Experimental observation and investigation of muonic catalysis of the fusion reaction of deuterium and tritium nuclei

V. M. Bystritskiĭ, V. P. Dzhelepov, Z. V. Ershova,[1)] V. G. Zinov, V. K. Kapyshev,[1)] S. M. Mukhamet-Galeeva,[1)] V. S. Nadezhdin, L. A. Rivkis,[1)] A. I. Rudenko, V. I. Satarov, N. V. Sergeeva, L. N. Somov, V. A. Stolupin, and V. V. Fil'chenkov
Joint Institute for Nuclear Research

(Submitted 6 January 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 4, 249–253 (20 February 1980)

The neutron yield from the reaction $dt\mu \to {}^4He + n + \mu^- + 17.6$ MeV induced by negative muons in the $D_2 + T_2$ gas mixture was measured by using a muon beam of the JINR 680-MeV synchrocyclotron. The rate of transfer of a muon from deuterium to tritium $\lambda_{dt} = (2.7 \pm 0.9) \times 10^8$ sec^{-1} and the lower boundary for the formation rate of $dt\mu$ molecules $\lambda_{dt\mu} > 10^8$ sec^{-1} were obtained on the basis of these data.

PACS numbers: 25.10. + s, 25.30.Ei

1. The fusion process of deuterium and tritium nuclei from the state of the muonic molecule $dt\mu$ (muonic catalysis of the fusion reaction $d + t$) can be written in the following way

$$t\mu + d \xrightarrow{\lambda_{dt\mu}} dt\mu \xrightarrow{\lambda_f} \begin{cases} \xrightarrow{1-\omega_s} {}^4He + n + \mu^- & \text{(1a)} \\ \xrightarrow{\omega_s} {}^4He\mu + n & \text{(1b)} \end{cases} + 17.6 \text{ MeV},$$

where $\lambda_{dt\mu}$ is the formation rate of the $dt\mu$ molecules, λ_f is the fusion reaction rate, and ω_s is the probability of "adhesion" of a muon to a ^{4}He nucleus.

The process (1) has not been studied experimentally heretofore. The theoretical values[1,2] of $\lambda_{dt\mu}$ obtained prior to 1977 were anomalously small: $\lambda_{dr\mu} \sim 3 \times 10^4$ sec^{-1}. After the existence of a weakly bound state in the $dt\mu$ system was established,[3] new calculations[3] of the value $\lambda_{dt\mu}$, which were based on the assumption that a resonance mechanism[4] for formation of muonic molecules exists, were performed. The existence of such mechanism was demonstrated experimentally in the study of the process of formation of $dd\mu$ molecules.[5,6] The values for the formation rate of $dd\mu$ molecules ($\lambda_{dd\mu}$) determined in these experiments are in good agreement with the results of theoretical calculations.[3]

It is important that the value $\lambda_{dt\mu} \sim 10^8$ sec^{-1} obtained in Ref. 3 exceeds by more than two orders of magnitude the disintegration rate of a free muon $\lambda_0 = 4.55 \times 10^5$ sec^{-1}. This means that in the $D_2 + T_2$ mixture one muon can successively initiate up to one hundred reactions (1a) (with allowance for smallness of the value $\omega_s \sim 1\%$) with the formation of a large number of fast neutrons.[7] It is clear that an experimental determination of $\lambda_{dt\mu}$ is of great interest.[7,8] This determination is absolutely necessary

 0021-3640/80/040228-05$00.60

if any serious attempt is made to investigate the possibility of using the μ-meson catalysis of the $d+t$ reaction for power engineering.[9]

The purpose of this experiment was to measure the formation rate of a $dt\mu$ molecule ($\lambda_{dt\mu}$) and the rate of transfer of a muon from a deuteron to a triton (λ_{dt}).

