Study of the fusion reaction $d\mu + d \rightarrow He^3 + n + \mu$ in gaseous deuterium

V. M. Bystritskiĭ, V. P. Dzhelepov, K. O. Oganesyan, M. N. Omel'yanenko, S. Yu. Porokhovoĭ, A. I. Rudenko, and V. V. Fil'chenkov

Joint institute for Nuclear Research
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In experiments with a gas target filled with ultrapure deuterium (content of impurities with $Z > 1 \lesssim 10^{-8}$) to a pressure of 41 atm, the yield and time distribution of neutrons from the fusion reaction in the $dd\mu$ mesic molecule were measured in the muon beam of the JINR synchrocyclotron. From analysis of this distribution (918 events) a value is obtained for the rate $\lambda_{dd\mu}$ of formation of $dd\mu$ molecules in gaseous deuterium at $T = 300\,°K$ and the rate λ_f of the nuclear reaction in this mesic molecule. The value obtained $\lambda_{dd\mu} = (0.73 \pm 0.07) \times 10^6$ sec^{-1} together with our earlier data for $T = 240\,°K$ (obtained in experiments with a diffusion chamber) confirms the theoretically predicted existence of a production mechanism for the $dd\mu$ molecule which is resonant in the energy of the $dd\mu$ atom. Direct data on λ_f were obtained for the first time; the experimental value $\lambda_f > 1.8 \times 10^6$ sec^{-1} (at the 90% confidence level) agrees with the theoretical values.

Nuclear fusion reactions in the deuterium mesic molecule

$$d\mu + D \rightarrow (dd\mu)^+ + e \quad (1)$$

$$(dd\mu)^+ \rightarrow \begin{cases} t + p + \mu \\ He^3 + n + \mu \end{cases} \quad (2)$$

have been studied by various groups.[1-4] Reaction (2) was first observed in our laboratory in experiments with a diffusion chamber.[3] The results obtained in Refs. 1–4 for the rate $\lambda_{dd\mu}$ of formation of the system $(dd\mu)^+$ are given in Table I. These data have been discussed in detail in ref. 4, where the large difference in the $\lambda_{dd\mu}$ values measured under different experimental conditions (liquid deuterium[1,2] and gaseous deuterium[3,4]) were explained by assumption of a mechanism for formation of the $(dd\mu)^+$ system resonant in the $d\mu$ atom energy.

Table I also gives theoretical values of $\lambda_{dd\mu}$. Zel'dovich and Gershteĭn and Cohen et al.[5] have made calculations for a $(dd\mu)^+$ mechanism of production by an electric dipole transition E1 with release of the binding energy to the electron. As can be seen from Table I, interpretation of the experimental data of ref. 4 on the basis of these calculations is extremely unsatisfactory.

Vesman[6] calculated $\lambda_{dd\mu}$ for a mechanism of $(dd\mu)^+$ formation, in a rotational state with angular momentum K = 1, in which the binding energy is transferred to excitation of vibrational levels of the system consisting of the $d\mu$ atom and a deuterium molecule. This mechanism should involve existence in the $(dd\mu)^+$ system of a level with a binding energy of several electron volts and turns out to be resonant in the energy of the $d\mu$ atom. The assumption made by Vesman[6] of existence in $(dd\mu)^+$ of an excited rotational-vibrational level with low binding energy is confirmed by calculations[7] in which a value of 0.7 eV is obtained for the binding energy of this level. As can be seen from Table I, the calculations made in ref. 6 quite satisfactorily explain the entire set of experimental data.

The purpose of the present work was to use electronic methods under conditions close to those of the early diffusion-chamber experiments[3,4] to verify the existence of a resonance mechanism for formation of the $(dd\mu)^+$ mesic molecule, and in addition to obtain direct information on the rate λ_f of the nuclear reaction in this molecule on the basis of a measurement of the time distribution of the neutrons from reaction (2). It should be recalled that the previous data[1-4] were obtained only on the basis of measurement of the integral yields of reactions (1) or (2) on the assumption that $\lambda_f \gg \lambda_0$, where $\lambda_0 = 4.55 \times 10^5$ sec^{-1} is the decay rate of the free muon.

