Charge exchange of mesonic deuterium atoms with ^{3}He and ^{4}He

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The charge-exchange rate of mesonic deuterium atoms with ^{3}He and ^{4}He nuclei is measured: $\lambda_{d^3\mathrm{He}} = (1.27 \pm 0.11) \times 10^8\ \mathrm{s}^{-1}$ and $\lambda_{d^4\mathrm{He}} = (3.68 \pm 0.18) \times 10^8\ \mathrm{s}^{-1}$. The results obtained confirm the validity of the molecular charge-exchange mechanism.

One of the processes which reduces the number of muon-catalysis events in nuclear fusion is the irreversible charge exchange of mesonic hydrogen atoms with helium nuclei (^{3}He and ^{4}He) which always accumulate in a deuterium-tritium mixture as a result of $dd\mu$ and $dt\mu$ catalytic reactions and β decay of tritium.

The rate of this process has until recently been determined on the basis of a model of a direct charge exchange.[1] The rate of charge exchange with helium predicted by this model is extremely low—$\sim 10^6\ \mathrm{s}^{-1}$, which is approximately four orders of magnitude lower than the rate of charge exchange with elements with $z > 4$. This situation stems from the fact that there is no crossing of the molecular terms in systems that participate in the charge exchange. This situation changed in 1981 as a result of an analysis by Aristov *et al.*[2] of a new (molecular) mechanism for charge exchange with helium, involving the scheme $\mathrm{H}\mu + \mathrm{He}^{++} \rightarrow [(\mathrm{H}\mu\mathrm{He})^*]^{++} \rightarrow \mathrm{H}^+[\mathrm{He}\mu]^+$, where $\mathrm{H} \equiv p$, d or t (Fig. 1). This mechanism accounted for charge-exchange rates 100 times higher than those of a direct charge-exchange model.

The charge-exchange rates are generally determined from the decrease in the lifetime of muons upon the addition of a known quantity of impurities into the hydro-

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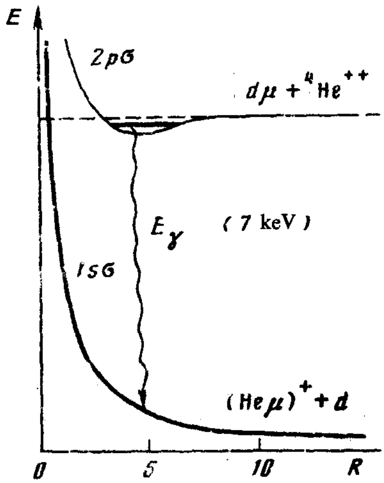

FIG. 1. Schematic representation of the molecular charge exchange of mesonic hydrogen atoms with helium nuclei. The $2p\sigma$ and $1s\sigma$ terms correspond to $d\mu + {}^4He^{++}$ and $d + ({}^4He\mu)^+$ systems in the limit $R \to \infty$, where R is the spacing between nuclei in units of muonic molecules.

gen or deuterium.[3–5] In the case of helium, however, the lifetime of the muons captured by it differs only slightly from the lifetime of free muons, essentially ruling out the use of this method. In this case the charge-exchange rate can be determined by a "triple-mixture" method, in which a certain amount of helium is added to a previously prepared mixture (of hydrogen and xenon, for example), thereby increasing the average lifetime of muons. Using this method, Placci *et al.*[3] estimated the rate of the charge exchange of muons from $d\mu$ atoms with helium to be $\lambda_{d^4He} \approx (8 \pm 10) \times 10^{-6}\,s^{-1}$. Bystritskiĭ *et al.*[6] have recently published the first reasonably accurate data on charge exchange of $p\mu$ atoms with helium: $\lambda_{p^4He} = (3.6 \pm 1.0) \times 10^7\,s^{-1}$, consistent with the predictions of the molecular mechanism in Ref. 2.

