Observation of Unexpected Density Effects in Muon-Catalyzed d-t Fusion

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New experimental results on muon-catalyzed d-t fusion are reported. Unexpected target-density effects have been discovered both in $dt\mu$ molecular formation in $t\mu + D_2$ collisions and in the effective sticking probability. The $dt\mu$ formation rate is significantly enhanced at high density, presumably because of a strong three-body contribution. The origin of the observed reduction of the sticking probability at high density remains unclear. Both effects increase the number of fusions per muon that can be achieved; 150 ± 4(stat.) ± 20(syst.) fusions per muon have been observed.

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The study of muon catalysis of d-t fusion (depicted in Fig. 1) has now entered a period of rapid development,[1-3] a few years after the experimental confirmation by Bystritsky *et al.*[4] that $dt\mu$ molecular formation is indeed fast on the scale of the muon lifetime (2.2 μs). In an earlier Letter,[1] we reported the first measurements of some of the basic parameters of this fascinating process. In particular, the sticking probability ω_s was measured, and the $dt\mu$ formation rates $\lambda_{dt\mu\text{-}d}$ and $\lambda_{dt\mu\text{-}t}$ for collisions of $t\mu$ atoms with D_2 and DT molecules were determined as functions of target temperature T. Targets of widely varying tritium fraction C_t but only two values of density ϕ were used, $\phi = 0.45$ and 0.60 (relative to liquid hydrogen density, 4.25×10^{22} atoms/cm^3). We have now made measurements over a much larger range of ϕ, and have consequently discovered some new and unexpected phenomena: Both ω_s and $\lambda_{dt\mu\text{-}d}$ *vary strongly with density* ϕ. These observations indicate clearly that in spite of extensive theoretical efforts,[5] our understanding of muon-catalyzed d-t fusion is still incomplete.

The experiment was performed at LAMPF using the methods described earlier.[1,2] In Fig. 2 we show the ϕ dependence of the *normalized* muon cycling rate $\lambda_c = \lambda_c^{obs}/\phi$ (λ_c^{obs} is the *observed* cycling rate) for a variety of temperatures and tritium fractions. It is conventional to normalize to liquid-hydrogen density because of the expectation that all relevant rates scale linearly with density. The cycling time ($= 1/\lambda_c^{obs}$) is dominated by the time that the negative muon spends in the $d\mu$-atom *ground state* waiting to transfer to a triton (rate $\phi\lambda_{dt}C_t$) and the time spent in the $t\mu$ ground state waiting for molecular formation to occur (rate $\phi\lambda_{dt\mu}C_d$, where C_d is the deuterium fraction). Thus

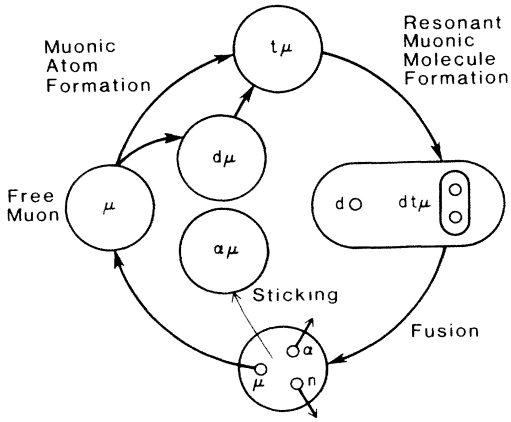

FIG. 1. The main $dt\mu$-catalysis cycle. Other channels (not shown) are discussed in the text.

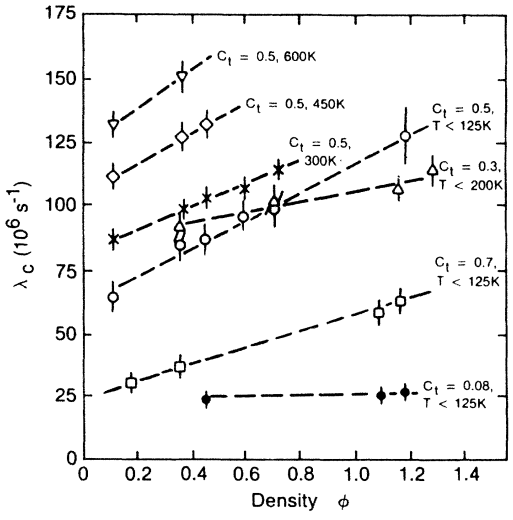

FIG. 2. Dependence of the normalized cycling rate λ_c on the density ϕ of the d-t mixture.

we write[6]

$$\frac{\phi}{\lambda_c^{\rm obs}} = \frac{1}{\lambda_c} \simeq \frac{q_{1s}C_d}{\lambda_{dt}C_t} + \frac{1}{\lambda_{dt\mu}C_d}. \quad (1)$$

The product $q_{1s}C_d$ is the probability that the muon reaches the $d\mu$ ground state; q_{1s} will deviate from unity both because of muon transfer to t from excited states of $d\mu$,[7] and because the initial atomic capture ratio might differ somewhat from the ratio C_d/C_t.

At the time of the present experiment the only predicted source of ϕ dependence was the factor q_{1s}. However, Fig. 2 shows clearly that, contrary to expectation, the ϕ dependence is *least* at small C_t where the first term of Eq. (1) is dominant, and is most striking at large C_t where the second term dominates. Hence we are forced to conclude that the normalized molecular formation rate $\lambda_{dt\mu}$ *increases with* ϕ. Thus $dt\mu$ formation, which occurs via the resonance mechanism,[8-11] is probably *not* a purely *two-body collision process* as previously assumed.

