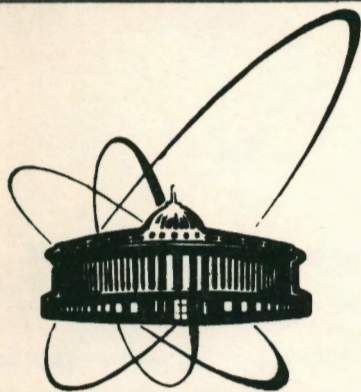


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ОБЪЕДИНЕННЫЙ  
ИНСТИТУТ  
ЯДЕРНЫХ  
ИССЛЕДОВАНИЙ  
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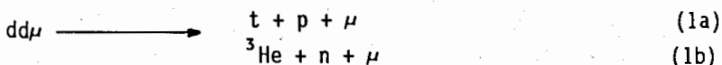
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MEASUREMENT OF THE TEMPERATURE DEPENDENCE  
OF THE  $dd\mu$ -MOLECULE FORMATION RATE  
IN GASEOUS DEUTERIUM  
AT THE PRESSURES 1.5 AND 0.4 KBAR

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1990

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The experimental study of the  $\mu\text{CF}$  reaction



was the foundation of physics of resonant formation of muonic molecules. Investigation of this process has allowed one to establish and explain the phenomena of resonant formation of  $\mu$ -molecules, which was then directly confirmed in the measurements of the temperature dependence of the rate of process (1)<sup>[1-4]</sup>. Now the main interest in the problem of  $\mu\text{CF}$  is concentrated on the investigation of the  $d + t$  fusion reaction. Nevertheless reaction (1) remains the object of intensive theoretical<sup>[5,6]</sup> and experimental<sup>[7-12]</sup> study. Due to relatively simple interpretation of process (1) one can reliably test the principal conclusions of the theory; the main hopes are connected with the accurate determination of the energy of the weakly bound level ( $J=1, v=1$ ) in the  $dd\mu$ -molecule.

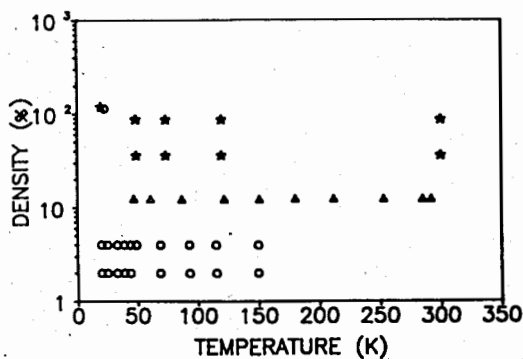


Fig. 1. Parameters of the experiments in which the  $dd\mu$ -molecule formation rate was measured as a function of the temperature. The deuterium density is in relative units  $\phi = n/n_0$ , where  $n_0 = 4.25 \times 10^{22}$  nucl/cm<sup>3</sup> is the liquid hydrogen density. ★ - the present work, △ - the experiments<sup>[8,9]</sup>, ○ - the measurements<sup>[10,11]</sup>.

Earlier the  $dd\mu$ -molecule formation rate ( $\lambda_{dd\mu}$ ) was measured in exp.<sup>[7-11]</sup>. The parameters of these experiments are shown in fig. 1. As usual, the deuterium density is given in relative units  $\phi = n/n_0$ , where  $n$  is the number of deuterium nuclei in 1 cm<sup>3</sup>,  $n_0 = 4.25 \times 10^{22}$  nucl/cm<sup>3</sup> is the liquid hydrogen density. The parameters of exp.<sup>[7]</sup> are not presented in the figure because they

were not given by the authors. Contrary to other experiments, in the work<sup>[7]</sup> the deuterium-tritium mixture was used.

The results of the measurements<sup>[7,11]</sup> are shown in fig. 2. The data of exp.<sup>[7-9]</sup> are shown as presented by the authors: namely as an "effective" (weighted for the spin states of  $d\mu$ -atom with  $F=3/2, 1/2$ ) values of  $\bar{\lambda}_{dd\mu}$ . The best accuracy values<sup>[10,11]</sup> of  $\lambda_{dd\mu}$  was obtained separately for each of the two spin states with  $F=3/2$  and  $F=1/2$ . For convenient comparison we transformed the data of ref.<sup>[10,11]</sup> to the "effective" values according to papers<sup>[5,13]</sup>.