In the present letter we propose a new method which is based on detecting the events involving a $dd\mu$ catalysis with use of a high-pressure ionization chamber which doubles as a target and a detector.[7] This method is based on the measurements of the time distribution of dd-fusion events induced by a muon which is stopped in the sensitive volume of the chamber. The time origin is the muon-stopping signal. The electrons of the μ decay were also detected. The high-speed chamber ($\Delta t \sim 300$ ns) had a 100% detection efficiency of the charged products of dd fusion and a reliable identification of events at the background level.

Under these conditions the temporal distribution of the first events of the dd fusion immediately following the stopping of muons are described by the exponential function

$$dN/dt \sim \exp\{-(\lambda_0 + \lambda_{dd\mu} + \lambda_{dz})(t - t\mu)\},$$

where λ_0 is the decay rate of muon, $\lambda_{dd\mu}$ is the formation rate of the $dd\mu$ muonic molecules, λ_{dz} is the charge-exchange rate with the impurity z, and $(t - t\mu)$ is the time interval between the muon-stopping signal and the first fusion event. The quantity $\lambda_{d\,He}$ can be determined from the difference between the arguments of the exponential functions after measuring the indicated temporal distribution in pure deuterium and in a mixture of deuterium and a known quantity of helium.

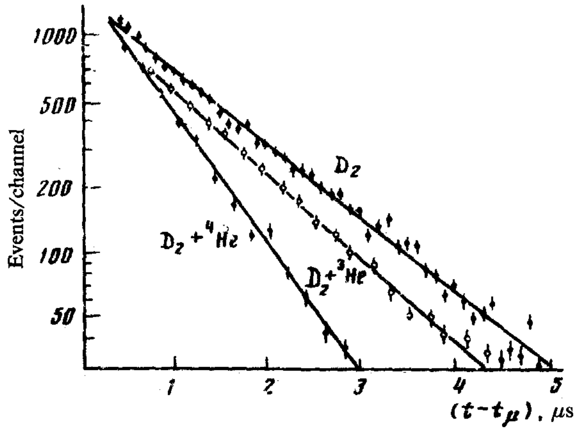

FIG. 2. Temporal distributions of the first fusion events in pure deuterium and with the addition of ^{3}He (1.97%) and ^{4}He (1.82%).

The experimental measurements of the charge-exchange of muonic deuterium atoms with ^{3}He and ^{4}He nuclei were carried out in the meson channel of the synchrocyclotron of the Leningrad Institute of Nuclear Physics. The preliminary results were published in Ref. 8. The temporal distribution is shown in Fig. 2. We see that upon addition of a small amount of helium, the argument of the exponential function of the temporal distribution of *dd*-fusion products increases appreciably. To eliminate the effect of impurities, which are added along with helium and which can imitate the observed effect, we have scrubbed the gas thoroughly and analyzed it before and after the experiment. The analysis showed the O_2 and N_2 impurities in the working mixture

