 \cdot 10^6 \sec^{-1}$), and C_{He} is the concentration of He.

The quantities λ_1 and λ_2 are determined by approximating the experimental time distributions of the first detected neutrons by the following expressions:

$$\left(\frac{dN_n^1}{dt}\right)^D = \varepsilon_n \beta \phi \lambda_{dd\mu} e^{-\lambda_1 t}, \quad (7)$$

$$\left(\frac{dN_n^1}{dt}\right)^{D/He} = W \varepsilon_n \beta \phi \lambda_{dd\mu} e^{-\lambda_2 t}. \quad (8)$$

In performing experiments with a $D_2 + {}^4He$ mixture at densities $\phi \sim 1$ and low concentrations of ^4He ($C_{He} \sim 10^{-3}$–10^{-2}) it is possible to neglect the direct settling of muons onto helium ($W_D \sim 1$) and in that way, according to Eq. (2), to determine the value of W_0. The method described for determining the quantities $\lambda^d_{^4He}$ and W_0 was realized by us in the experiment which is described below.

EXPERIMENTAL ARRANGEMENT

The experiment was carried out in the muon channel of the JINR synchrophasotron. In Fig. 2 we show a diagram of

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TABLE I. Experimental and theoretical values of the rates of transfer of muons from muonic atoms of hydrogen isotopes in the ground state to helium nuclei.

Quantity	Experimental conditions			Value of transfer rate (10^8 sec^{-1})	
	T, K	φ	C, %	Experiment	Theory[9]
$\lambda^p_{^4He}$	300	0,04–0,05	25; 48	–	0,35
		0,025–0,066	16–68	0,36±0,10 [1]	
		0,03–0,04	4,7–22	–	
		0,02	17; 34	0,88±0,09 [4]	
		0,006	25	0,032±0,013 [5]	
$\lambda^d_{^4He}$	20	1,2	0,043	13,1±1,2 [6]	11,8
	300	0,1	1,8	3,68±0,18 [7]	3,22 **
	300	0,84	0,05–1,0	2,75±0,22 *	2,96 ***
	300	0,008	4,8	≤0,2 [3]	
$\lambda^d_{^3He}$	300	0,1	1,8	1,27±0,11 [7]	1,43 **
	300	0,45; 0,6	0,04	2±1 [8]	1,30 ***
$\lambda^t_{^4He}$	300	0,45; 0,6	0,04	15±2,5 [8]	8,7 **

*—Data of the present work; ** and ***—calculations carried out in a simple approach taking into account electronic screening with averaging over a Maxwellian distriubtion of velocities of $d\mu$ atoms respectively in the frozen and unfrozen core models. The notation is explained in the text following Eqs. (2)–(6).

the experimental apparatus (this apparatus was used previously in the experiment of Ref. 12 on measurement of the rate of production of $dd\mu$ molecules at deuterium pressures up to 1500 atm).

A beam of muons with momentum 130 MeV/c and intensity $2\cdot 10^4$ sec^{-1} passed through scintillation detectors 1–4 and a CH_2 absorber to slow down the particles and entered a high-pressure target.[13] For detection of electrons from muon decay and identification of the stopping of a muon in the target volume we placed around it a scintillation detector 5 (a cylindrical plastic scintillator with diameter 100 mm, length $l = 150$ mm, and wall thickness $d = 5$ mm). Detection of neutrons from the dd fusion reaction was accomplished by means of two neutron detectors with ND-213 liquid scintillator,[14] which were placed symmetrically with respect to the target. The cuvettes for the NE-213 scintillators had diameter 310 mm and length 160 mm.

The target consisted of a thick-walled cylinder T of inner diameter 42 mm and length 100 mm made of alloy ÉI 437B. The thickness of the target walls was 9 mm. The target was placed inside a cryostat whose cooling agent, when needed, was liquid hydrogen. High pressures ($P \approx 1350$ atm) were obtained by liquefication of isotopically pure deuterium (concentration of protium $\leqslant 3\cdot 10^{-3}$) in the target volume and subsequently heating it. This means of obtaining high pressures guarantees preservation of the purity of the deuterium. Before liquefication of the deuterium in the target it was purified with use of the system described in Ref. 15.