TABLE 1. Rate of formation of deuterium mesic molecules (reduced to liquid-deuterium density)

	$\lambda_{dd\mu}$, 10^6 sec^{-1}	
	Experiment	Theory
Liquid deuterium	0.072 ± 0.014[1] 0.098 ± 0.001[2]	0.04[5]; 0.09[6]
Gaseous deuterium	0.75 ± 0.11[4] 0.73 ± 0.07 *	0.04[5]; 0.85[6]

* Present work

The work was performed in the muon beam of the JINR synchrocyclotron with a hydrogen gas target. The target was filled with ultrapure deuterium to a pressure of 41 atm (density of deuterons $\rho_D = 2.13 \times 10^{21}$ cm^{-3}). The relative content in the deuterium of impurities with Z > 1 was no greater than 10^{-8}.

Identification of muon stoppings in the gas was accomplished by means of scintillators located inside the target. The neutrons were detected by scintillation counters with stilbene crystals placed around the target. The neutrons were detected in a delayed time gate triggered by the muon stopping signal. The apparatus and electronic logic are entirely similar to those described in our previous work[8] (μ capture in hydrogen) with the following exceptions:

1. In view of the fact that the neutron energy in reaction (2) is 2.5 MeV, i.e., roughly a factor of two lower than in muon capture by a proton, the energy range of recoil-proton detection was shifted to lower energies and extended from 1.6 to 4.6 MeV or from 0.3 to 1.5 MeV on the scale of equivalent electron energy (in light yield).

2. The logic scheme employed anticoincidences with decay electrons. In ref. 8 in the "neutron" runs it was

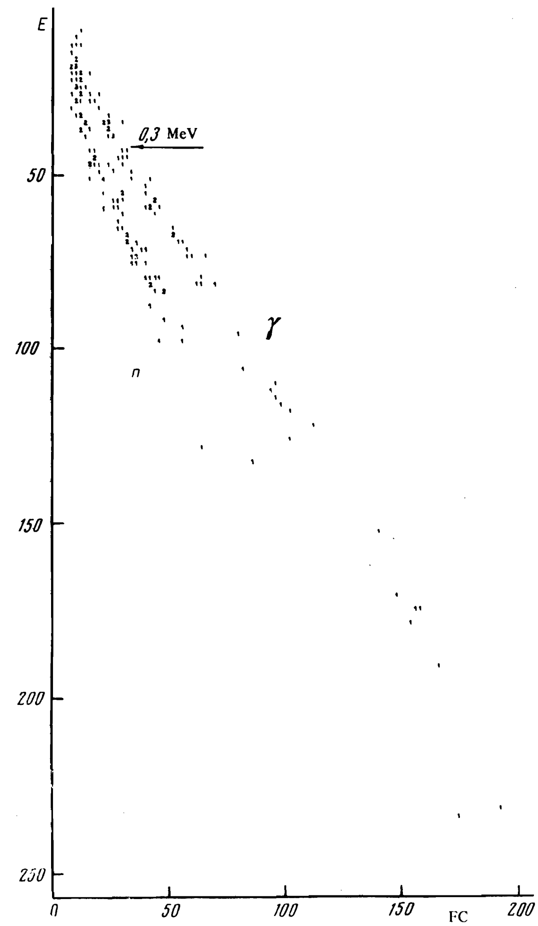

FIG. 1. Distribution characterizing the separation of neutrons and γ rays, measured in neutron runs with deuterium, for one of the detectors. The distribution was obtained by means of a multichannel pulse-height analyzer and a Minsk-22 computer. The abscissa is the channel number for the pulse height of the signal proportional to the fast component of the light pulse in stilbene, and the ordinate is the channel number for the pulse height of the signal proportional to the total area of the light pulse, or energy.

required that there be no counter 5 pulses due to electrons (see Fig. 2 in ref. 8) in a large time interval (10 μsec). Use of this requirement in the present work would lead to a substantial suppression of neutrons from reaction (2). Therefore the blocking of "electron" triggers in the "neutron" runs was accomplished by (5, n) coincidences with a resolving time no greater than 0.3 μsec. This blocking obviously serves only to reduce the neutron-counter loading and has practically no effect on the number of triggers. The loss in neutron-detection efficiency due to this blocking was 4 ± 2%.

