Experimental Investigation of Muon-Catalyzed *d*-*t* Fusion

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(Received 15 August 1983)

Measurements of the absolute neutron yield and the time dependence of the appearance of neutrons resulting from muon-catalyzed fusion have been carried out in high-density deuterium-tritium mixtures. The temperature dependence of the resonant $dt\mu$-molecular formation process has been determined in the range 100 to 540 K. Mesomolecular formation is found to be resonant for DT as well as D_2 target molecules. The sticking probability and other fundamental parameters have been measured for the first time.

PACS numbers: 36.10.Dr, 25.30.-c

Since the dimensions of a muonic hydrogen molecule are about 200 times smaller than those of an ordinary hydrogen molecule, negative muons stopped in a mixture of hydrogen isotopes can very rapidly bring about fusion reactions. Muon-catalyzed fusion was first seen by Alvarez *et al.*[1] in 1957 but had been predicted even earlier by Frank and others.[2] The recent revival of interest in the *d*-*d* and *d*-*t* reactions is mainly due to the discovery of a resonant molecular formation process (see Fig. 1) that precedes the fusion reactions.[3] For *d*-*t*, this allows the formation of a loosely bound excited state of the $dt\mu$ mesomolecule, with the released energy going into vibration and rotation of the resulting large molecule (of which the $dt\mu$ is one nucleus) rather than electron emission. This resonant process is predicted to enhance the molecular formation rate by two orders of magnitude and to induce a strong temperature dependence. In dense *d*-*t* mixtures this opens the interesting possibility of a single negative muon catalyzing ~100 fusions.[4-6]

This Letter reports an experiment to measure the parameters governing muon-catalyzed fusion in deuterium-tritium mixtures. The processes involved are shown schematically in Fig. 2. Of the rates defined there, only the transfer rate λ_{dt} and a lower limit on the molecular formation rate $\lambda_{dt\mu}$ had been determined previously.[7] We have now measured λ_{dt}, $\lambda_{dt\mu}$ as a function of temperature in the range 100 to 540 K, the sticking probability ω_s (muon retention by the fusion product α), and the ^{3}He scavenging parameters (see below). (The fusion rate λ_f and the atomic capture rate λ_a are too fast to be measured.) Furthermore, we are able to separate the two constituents[8] of $\lambda_{dt\mu}$:

$$\lambda_{dt\mu-d}\text{:}\quad t\mu + D_2 \rightarrow [(dt\mu)\, d\, 2e^-]^*, \tag{1a}$$

$$\lambda_{dt\mu-t}\text{:}\quad t\mu + DT \rightarrow [(dt\mu)\, t\, 2e^-]^*. \tag{1b}$$

The experiment was performed at the LAMPF biomedical channel with the apparatus shown in Fig. 3. The deuterium-tritium mixtures (0.45 and 0.60 of liquid hydrogen density) were contained in gold-lined stainless-steel vessels which could be heated or cooled.[9] Entering negative muons were registered by a scintillator telescope, the 14-MeV fusion neutrons by three liquid-scintillation detectors, and the muon-decay electrons

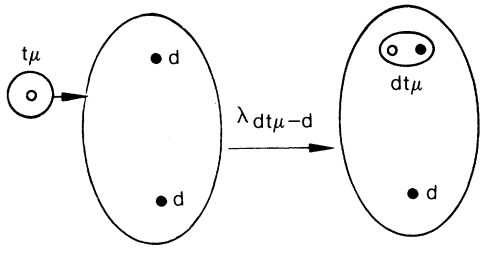

FIG. 1. Resonant production of $dt\mu$ molecules.

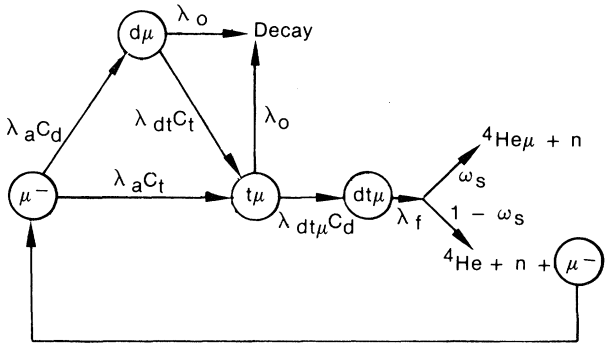

FIG. 2. Muon catalysis in a mixture of deuterium and tritium.