2. To determine the values of $\lambda_{dt\mu}$ and λ_{dt}, we measured the absolute yield (η_n) and the time distribution ($d\eta_n/dt$) of 14.1-MeV neutrons from the reaction (1). If the process (1) occurs in a $D_2 + T_2$ gas mixture, then the expressions for η_n and $d\eta_n/dt$ can be written in the following way[10]:

$$\eta_n = \frac{(\lambda_o + \lambda_{dt}\phi)\,\lambda_{dt\mu}\phi C_d C_t}{\lambda^2(\lambda_o + \lambda_{dt}\phi C_t + \lambda_{dt\mu}\phi C_d^2)}, \qquad (2)$$

$$\frac{d\eta_n}{dt} = \frac{\lambda_{dt\mu} C_d C_t \phi}{\lambda_{dt} C_t + \lambda_{dt\mu} C^2 d}\{\lambda_{dt} e^{-\lambda_o t} + C_d(\lambda_{dt\mu} C_d - \lambda_{dt})\, e^{-\lambda_1 t}\},$$

$$\lambda_1 = \lambda_o + \lambda_{dt\mu} C_d^2 \phi + \lambda_{dt} C_t \phi , \qquad (3)$$

where $\lambda_{dt\mu}$ and λ_{dt} are the rates of formation of $dt\mu$ molecules and of the isotopic exchange $d\mu + t \rightarrow t\mu + d$: normalized to the density of liquid hydrogen $n_0 = 4.22\times 10^{22}$ cm^{-3}, C_d and C_t are the atomic concentrations of deuterium and tritium ($C_d + C_t = 1$), and ϕ relates the density of the $D_2 + T_2$ gas mixture to n_0. The values $\lambda_{dt\mu}$ and λ_{dt} were determined by comparing the experimental values of η_n and $d\eta_n/dt$ with the expressions (2) and (3).

3. The experiment was performed using the muon beam of the JINR 680-MeV synchrocyclotron. The experimental setup is shown in Fig. 1. After passing through the monitor counters (1)–(3), the muons were slowed down by a moderator (6), recorded by the counter (4) [CsI(Tl) scintillator], and directed to a gas target (8). The target was filled with a deuterium-tritium mixture, which was purified from the impurities of other gases at the level of 10^{-7} volume fraction. The neutrons from the reaction (1a) were recorded by using four N detectors (NE-213 scintillator) in which the neutrons and γ-ray quanta were separated according to the shape of the scintillation pulse. Eight E detectors arranged in pairs (plastic scintillator) were used to record the electrons from the decay of muons stopped in gas.

The main idea of the measuring technique involved a systematic recording, in the time interval of 0 to 10 μsec after the muon had stopped, first by the neutron detector and then by any pair of electron detectors (neutron-electron "delayed coincidences"). This enabled us to identify the investigated process (1) reliably, in which the neutron from the $d+t$ fusion reaction is accompanied by an electron from the subsequent muon decay, and to add the background due to stopping of muons in the target walls.

During the experiment the exposures were made at different pressures of the

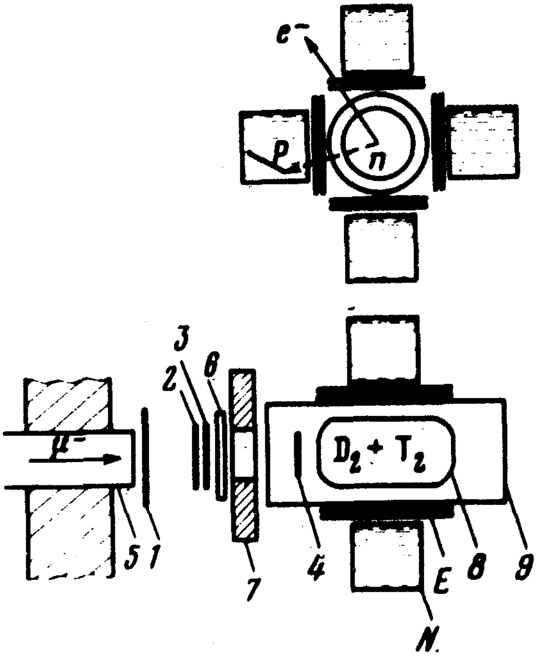

FIG. 1. Schematic of the experimental setup: 1–3, monitor counters with a plastic scintillator; 4, a counter with a CsI(Tl) scintillator; 5 and 7, collimators; 6, moderator; 8, gas target; 9, vacuum jacket; *N*, neutron detectors; and *E*, electron detectors.