The procedures for measurement and analysis of the events are completely identical to those described in ref. 8. The entire series of measurements occupied about 40 hours. As in ref. 8, neutron runs were alternated with electron runs, and calibration measurements with γ sources were made periodically. The accidental-coincidence background was determined in runs with an evacuated target, and its relative contribution turned out to be ~10%. For discrimination against the γ-ray background (accidental coincidences and electron bremsstrahlung), separation of neutron from γ rays was utilized in the measurements.

Figure 1 shows a distribution characterizing the separation of these particles (it is obtained by pulse-

TABLE 2. Data on measurements of neutron yield in runs with deuterium

Parameter	Value	Parameter	Value
$N_\mu \cdot 10^{-6}$	3.12±0.10	$\eta_n \cdot 10^4$	2.942±0.195
N_n	1148±34	$\varepsilon_n \cdot 10^2$	1.43±0.088
$\bar{N}_n$	918±61	$\eta_n^0 \cdot 10^2$	2.06±0.18

shape discrimination in the stilbene for protons and electrons[8,9]). This distribution is given for one of the neutron detectors in the runs with deuterium.

The total number of muon stoppings N_μ for neutron runs with deuterium is listed in the first line of Table II. This number was found from the electron yield measured in the electron exposure and the electron-detection efficiency ϵ_e calculated by computer. The accuracy of the N_μ value is determined by the statistical accuracy of the electron-yield measurements, by some uncertainty in the calculation of ϵ_e, and by the uncertainty in the location of the threshold in the electron pulse-height spectrum.

The total number N_n of events recorded in neutron runs is given in the second line of Table II. In the next line is given the number $\bar{N}_n$ of events after subtraction of the background and corrected for the effects of the selection criteria used for separation of neutron events in the two-dimensional distributions (FC, E). The data of ref. 8 were used to determine the background from diffusion of $d\mu$ atoms and also from photonuclear reactions in the stilbene. Here it turned out that for the measurements with deuterium the combined level of this background is about 1%.

In Table II we give the experimental neutron yield $\eta_n = \bar{N}_n/N_\mu$. In order to obtain the absolute yield $\eta_n^0 = \eta_n/\epsilon_n$, it is necessary to know the efficiency ϵ_n for detection of neutrons from reaction (2). As in ref. 8, this efficiency was determined by Monte Carlo calculations in a computer, in the course of which we also determined the shape of the pulse-height distribution for neutrons from reaction (2).

The experimental pulse-height distribution is shown in Fig. 2. The distribution is given after subtraction of the normalized accidental-coincidence background. As can be seen from the figure, good agreement is observed between the distributions and experiment.

The value of ϵ_n calculated by computer for an energy threshold of 0.3 MeV and the absolute yield value η_n^0 are given in the last two lines of Table II. It should be pointed out that the value given for ϵ_n does not include the time gate factor which takes into account the loss in efficiency as the result of delay of the trigger and the finite duration of the gates, and therefore the value of η_n^0 refers to the time interval (T_1, T_2) determined by the location of these gates.

The rate $\lambda_{dd\mu}$ is related to η_n^0 by the expression

$$\eta_n^0 = \int_{T_1}^{T_2} f(\lambda_{dd\mu}, \lambda_f; t)\, dt, \tag{3}$$

where $f(\lambda_{dd\mu}, \lambda_f; t)$ is the normalized time-distribution function of neutrons from reaction (2). This function is described as follows:

$$f(\lambda_{dd\mu}, \lambda_f; t) = \frac{1}{2}\lambda_{dd\mu}\lambda_f \frac{\exp\{-(\lambda_0+\lambda_{dd\mu})t\} - \exp\{-(\lambda_0+\lambda_f)t\}}{\lambda_f - \lambda_{dd\mu}} \times \left(1 + \frac{\lambda_{dd\mu}\lambda_f t}{\lambda_f - \lambda_{dd\mu}}\right). \tag{4}$$

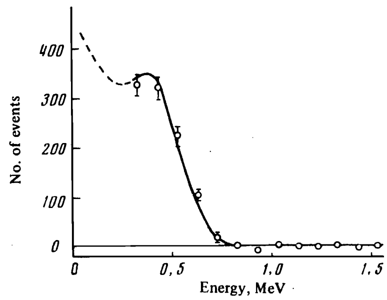

FIG. 2. Experimental pulse-height distribution. The abscissa is the recoil-proton energy on an equivalent-electron-energy scale, and the ordinate is the number of events per 0.06-MeV interval. The smooth curve shows the dependence calculated by computer.