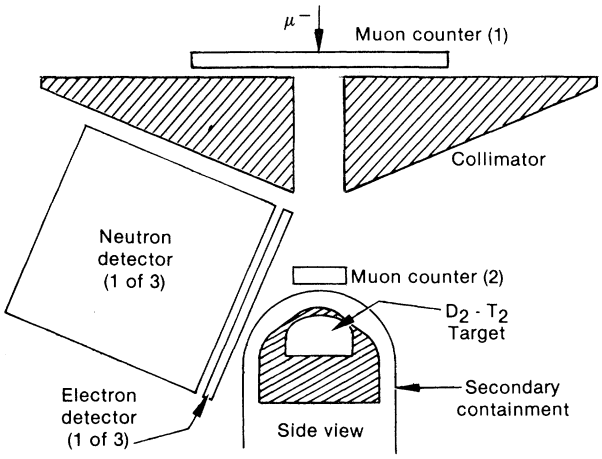

FIG. 3. Layout of the experiment.

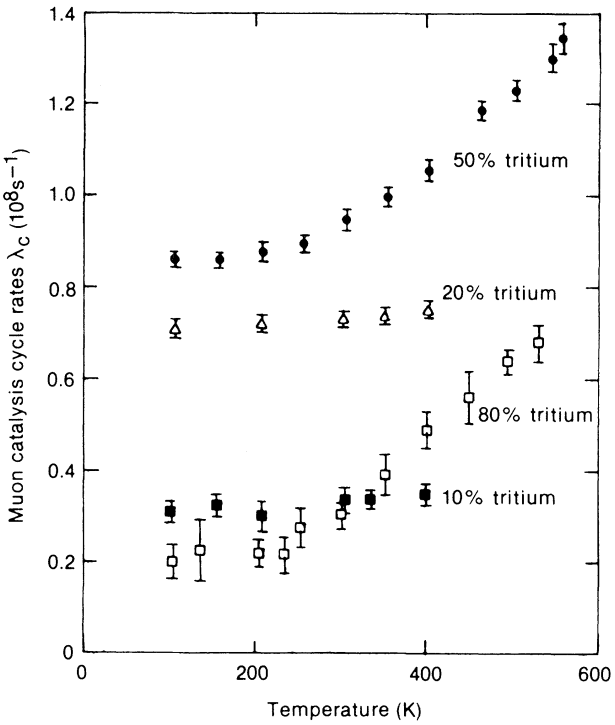

FIG. 4. Muon cycle rate λ_c normalized to liquid hydrogen density as a function of temperature.

by three plastic scintillation counters in coincidence with the liquid scintillators. An accepted event in this experiment required (1) entry of a single muon; (2) detection of one or more neutrons following (1); and (3) detection of the muon-decay electron following (2). The times between neutron or e^- pulses following muon arrival were recorded. Neutron and γ events in the neutron detectors were distinguished by fast pulse-shape discrimination. These methods reduced background to acceptable levels. The neutron detector efficiencies were determined with use of the Los Alamos Van de Graaff accelerator as a 14-MeV neutron source in conjunction with Monte Carlo calculations which incorporate geometrical acceptance.[10] Overall neutron detection efficiency ϵ was found to be $(3.4 \pm 0.3)\%$.