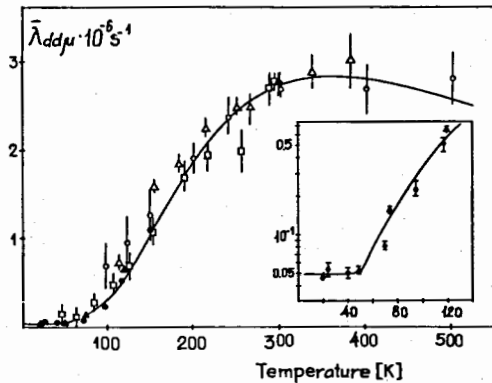


Fig.2. Results of measurements of the temperature dependence of the  $dd\mu$ -molecule formation. The figure is taken from ref.<sup>[9]</sup>, additionally, the present data for  $\phi = 0.88$  and the results of exp.'s<sup>[10,11]</sup> are shown in it. The points indicate the results of the experiments:  $\Delta$  - [4],  $\circ$  - [7],  $\square$  - [8,9],  $\bullet$  - [10,11],  $\blacktriangle$  - the present work.

The present work is aimed to measure the value of  $\bar{\lambda}_{dd\mu}$  in the deuterium temperature range  $T=20-300$  K at a high deuterium density  $\phi \approx 1$ . The parameters of our experiment are presented in fig.1 and in the table. The main difference between our experiment and works<sup>[8-10]</sup> is the use of deuterium of high density, and, as far as the experimental technique is concerned, the employment of high efficiency ("full absorption") neutron detectors. The values of  $\bar{\lambda}_{dd\mu}$  were determined from the analysis of the yields and time distributions of neutrons from reaction (1b).

The experiment has been performed on the muon beam of the 680 MeV JINR phasotron. The apparatus was described in our work<sup>[12]</sup>. The scheme of the experimental set-up is shown in fig. 3. A gaseous deuterium target ( $\phi 42 \times 100$  mm) of high pressure (1.5 kbar)<sup>[14]</sup> was filled with pure deuterium (the protium contamination was less than 0.3% and the contamination of the possible impurities with  $Z > 1$  was  $10^{-7}$ ). The target was placed in a cryostat (not shown in the figure) which allowed the target temperature to be kept in the range 20-300 K with an accuracy 1-1.5 K. Scintillation counters 1,2,3 (plastic scintillators) and 4 (CsJ(Tl), 40x80x3 mm) were to detect the muons.

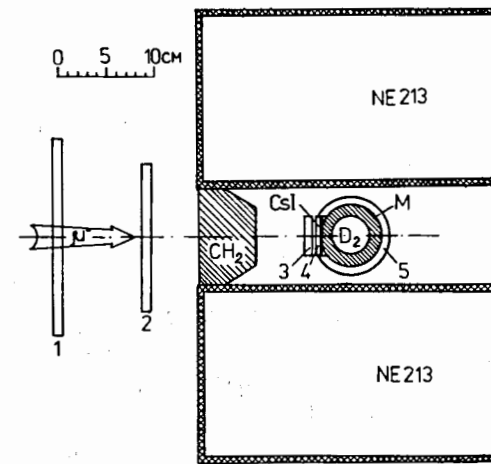


Fig.3. Experimental layout.

Counter 5 with a plastic scintillator of cylindrical form around the target served as an anticoincidence detector for muons and for identification of electrons from muons decaying in the target. For this purpose the signal of counter 5 was divided into two channels. The discriminator level for the signal in the electron registration channel was chosen so that to prevent the detection of neutrons from reaction (1b).

Neutrons from reaction (1b) were detected by two "full absorption" neutron detectors<sup>[12,15,16]</sup> with dimensions  $\phi 310 \times 165$  mm (the volume of each detector  $V=12$  l) which were located symmetrically around the target. The  $n-\gamma$  separation was realized by the amplitude analysis of fast and slow components of the light signal<sup>[18]</sup>, the reliable  $n-\gamma$  separation was achieved starting from the energy  $E_e^{thr} = 100$  Kev (electron energy scale). Energy calibration with standard  $\gamma$ -sources was periodically performed in the experiment.

The efficiency of the neutron detectors was calculated by Monte-Carlo code with allowance for neutron interactions with deuterium in the target, with the material of the target wall and with the intermediate material. It was  $\epsilon = 14.2 \pm 0.6\%$  (for deuterium density  $\phi = 0.883$ ) for each neutron detector. The large neutron detection efficiency enables us to detect the successive events of  $\mu CF$  reactions<sup>[17,22]</sup>.