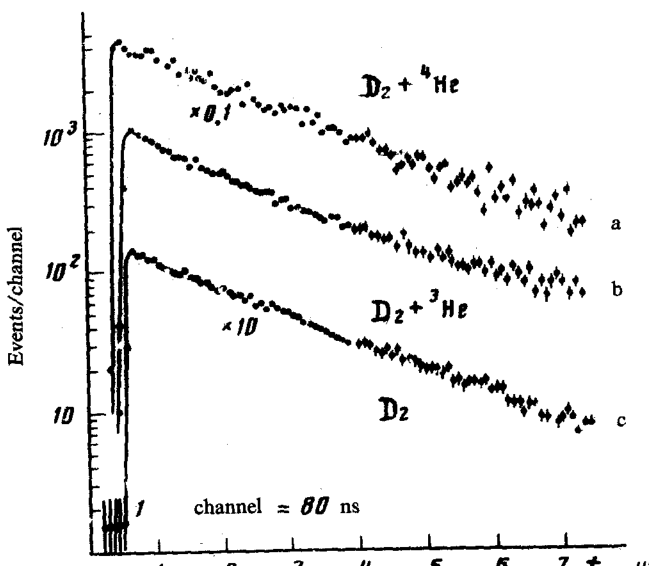

FIG. 3. Temporal distributions of the μ-decay electrons. The distributions were approximated by means of the expression $dN/dt = A + B\exp(-t/\tau)$. The following values of the parameter τ were found by fitting: a—$\tau(D_2 + {}^4He) = (2.179 \pm 0.043\ \mu s$; b—$\tau(D_2 + {}^3He) = 2.176 \pm 0.054\ \mu s$; c—$\tau(D_2) = 2.145 \pm 0.041\ \mu s$.

TABLE I. A summary of the measurement data on the charge-exchange rates of mesonic hydrogen atoms with helium.

Article	Measured parameter[1)]	Target pressure, atm	Atomic percentage of helium, %	Charge-exchange rate, 10^8 s^{-1}		
				Experiment	Theory	
					1	2
Bystritskiĭ *et al.*[6] (1982)	λ_{p^4He}	16 −25	5 − 70	0.36 ± 0,1	0,055	0.44
Jones *et al.*[9] (1983)	λ_{t^3He}	~700	$\sim 4\times10^{-2}$	7 ± 2	–	5,62
	λ_{d^3He}	~ 700	$\sim 4\times10^{-2}$	2 ± 1	0,013	1,48
Present study	λ_{d^3He}	76,9	1,97 ± 0,03	1.27 ± 0.11	0.013	1,48
	λ_{d^4He}	85,9	1,82 ± 0,02	3,68 ± 0.18	0,01	2,03

[1)] All charge-exchange rates are normalized to the helium density, which is equal to the density of liquid hydrogen $\rho_0 = 4.25\times10^{22}$ at/cm^3.

did not exceed 3×10^{-6} parts by volume, contributing no more than 10% to $\lambda_{d\mathrm{He}}$ being measured.

An additional test of the absence of the effect of impurities on the measurement results are the time spectra of the μ-decay electrons, shown in Fig. 3. As we can see, the lifetimes of muons in the mixtures studied are the same as the lifetimes of muons in pure deuterium. A change in the dN/dt distribution due to the presence of impurities in helium as a result of the addition of helium can therefore be ruled out. The most recent measurement results of the charge-exchange processes are summarized in Table I. This table also gives the preliminary results obtained by the Los Alamos group, who measured the charge-exchange rates from the neutron yield of the *dt* fusion.[9] A good general agreement of the data obtained through the predictions of the model of the molecular charge-exchange mechanism[2] allows us to conclude that this mechanism has now been confirmed experimentally in a satisfactory manner.

[1]S. S. Gershteĭn, Zh. Eksp. Teor. Fiz. **43**, 706 (1962) [Sov. Phys. JETP **16**, 501 (1963)].
[2]Yu. A. Aristov, A. V. Kravtsov, N. P. Popov, *et al.*, Yad. Fiz. **33**, 1066 (1981) [Sov. J. Nucl. Phys. **33**, 564 (1981)].
[3]A. Placci, E. Zavattini, *et al.*, Nuovo Cim. **52A**, 1271 (1967).
[4]A. A. Quaranta, A. Bertin, *et al.*, **47B**, 92 (1967).
[5]A. Bertin, M. Bruno, *et al.*, Phys. Rev. **7A**, 462 (1973).
[6]V. I. Bystritskiĭ, V. P. Dzhelepov, *et al.*, Preprint P1-82-646, Dubna, 1982.
[7]D. V. Balin *et al.*, Preprint LIYaF No. 964, 1984, p.54.
[8]D. V. Balin *et al.*, Preprint LINP-985, 1983; D. V. Balin *et al.*, Proc. PANIC Conf., Heidelberg, 1984, Vol. 11, p. L25.
[9]S. E. Jones, A. J. Gaffrey, *et al.*, Phys. Rev. Lett. **51**, 1757 (1983).

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