For any set of experimental conditions there are two basic quantities to be determined: $\bar{n}$, the average number of neutrons produced per muon stopped in the gas; and λ_n, the rate associated with the time dependence of the appearance of the neutrons. The most obvious way of determining $\bar{n}$ is to use the observed distribution of multiplicities of detected neutrons. (In the absence of dead-time effects, the neutron multiplicity distribution is geometrical.) However, since under some conditions as many as twenty neutrons are detected in the 5-μs time window following muon arrival, dead time can be significant. To avoid dead-time corrections, we take advantage of the presence of more than one neutron detector in the experiment, allowing both of the required quantities to be obtained from the distribution of time intervals between successive neutron detections (or between the muon arrival and the first neutron detection). The interval distribution has the form $P(t) \simeq \epsilon\lambda_c \exp[-(\epsilon\lambda_c + \lambda_n)t]$, where λ_c is the muon cycling rate (see below) and the distribution $P(t)$ and the neutron detection efficiency ϵ refer to any one or any combination of neutron detectors. The rates λ_c and λ_n are determined by fitting the slopes of semilog plots of the $P(t)$'s observed for detectors taken one, two, or three at a time, in the time interval 500 ns $< t <$ 1500 ns (500 ns is long enough to eliminate the transients and dead-time effects). Then $\bar{n} = \lambda_c/\lambda_n$. This method sacrifices statistical accuracy to reduce systematic errors.

While the equations relating $\bar{n}$, λ_c, and λ_n to the fundamental rates can be derived from rate equations[8] implied by Fig. 2, they can more easily be deduced from some simple considerations: Since λ_f and λ_a are very large,[5] the cycling time $(1/\lambda_c)$ of the muon is simply the sum of the time spent waiting to transfer from d to t for that fraction captured in deuterium, C_d, plus the time the $t\mu$ atom waits for molecular formation. Therefore

$$\frac{1}{\lambda_c} = \frac{C_d}{\varphi\lambda_{dt} C_t} + \frac{1}{\varphi\lambda_{dt\mu} C_d}. \qquad (2)$$

(By convention, the fundamental rates are nor-

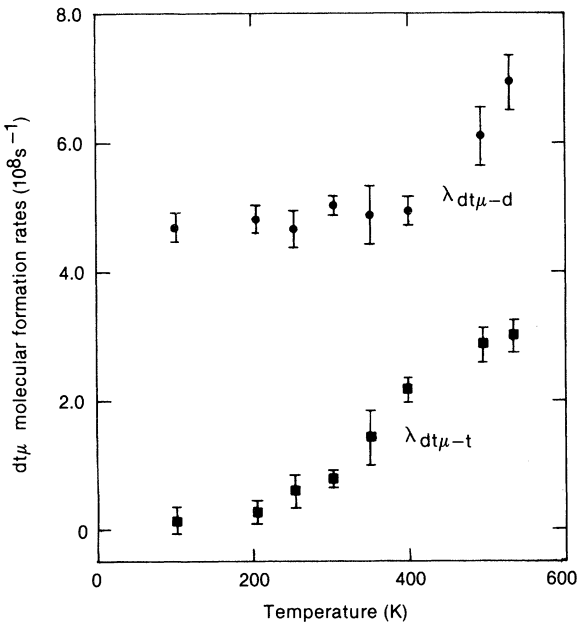

FIG. 5. Mesomolecular formation rates as functions of temperature.

malized to liquid hydrogen density; hence there is the density factor φ, which is the ratio of the actual number density to liquid hydrogen density.) The rate λ_n depends on all the processes that remove muons from the cycle; for small ^{3}He concentrations

$$\lambda_n = \lambda_0 + \omega_s \lambda_c + C_{^3\mathrm{He}} \lambda_c \left(\omega_{\mathrm{He}} + \frac{C_d}{C_t} \frac{\lambda_{d\mathrm{He}}}{\lambda_{dt}} + \frac{\lambda_{t\mathrm{He}}}{C_d \lambda_{dt\mu}} \right), \quad (3)$$

where ω_{He} is the probability for initial capture on ^{3}He plus the probability of transferring to ^{3}He during the muonic hydrogen cascade, while $\lambda_{d\mathrm{He}}$ and $\lambda_{t\mathrm{He}}$ are the rates for transfer from the ground state of the muonic hydrogen atoms. Finally, as indicated by the reactions of Eq. (1) there are two components of $\lambda_{dt\mu}$:

