Muon catalysis of *dd* nuclear fusion in the pressure range 51.6–93.0 atm

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The rate of production of $dd\mu$ molecules at deuterium pressures of 51.6, 70.4, 79.6, 91.6, and 93.0 atm has been measured at a temperature of 293 K. The ratio of the yields of the *dd* fusion reactions and the effective muon attachment coefficient are determined.

Muon catalysis of *dd* nuclear fusion is characterized by the following main parameters: the rate of production of $dd\mu$ molecules, $\lambda_{dd\mu}$; the ratio of the fusion reaction yields, $R = Y(d+d \rightarrow {}^3\mathrm{He}+n)/Y(d+d \rightarrow t+p)$; and the effective muon attachment coefficient $\tilde{\omega}_{dd,{}^3\mathrm{He}}$. The rate of $dd\mu$ production is customarily corrected to the density of liquid hydrogen:

$$\lambda^0_{dd\mu} = \lambda_{dd\mu}\rho_0/\rho_D ,$$

where ρ_D is the density of deuterium under the particular experimental conditions, and $\rho_0 = 4.25\times 10^{22}$ atom/cm^3 is the density of liquid hydrogen. The effective muon attachment coefficient $\tilde{\omega}_{dd,{}^3\mathrm{He}}$ is defined by

$$\tilde{\omega}_{dd,\,{}^3\mathrm{He}} = \omega'_{dd,\,{}^3\mathrm{He}}\,\gamma_{{}^3\mathrm{He}} ,$$

where $\tilde{\omega}_{dd,{}^3\mathrm{He}}$ is the probability for the attachment of a muon to a ^{3}He nucleus that has formed, and $\gamma_{{}^3\mathrm{He}}$ is the probability for retention of the muon during the stopping of the $({}^3\mathrm{He}\mu)^+$ ion. The overall effective muon attachment coefficient $\tilde{\omega}_{dd}$ is calculated from

$$\tilde{\omega}_{dd} = \tilde{\omega}_{dd,\,{}^3\mathrm{He}}\,R/(R+1).$$

We assume[1] $\tilde{\omega}_{dd,t} = 0$.

For this study of muon catalysis of *dd* nuclear fusion we have developed a novel experimental method[2,3] based on the use of a deuterium-filled high-pressure pulsed ionization chamber to detect the charged fusion products. This apparatus made it possible to detect, along with the stopping of the muon, up to three successive *dd* fusion events in a 4π geometry with a high efficiency ($\sim 100\%$). We measured the time at which each signal appeared, its height, and its duration. Analysis of the signals from the stopping of muons made it possible to effectively select useful events. After this selection, the admixture of background events did not exceed 0.3%.

By analyzing the temporal distribution of the fusion signals, we determined $\lambda_{dd\mu}$. Several independent methods were developed for determining this quantity, and the results obtained by the different methods were found to agree. An important point is

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TABLE I. Experimental results on the parameters of *d*-μ-*d* catalysis

Pressure, atm	$\lambda^0_{dd\mu}$, 10^6 s^{-1}	R	$\tilde{\omega}_{dd,\,^3He}$	$\tilde{\omega}_{dd}$
51.6	2.4 ± 0.6	—	—	—
70.4	2.86 ± 0.11	1.32 ± 0.05	0.125 ± 0.005	0.071 ± 0.003
79.6	2.74 ± 0.14	1.52 ± 0.11	0.116 ± 0.008	0.070 ± 0.005
91.6	2.76 ± 0.08	1.39 ± 0.04	0.126 ± 0.004	0.073 ± 0.003
93.0	2.84 ± 0.10	1.47 ± 0.06	0.111 ± 0.006	0.066 ± 0.004
Average value	—	1.39 ± 0.03	0.122 ± 0.003	0.071 ± 0.002

that the methods used by us to determine $\lambda_{dd\mu}$ do not depend on the purity of the gas. From an analysis of the pulse-height spectra we determined the ratio (R) of the yields of the isotopically symmetric fusion channels and the magnitude of the effective attachment coefficient[4] $\tilde{\omega}_{dd,^3He}$. In a single experiment we thus determined all three main parameters of the *d*-μ-*d* catalysis. All previous studies of *d*-μ-*d* catalysis had actually been restricted to measurements of $\lambda_{dd\mu}$. Our experimental procedure is described in detail in Ref. 5.