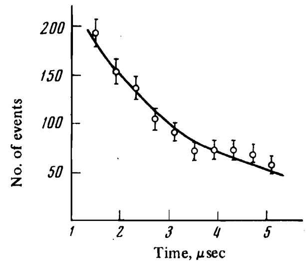

FIG. 3. Time distribution of neutrons, measured in neutron runs with deuterium. The abscissa is the time relative to the time of muon stopping, and the ordinate is the number of events in a 0.5-μsec interval. The smooth corresponds to Eq. (5) with the value (6) obtained for $\lambda_{dd\mu}$.

In this expression the factor ½ takes into account the contribution of reaction (1) to the destruction of the $(dd\mu)^+$ system. The derivation of Eq. (4) took into account only single regeneration of muons in reactions (1) and (2) and neglected the formation of the bound systems $p\mu$, $t\mu$, or $He^3\mu$ in these reactions. The experimental time distribution of neutrons is given in Fig. 3. For the purpose of determining the quantities $\lambda_{dd\mu}$ and λ_f, this distribution was approximated by the following function:

$$dN_n/dt = Af(\lambda_{dd\mu}, \lambda_f;\ t) + C, \qquad (5)$$

where $f(\lambda_{dd\mu}, \lambda_f; t)$ corresponds to the function (4), A is a normalization factor, and C is the accidental-coincidence level. In analysis of the time distribution we used the numbers of muon stoppings N_μ and absolute yield η_n^0 given in Table II, and also the accidental-coincidence background level found by us. The normalized value of this background was $32 \pm 13\ \mu sec^{-1}$, which corresponds to a ratio of background to effect of 8% for the first interval of the time distribution.

The results of a χ^2 analysis are shown in Fig. 4. As can be seen, the optimal value of $\lambda_{dd\mu}$ does not depend on the value of λ_f for $\lambda_f > 2 \times 10^6\ sec^{-1}$, which is due to the form of the function (4). At the 90% confidence level

$$\lambda_f > 1.8 \cdot 10^6\ sec^{-1},$$

which is in agreement with the theoretical predictions.[5,10,11]

For the rate of formation of the $(dd\mu)^+$ system we obtained the value

$$\lambda_{dd\mu} = (0{,}73 \pm 0{,}07) \cdot 10^6\ sec^{-1} \qquad (6)$$

(recalculated to the density of liquid deuterium); it is listed in Table I.

In Fig. 3 the smooth curve corresponds to Eq. (5)

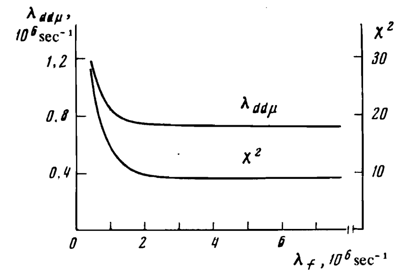

FIG. 4. Results of χ^2 analysis of the time distribution of neutrons. The abscissa is the rate λ_f of the fusion reaction in $(dd\mu)^+$. The ordinate is the rate $\lambda_{dd\mu}$ of formation of $(dd\mu)^+$ and the χ^2 value (the expected value of χ^2 is 8). The functions are plotted on the basis of data from a computer optimization of the parameters λ_f and $\lambda_{dd\mu}$ in Eq. (5) in comparison of this equation with the experimental distribution.

with the values found for $\lambda_{dd\mu}$ and λ_f. As can be seen from the figure, the agreement of this dependence with experiment is quite satisfactory.

Introduction of corrections taking into account multiple regeneration of muons and the probabilities of formation of $t\mu$, $p\mu$, and $He^3\mu$ determined in ref. 4 changes the result insignificantly (by about 1%). As can be seen from the data in Table I, the value of $\lambda_{dd\mu}$ obtained by us is in good agreement with the earlier measurements made in our laboratory[3,4] and confirms the existence of the $(dd\mu)^+$ production mechanism suggested in ref. 6.

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