$D_2 + T_2$ mixture in the target, at different tritium concentrations, and at different temperatures. The parameters of the experiment are given in Table I.

Exposure 7 (deuterium) and exposure 8 (vacuum) were made to determine the neutron and electron background.

In each exposure we measured the time spectra of the events recorded by the *E* and *N* detectors and also the amplitude distributions for the pulses from the neutron detectors. Figure 2, for example, shows a two-dimensional amplitude distribution obtained in exposure 14 for one of the neutron detectors.

4. At present, only a preliminary analysis of the experimental data has been made. In this case, the rate of transfer of a muon from a deuteron to a triton is

TABLE I. Experimental condition.

Expositions	1 – 4	5	6	7	3	9 – 13	14
Gas pressure (at $T = 293$ K), atm	21	10.5	21	21	0	6.6	66.2
Tritium content, %	3.0	3.0	1.6	0	–	7.8	0.81
Target temperature, °K	293 – 613	293	293	293	293	93 – 293	93

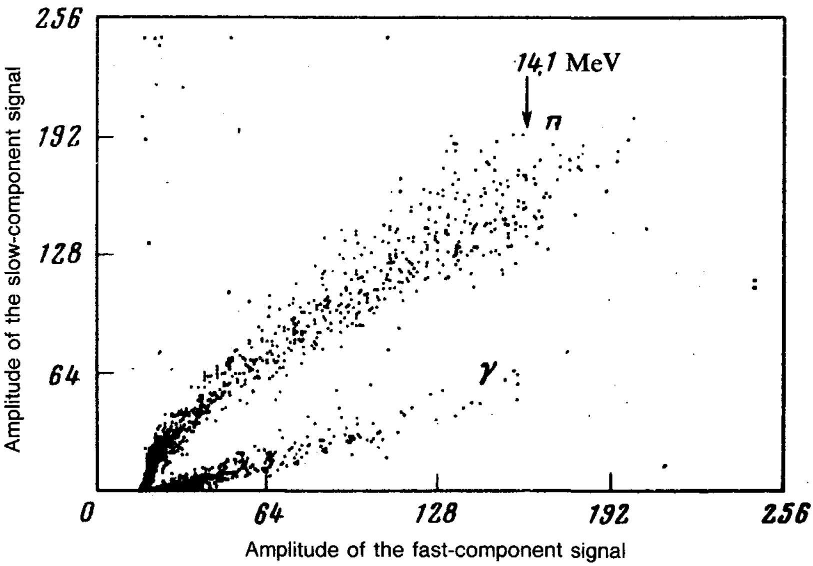

FIG. 2. Two-dimensional amplitude distribution of events recorded by a neutron detector in one of the exposures.

$$\lambda_{dt} = (2.7 \pm 0.9)\times 10^{8}\ \text{sec}^{-1},$$

and for the rate of formation of $dt\mu$ molecules we determined the lower boundary: $\lambda_{dt\mu} > 10^8$ sec^{-1} at the 90% confidence level.