The present measurements were carried out at deuterium pressures of 51.6, 70.4, 79.6, 91.6, and 93.0 atm at a temperature of 293 K. The largest number of events was recorded at a pressure of 91.6 atm: 18 800 fusion events. The results of an analysis of the experimental data are listed in Table I. We see that the value of $\lambda^0_{dd\mu}$ is essentially

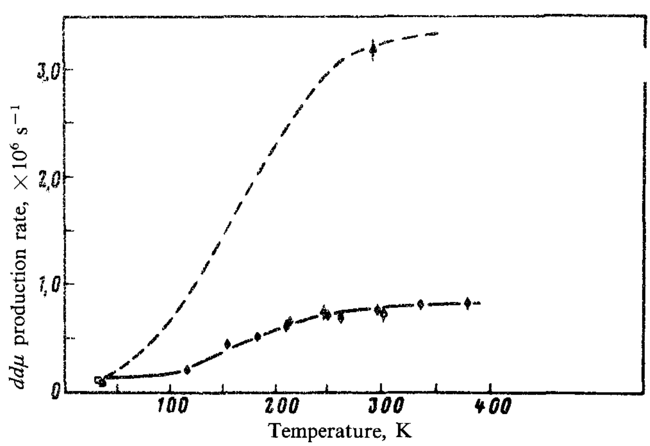

FIG. 1. Temperature dependence of the rate of production of $dd\mu$ molecules, referred to the density of liquid deuterium, $\rho^0_D = 4.93\times 10^{22}$ atm/cm^3. The dashed curve is the result of a renormalization of the resonance curve of Ref. 10 to our value of $\lambda_{dd\mu}$. The data of Ref. 10 are relative, normalized to the results of Refs. 8 and 9. ■—Fetkovich *et al.*[6]; □–Doede[7]; △–Dzhelepov *et al.*[8]; O—Bystritskiĭ *et al.*[9]; ●—Bystritskiĭ *et al.*[10]; ▲—present study.

independent of the pressure over the range studied. Since R, $\tilde{\omega}_{dd,^3\mathrm{He}}$, and $\tilde{\omega}_{dd}$ should be independent of the pressure, we have also listed their average values in Table I.

Figure 1 shows the results of previous experiments on the temperature dependence of the rate of production of $dd\mu$ molecules.[6–10] Also shown in this figure is the value that we found for $\lambda^0_{dd\mu}$ at 91.6 atm. This value differs by a factor of four from the results obtained by the Dubna group[8,9] and is evidence of an even more strongly expressed resonance behavior of the $dd\mu$ producton rate. The discrepancy between our data and the data of the Dubna group cannot be explained on the basis that the Dubna measurements were carried out at slightly lower pressures[8,9] ($P \lesssim 40$ atm), since $\lambda^0_{dd\mu}$ is essentially independent of the pressure, as we have shown.

The value of the effective muon attachment coefficient $\tilde{\omega}_{dd,^3\mathrm{He}} = 0.122 \pm 0.003$ found by us is slightly below the value of 0.147 derived theoretically in Ref. 1. There may be a similar situation in the case of the muon catalysis of dt fusion. If so, it would be of practical importance, since it would mean that the limiting number of dt fusion events caused by a single muon is higher than the theoretically predicted value[1] of 110. As for the deviation from isotopic symmetry in the dd fusion reaction observed in our experiments ($R = 1.39 \pm 0.03$), this effect has yet to be explained theoretically in a reliable way. It may be linked to the anomalies observed in the dd-scattering P wave at low energies,[11] since the particular properties of the $dd\mu$ system are such that the fusion occurs principally in the P state.

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