A muon-stopping signal $1234\bar{5}$ triggered gates of duration 10 μsec during which dd-synthesis neutrons and muon-decay electrons were recorded. To decrease the background due to muon stoppings in the scintillator of detector 4, it was made of Cs(Tl) (the muon lifetime in Cs(Tl) is $\tau_\mu \approx 0.08$ μsec, which in turn permits correct separation in time of background events and events of the process under investigation). Blocking in the case of doubled muons and electrons was accomplished by means of detectors 1 and 5 respectively. Transfer of information to a computer was carried out on fulfillment of the following conditions: a) presence within the gates of only one signal from detector 5 and a signal from either of the two NE-213 neutron detectors; b) absence of a signal from detector 1 during the gates. In the final analysis of the experimental data we selected only those events for which the condition $t_e > t_n$ was satisfied, where t_e and t_n are respectively the times of appearance of the muon-decay electron and the neutron from the dd-fusion reaction.

Discrimination of the background from γ rays was accomplished by a multipulse n-γ separation system employing a parallel analog-to-digital converter.[16] For suppression of the prompt background due to muon stoppings in the neutron detector scintillator and the target walls we used fast

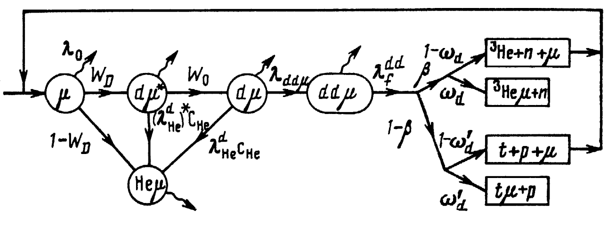

FIG. 1. Diagram of muon-atom and muon-molecule processes occurring in a D_2 + ^4He mixture.

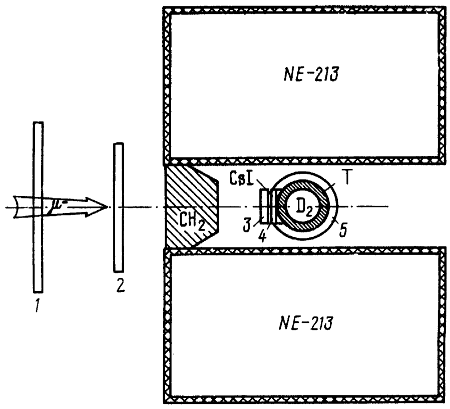

FIG. 2. Diagram of experimental apparatus for study of the transfer of muons from $d\mu$ atoms to ^4He nuclei.

(≈ 50 nsec) anticoincidences 123 $\overline{\Sigma N}$, and to increase the efficiency of selection of neutron events we used anticoincidences $N\bar{5}$ (≈ 25 nsec).

The threshold for efficient n-γ separation in units equivalent in light yield to the electron energy was ~ 0.1 MeV. Energy calibration of the neutron detectors was carried out by means of a ^{137}Cs γ source.

The experiment on measurement of the characteristics of the muon transfer from $d\mu$ atoms to ^4He nuclei included eight experiments: (a)—with pure deuterium ($P = 1350$ atm, $T = 300$ K); (b)—five runs with a $D_2 + {}^4He$ mixture with various helium concentrations [$P = 1350$ atm, $T = 300$ K, $C_{He} = (0.50 \pm 0.15)\cdot 10^{-3}$, $(0.13 \pm 0.03)\cdot 10^{-2}$, $(0.31 \pm 0.06)\cdot 10^{-2}$, $(0.64 \pm 0.09)\cdot 10^{-2}$, and $(1.0 \pm 0.10)\cdot 10^{-2}$]; (c) with pure helium ($P = 1050$ atm); (d) with an evacuated target. Runs (c) and (d) were background runs.

Addition of helium to the deuterium contained in the target was accomplished as follows. First gaseous deuterium was liquefied at a temperature ≈ 20 K (vapor pressure of deuterium ≈ 266 mm Hg), and then we admitted helium from a special measured volume at a pressure ≈ 30 atm in a quantity corresponding to a concentration $C_{He} = 0.5\cdot 10^{-3}$. After this the liquid hydrogen was removed from the cryostat and the target was heated to room temperature with an electrical heater mounted on its casing. Addition of the next portion of helium to that contained in the target was accomplished similarly to the procedure described above. Measurement of the target temperature was accomplished by means of copper-Constantan thermocouples mounted on the target. Hermetical sealing of the target was accomplished by means of a high-pressure valve with a Sylphon bellows.[17]

ANALYSIS OF EXPERIMENTAL DATA AND DISCUSSION OF RESULTS

The time distributions of the first detected neutrons obtained in experiments (a) and (b) were approximated by Eqs. (7) and (8) in order to determine the yields and the arguments λ_1 and λ_2 of the exponentials.