The obtained value of λ_{dt} is in good agreement with the results of the theoretical calculations.[11] The obtained lower boundary of the rate of formation of the $dt\mu$ molecules is in good agreement with the theoretical value $\lambda_{dt\mu} \sim 10^8$ sec^{-1} calculated in Ref. 3 under the assumption that a resonance mechanism exists for formation of $dt\mu$ molecules. According to this mechanism, there must be a critical dependence of the formation rate $\lambda_{dt\mu}$ on the temperature of the $D_2 + T_2$ mixture, which should take the form of variation of the neutron yield from the reaction (1a) with the temperature. However, the neutron yield (η_n) observed experimentally is independent of the temperature of the gas within the measurement errors ($\leqslant 10\%$). This can be explained by the fact that the value of $\lambda_{dt\mu}$ exceeds several fold the disintegration rate of a free muon λ_0 over the entire temperature range investigated by us, and hence the variation of $\lambda_{dt\mu}$ does not change the value of η_n in a broad range [see Eq. (2)].

Another possible interpretation is based on the fact that since the thermalization time of the $t\mu$ atom exceeds the formation time of $dt\mu$ molecules, it is not capable of attaining those small energies at which the rate of formation of $dt\mu$ molecules, according to the resonance mechanism, must decrease sharply.

In conclusion, the authors thank A. A. Bochvar and A. S. Nikiforov for their participation in this work, S. S. Gershteĭn and L. I. Ponomarev for many productive discussions of the μ-meson catalysis, P. F. Ermolov for pointing out the importance of taking into account the thermalization process of $t\mu$ atoms, A. T. Vesilenko and V. M. Romanov for their help in designing the hardware, G. M. Osetinskiĭ and A. I. Filippov for discussion of the problems connected with building of the experimental setup with a tritium target, and A. A. Borisova and L. N. Starshina for their assistance.

[1)]All-Union Research Institute of Inorganic Materials, Moscow.

---

[1]Ya. B. Zel'dovich and S. S. Gershteĭn, Usp. Fiz. Nauk **71**, 581 (1960) [Sov. Phys. Usp. **3**, 593 (1960)] V. B. Belyaev *et al.*, Zh. Eksp. Teor. Fiz. **37**, 1652 (1959) [Sov. Phys. JETP **10**, 1171 (1959)].
[2]L. I. Ponomarev and M. P. Faĭfman, Zh. Eksp. Teor. Fiz. **71**, 1689 (1976) [Sov. Phys. JETP **44**, 886 (1976)].
[3]S. I. Vinitskiĭ *et al.*, Zh. Eksp. Teor. Fiz. **74**, 849 (1978) [Sov. Phys. JETP **47**, 444 (1978)].
[4]É. A. Vesman, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 113 (1967) [JETP Lett. **5**, 91 (1967)].
[5]V. P. Dzhelepov *et al.*, Proc. XII International Conf. on High Energy Physics, Dubna, 1964; V. P. Dzhelepov *et al.*, Zh. Eksp. Teor. Fiz. **50**, 1235 (1966) [Sov. Phys. JETP **23**, 820 (1966)]; V. M. Bystritskiĭ *et al.*, Zh. Eksp. Teor. Fiz. **66**, 61 (1974) [Sov. Phys. JETP **39**, 27 (1974)].
[6]V. M. Bystritskiĭ *et al.*, Proc. International Symposium on Meson Chemistry and Mesomolecular Processes in Matter, Dubna, 1977; Zh. Eksp. Teor. Fiz. **76**, 460 (1979) [Sov. Phys. JETP **49**, 232 (1979)].
[7]S. S. Gershteĭn and L. I. Ponomarev, Phys. Lett. **72 B**, 80 (1977).
[8]L. I. Ponomarev, Proc. VII Int. Conf. on High Energy Physics and Nuclear Structure, Zurich, 1977.
[9]Yu. V. Petrov, Proc. XIV School on Nuclear Physics, USSR Academy of Sciences, L., 1979.
[10]S. S. Gershteĭn *et al.*, Preprint JINR, P4-11729, Dubna, 1978.
[11]L. I. Ponomarev, Proc. VI Int. Conf. on Atomic Physics (p. 182), Riga, 1978, Zinante-Riga, USSR, Plenum Press, New York and London.