The electronic trigger allowed the "neutron events" for which the delayed coincidence of the neutron detection signal (5,ND) and the electron detection signal (5) was in the time interval  $T=10 \mu s$  after muon stop in the target (signal 1-4,5) to be selected for the computer analysis. The "electron events" (a signal from counter 5 in the time gate) were recorded and analysed separately. They were used for normalization of "neutron events".

There were nine main exposures with deuterium of different density and temperature, their parameters are presented in fig.1 and in the table. Besides, the runs with helium and with an empty target were performed to

determine the background of neutrons and electrons. The values of  $\bar{\lambda}_{dd\mu}$  were determined for each exposure with deuterium from the analysis of the data on the yield ( $\eta$ ) and time distribution ( $dN/dt$ ) of the first detected "neutron events"<sup>[18]</sup> :

$$\eta = N_n/N_e = \varepsilon\beta\phi\bar{\lambda}_{dd\mu}/\lambda \quad (2)$$

$$dN_n/dt = \varepsilon\beta\phi\bar{\lambda}_{dd\mu} \exp(-\lambda t) \quad (3)$$

$$\lambda = \lambda_0 + (\varepsilon + \omega - \varepsilon\omega)\beta\phi\bar{\lambda}_{dd\mu} \quad (4)$$

In the expressions (2-4)  $N_n$  and  $N_e$  are the number of detected neutrons from reaction (1b) and electrons from the decay of muons stopped in the target;  $\lambda_0 = 0.455 \mu s^{-1}$  is the muon disappearance rate;  $\beta$  is the branching ratio of reaction (1b),  $\omega$  - the probability of muon sticking to helium in the reaction (1b).

The procedure of data handling was as follows. The number of neutrons  $N_n$  and the value of the exponential factor  $\lambda$  were determined from the analysis of the neutron time spectra. The number of electrons  $N_e$  was obtained from the analysis of the electron time spectra. The value of  $\bar{\lambda}_{dd\mu}$  was determined by substituting these values of  $N_n, N_e, \lambda$  to expression (2) and using the calculated value of the neutron detection efficiency  $\varepsilon$ . For the exposures with deuterium densities  $\phi=0.883$  and  $\phi=0.364$  the values of  $\varepsilon$  differed by 10% due to the different contribution of n-d interaction in the target. As in ref.<sup>[10]</sup>, for the resonant  $dd\mu$ -molecule formation (which dominates at the temperatures  $T>100$  K) we used the value  $\beta=0.582 \pm 0.017$ <sup>[8]</sup> and for nonresonant formation ( $T=20-50$  K) -  $\beta=0.53$ <sup>[21]</sup>.

The following fact is worth mentioning. When the spin effects in the resonant formation of  $dd\mu$ -molecules are taken into account, the time distribution of the first detected neutron events is expressed as a sum of two exponents - fast and slow<sup>[5,13,20]</sup>. At present we analysed only the slow component of the neutron time distribution. Therefore the values of  $\bar{\lambda}_{dd\mu}$  obtained by us are determined by the  $dd\mu$ -formation rate from the  $d\mu$ -atom spin state with  $F=1/2$  with some addition (up to 15%<sup>[5,13]</sup>) which is caused by contribution of the  $F=3/2$  state.

Due to some difference in the parameters of two neutron detectors (dead time, energy threshold and some others) the data, from each neutron detector were analysed separately. It turns out that the results obtained for two detectors agree for each exposure, and it allows us to combine the results for two neutron detectors.

We analysed not only the first detected neutron events but also the multiple (the second and the third) detected events<sup>[12]</sup>. In this case we used the sticking probability value  $\omega=0.126 \pm 0.004$ <sup>[8]</sup>. The values of  $\bar{\lambda}_{dd\mu}$

obtained in this way are in agreement with those determined from the analysis of the first detected events, but their accuracy was noticeably lower, especially for low temperatures. For the exposure  $T=300$  K, where the yield of the second neutrons is large enough, its value was used for estimation of the sticking probability  $\omega$ . The value  $\omega=0.118 \pm 0.025$  was obtained, which agrees with the precise result<sup>[8]</sup>.

Our values of  $\bar{\lambda}_{dd\mu}$  measured for different temperatures and deuterium densities are presented in the table.

Table.

Measured values of  $\bar{\lambda}_{dd\mu}$  ( $10^6 s^{-1}$ ) as a function of deuterium temperature and density.