$$\lambda_{dt\mu} = \lambda_{dt\mu-d} C_d + \lambda_{dt\mu-t} C_t. \quad (4)$$

Our principal experimental results are displayed in Figs. 4 and 5 and in Table I; the error bars in the figures are statistical while the errors quoted in the table include systematic errors. Figure 4 shows the temperature dependence of λ_c for four concentration ratios. While the low-C_t data show no significant temperature dependence, in agreement with the experiment of Bystritskiĭ *et al.*,[7] the temperature dependence for the higher tritium concentrations is quite striking. The low-tritium-concentration data are flat because the cycling time is dominated by the $d \rightarrow t$ transfer time ($1/C_t \lambda_{dt}$). The rate λ_{dt} (assumed to be independent of temperature) extracted from our data agrees very well with that reported in Ref. 7 (see Table I).

Once λ_{dt} is determined, $\lambda_{dt\mu}$ can be obtained using Eq. (2). From the concentration dependence of Eq. (4), the separate components of $\lambda_{dt\mu}$ are found (Fig. 5). Both of these components appear to be resonant. However, while $\lambda_{dt\mu-t}$ has the expected property of approaching zero as $T \rightarrow 0$, $\lambda_{dt\mu-d}$ surprisingly appears to be constant in the temperature range 100–400 K.

The experiment also determined the sticking probability ω_s [see Eq. (3)]. The result for ω_s, $(0.77 \pm 0.08)\%$, is in fair agreement with the two calculations.[11,12] (High-Z contamination of our target gas, which could produce an artifically large value of ω_s, was calculated to be less than 2 ppm, and therefore negligible, but was not measured.)

TABLE I. Parameters of muon catalysis in deuterium-tritium mixtures.

	λ_{dt} (s^{-1})	$\lambda_{dt\mu}$ (s^{-1})	ω_s	ω_{He}	$\lambda_{d\mathrm{He}}$ (s^{-1})	$\lambda_{t\mathrm{He}}$ (s^{-1})	$\bar{n}$
Theory	2×10^8 [b]	$\sim 10^8$ [c]	0.86% [d] 0.91% [e]	~ 1 [f]	1.5×10^8 [g]	5.6×10^8 [g]	$\sim 10^2$ [c]
Previous experiment [a]	$(2.9 \pm 0.4) \times 10^8$	$>10^8$	...	...	...	...	...
Present experiment	$(2.8 \pm 0.3) \times 10^8$	see Fig. 5	$(0.77 \pm 0.08)\%$	1 ± 1	$(2 \pm 1) \times 10^8$	$(7 \pm 2) \times 10^8$	90 ± 10

[a] Ref. 7.
[b] Ref. 8.
[c] Ref. 5.
[d] Ref. 11.
[e] Ref. 12.
[f] Ref. 14.
[g] Ref. 13.

The final result concerns the scavenging of muons by ^{3}He produced from tritium decay. The three contributions to this scavenging have been roughly separated by their λ_c and C_t dependence [see Eq. (3)], and the results are shown in Table I. The $\lambda_{d\mathrm{He}}$ and $\lambda_{t\mathrm{He}}$ values agree well with the calculations of Aristov *et al.*,[13] and the ω_{He} value is quite reasonable.[14]

In summary, this first investigation of muon-catalyzed fusion in high-density *d-t* mixtures has produced a number of new results. Formation rates for $dt\mu$ molecules have been observed to be large and dependent on temperature, and quite different for the two molecular species involved (D_2 and DT). The measured sticking probability, ω_s, is consistent with calculation. The cycle rates and neutron yields demonstrate that a significant number of *d-t* fusions per muon can be realized. Indeed, our measurements indicate that an average of 90 ± 10 fusions per muon will be produced in an equimolar deuterium-tritium mixture at $\varphi = 1$ and 540 K.

We wish to acknowledge the assistance of many persons at the Idaho National Engineering Laboratory and the Los Alamos National Laboratory. In particular we thank L. O. Johnson (INEL) for developing the specialized electronics used in the experiment and D. M. Drake (LANL) for assisting in neutron-detector calibration. This work was supported by the U. S. Department of Energy, in part by its Advanced Energy Projects Division, under Contracts No. DE-AC07-76ID01570 and No. W-7405-ENG-36.

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