In Fig. 3 we have shown for illustration time distributions of the first detected neutrons measured in the experiments with pure deuterium and with a $D_2 + {}^4He$ mixture ($C_{He} = 0.31\%$). For each run with a $D_2 + {}^4He$ mixture, by substitution of the values found for η_1^D, $\eta_1^{D/He}$, λ_1, and λ_2 into Eq. (2), we determined the values of W_0, the probability of transition of a $d\mu$ atom from the excited state to the ground state. Since the error in determination of the values of W_0 in this range of variation of C_{He} is 3–4%, while the difference between neighboring values of the quantity W_0 does not exceed this uncertainty, we have given lower limit values of W_0, at the 90% confidence level, corresponding to the minimal and maximal concentrations of helium:

$$W_0(C_{He}=0{,}5\cdot 10^{-3}) \geqslant 0{,}96, \quad W_0(C_{He}=1{,}0\cdot 10^{-2}) \geqslant 0{,}90.$$

The limiting values obtained for W_0 are in agreement with the results of the calculations of Ref. 18.

The rate of transfer $\lambda^d_{^4He}$ of muons from $d\mu$ atoms in the ground state to ^4He nuclei was determined by means of Eq. (5) and the known values of $\lambda_{dd\mu}$ corresponding to a deuterium temperature $T = 300$ K.[11,12]

In Fig. 4 we have given values of $\lambda^d_{^4He}$ obtained in runs with a $D_2 + {}^4He$ mixture with variation of the helium concentration from $0.5\cdot 10^{-3}$ to $1.0\cdot 10^{-2}$. The error in the measured value in each run is due mainly to inaccurate knowledge of the concentration of the helium dissolved in the liquid deuterium in the process of its addition to the target. As a result of processing the entire set of experimental data the value found turned out to be

$$\lambda^d_{^4He} = (2{,}75 \pm 0{,}22)\cdot 10^8\ \text{sec}^{-1}.$$

As can be seen from the table, the values of the rate of charge exchange of $d\mu$ atoms on ^4He nuclei, which were obtained at a pressure $P = 1350$ atm of the $D_2 + {}^4He$ mixture, are less than the values of $\lambda^d_{^4He}$ measured at a pressure ≈ 100 atm,[7] but are substantially greater than the limiting value of this quantity found in the experiment of Ref. 3 ($P = 10$ atm). The reason for this discrepancy is still not clear. In regard to comparison of the value of $\lambda^d_{^4He}$ measured by us with the results of calculations, good agreement is observed with the calculated value of the transfer rate obtained in a simple approach in the model of statistical rearrangement of the core (unfrozen core) and with averaging over a Maxwellian distribution of the velocities of the $d\mu$ atoms.

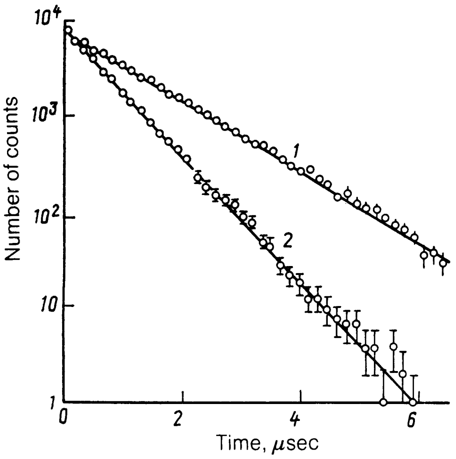

FIG. 3. Time distributions of the first detected neutrons from the dd-fusion reaction: 1—experiment with pure deuterium; 2—experiment with a $D_2 + {}^4He$ mixture ($C_{He} = 0.31\%$); solid curves—result of fits.

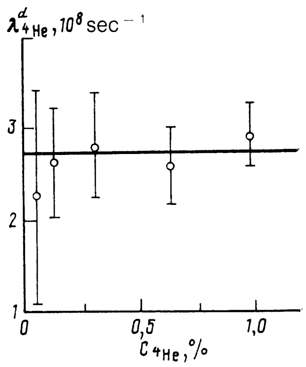

FIG. 4. Values of the rate of transfer of muons from the ground state of $d\mu$ atoms to ^4He nuclei, measured with various concentrations of helium in a $D_2 + {}^4He$ mixture. The straight line is the result of a fit of the experimental data.

Improvement of the calculations and performance of more precise measurements of $\lambda^{d}_{^4He}$ over a wide range of helium concentration and mixture density will permit understanding or removal of the existing discrepancy between the values found for the rates of transfer of muons from $d\mu$ atoms to ^{4}He atoms.

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