Relative deuterium density, $\phi$	Temperature (K)				
	20.3	49	74	120	300
1.20	0.0471(25)				
0.883		0.0528(29)	0.155(9)	0.663(32)	2.73(13)
0.367		0.0559(37)	0.141(10)	0.647(38)	2.75(13)

The values of  $\bar{\lambda}_{dd\mu}$  shown in the table are normalized to liquid hydrogen density, their uncertainties include statistical (2-4%) and systematic errors. The main source of the systematic errors (4%) is caused by using the calculated value of the neutron detection efficiency with allowance for some uncertainties in the experimental geometry and in the position of the energy threshold in the amplitude spectrum of recoil protons.

As seen from the table, the values of  $\bar{\lambda}_{dd\mu}$  obtained for two deuterium densities, differing by a factor of 2.4, are in satisfactory agreement in the whole temperature region investigated. The data of the present experiment confirm our earlier conclusion<sup>[12]</sup> that the value of  $\bar{\lambda}_{dd\mu}$  is independent (with an accuracy 2-3%) of the density for the temperature  $T=300$  K.

The comparison of our results with the data of other experiments can be made using fig. 2. It is taken from paper<sup>[9]</sup>, and the present data for  $\phi=0.883$  and the results of expts<sup>[10,11]</sup> are shown in it. As seen from the figure, there is a satisfactory agreement of our results with the measurements<sup>[7-9]</sup> and calculations<sup>[5]</sup> (made for the "effective" fusion rate in  $dd\mu$ -molecule  $\bar{\lambda}_f=0.41 \times 10^9 s^{-1}$ ). However the accuracy of the expts.<sup>[7-9]</sup> is rather low. Besides, as shown in ref.<sup>[5,13]</sup>, the "effective" values of  $\lambda_{dd\mu}$  measured under various experimental conditions can differ both from one another and from the calculations.

Therefore it is more interesting to compare our results with the most accurate data<sup>[10,11]</sup> obtained by the authors for the  $dd\mu$ -molecule formation rate from the state with  $F=1/2$  and transformed by us to the

"effective" rates. This comparison shows that there is fairly good agreement of our results with those obtained in ref.<sup>[10,11]</sup>. Noteworthy is good agreement of our result for  $T=300$  K with an accurate measurement<sup>[8]</sup>. Note also that our value of the  $dd\mu$ -molecule formation rate in liquid deuterium  $\bar{\lambda}_{dd\mu}=(0,0471\pm 0,0025) \mu s^{-1}$ , as well as the value obtained in exp.<sup>[11]</sup>, are consistent with the theory of nonresonant formation of  $dd\mu$ -molecule<sup>[3,21]</sup>. Thus the discrepancy between the experiment<sup>[22]</sup> and the theory has been removed.

We intend to carry out accurate comparison of our data with the theory of the  $dd\mu$ -molecule resonant formation at the next stage of the investigation, after the values of  $\lambda_{dd\mu}$  for different  $d\mu$ -atom spin states are obtained.

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Измерение температурной зависимости скорости образования  $dd\mu$ -молекул в газообразном дейтерии при давлении 1,5 и 0,4 кбар

В опытах с газовой дейтериевой мишенью высокого давления на мюонном пучке фазотрона ОИЯИ исследована температурная зависимость скорости ( $\lambda_{dd\mu}$ ) образования мюонных молекул  $dd\mu$ . Измерения выполнены с жидким дейтерием при температуре 20,3 К и с газообразным дейтерием при давлении 1500 и 400 бар в диапазоне температур 49–300 К. Показано, что при каждой температуре значения величины  $\lambda_{dd\mu}$  не зависят от плотности дейтерия. Полученные результаты находятся в удовлетворительном согласии с теорией и данными других экспериментов, выполненных при существенно меньшей /на один-два порядка/ плотности дейтерия.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1990

Bystritsky V.M. et al.

E1-90-322

Measurement of the Temperature Dependence of the  $dd\mu$ -Molecule Formation Rate in Gaseous Deuterium at the Pressures 1.5 and 0.4 Kbar

In the experiment with a gaseous deuterium target of high pressure on the muon beam of the JINR phasotron the temperature dependence of the  $dd\mu$ -molecule formation rate ( $\lambda_{dd\mu}$ ) has been measured. Measurements have been performed with liquid deuterium at the temperature  $T = 20.3$  K and with gaseous deuterium at pressure 1500 and 400 bar in the temperature region  $T = 49-300$  K. It is found that the value  $\lambda_{dd\mu}$  does not depend on the deuterium density for each temperature. The obtained results are in fairly good agreement with theory and with the data of other experiments made with deuterium of sufficiently (one-two order) lower density.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1990