Separation of the contributions of the two terms in Eq. (1) is complicated by the possibility that q_{1s} may depend on both C_t and ϕ, and requires further assumptions. Our procedure is first to estimate $\lambda_{dt\mu}$ from the high-C_t data and λ_{dt}/q_{1s} from the low-C_t data, and then to use these values as the starting point for a global fit.[12] We assume that λ_{dt} depends only on T and that all residual dependence of λ_{dt}/q_{1s} on ϕ and C_t is due to q_{1s}. In contrast to recent calculations of Menshikov and Ponomarev (MP),[7] which predict values $q_{1s}^{\rm MP}$ which fall precipitously with increasing C_t and ϕ, our results suggest a relatively weak dependence on C_t and negligible dependence on ϕ. *For example,* for $C_t = 0.5$ and $T = 300$ K, we obtain $\lambda_{dt}/q_{1s} = (446 \pm 93) \times 10^6$ s^{-1} at $\phi = 0.12$ and $\lambda_{dt}/q_{1s} = (457 \pm 58) \times 10^6$ s^{-1} at $\phi = 0.72$, while MP predict an increase by over a factor of 2 ($q_{1s}^{\rm MP}$ decreasing from 0.195 to 0.085). Similarly, for $C_t = 0.04$, $T = 300$ K, and $\phi = 0.72$, we obtain $\lambda_{dt}/q_{1s} = (328 \pm 25) \times 10^6$ s^{-1}; this is only a factor of ~ 1.5 less than at the higher $C_t = 0.5$, compared to the predicted decrease by a factor of ~ 7 ($q_{1s}^{\rm MP} = 0.62$ for the $C_t = 0.04$ case).[13]

On the other hand, our results for q_{1s} are consistent with recent experimental findings[14] for π^- capture in mixtures of hydrogen and deuterium at $\phi \lesssim 0.11$. Extrapolating from those results, which show *no* density dependence, we *infer* that $q_{1s} \simeq [1-(1-\gamma_1)C_x] \times (\gamma_2)^{2C_x}$ with $\gamma_1 = 0.81 \pm 0.01$, $\gamma_2 = 0.83 \pm 0.01$, and $x = d$ for a chemically equilibrated mix of H_2, HD, and D_2. Then using the same functional form to analyze our data we find (now with $x = t$) $\gamma_1 \simeq \gamma_2 = 0.75 \pm 0.20$, and

$$\lambda_{dt} \simeq [1 + (6 \pm 1) \times 10^{-4} T](280 \pm 40) \times 10^6 \text{ s}^{-1}$$

for the temperature range 20–500 K. This value of λ_{dt} agrees with the low-ϕ, low-C_t experiment of Bystritsky *et al.*[4] The temperature dependence is not quite as strong as predicted[15] but shows the same trend.

The rate $\lambda_{dt\mu}$ has contributions from $t\mu$ collisions with both D_2 and DT,[16] so that $\lambda_{dt\mu} = C_d\lambda_{dt\mu\text{-}d} + C_t\lambda_{dt\mu\text{-}t}$. We write $\lambda_{dt\mu\text{-}x} = \lambda_{dt\mu\text{-}x}^{(1)} + \lambda_{dt\mu\text{-}x}^{(2)}\phi$, the superscripts indicating the power of ϕ appearing in the observed (rather than normalized) $dt\mu$ formation rates. A global fit with all four terms present shows that the $\lambda_{dt\mu\text{-}t}^{(2)}$ values are consistent with zero. Fitting with $\lambda_{dt\mu\text{-}t}^{(2)}$ *constrained* to be zero gives the values shown in Table I, and the $\lambda_{dt\mu\text{-}d}(\phi)$ for $T < 130$ K shown in Fig. 3. We conclude that our data show a strong *linear* ϕ *dependence* for (normalized) $\lambda_{dt\mu\text{-}d}$, but not for $\lambda_{dt\mu\text{-}t}$. The large values of $\lambda_{dt\mu\text{-}d}^{(2)}$ are evidence of significant resonant $dt\mu$ formation via *three-body collisions.*

Menshikov and Ponomarev[17] have recently discussed a mechanism for three-body resonant molecular formation, e.g., $t\mu + D_2 + D_2 \rightarrow [(dt\mu)d2e]^* + D_2 + \Delta E$. The singlet $t\mu + D_2$ collisions are special in having their strongest resonances *just below threshold,* where they are not accessible in two-body collisions.[9] By absorbing some kinetic energy, the spectator molecule (D_2, DT, or T_2) moves these strong resonances above threshold, allowing them to contribute to molecular formation.

We turn now to the mechanisms of muon loss from the catalysis cycle. The muon may be captured and retained by a helium nucleus synthesized during $dt\mu$, $dd\mu$, or $tt\mu$ fusion, with sticking probabilities ω_s, ω_d, and ω_t, respectively. In addition, small amounts of protium are present ($C_p \lesssim 1\%$), resulting in $pd\mu$ and $pt\mu$ fusion, with sticking probabilities ω_{pd} and ω_{pt}. The muon may also be scavenged by ^{3}He introduced by tritium decay (normally $C_{\rm He} << 1\%$). The total muon loss probability per cycle can be written as[1,5]

$$w \simeq \frac{q_{1s}C_d}{\lambda_{dt}C_t + \lambda_{dd\mu}C_d}(0.58\lambda_{dd\mu}C_d\omega_d + \lambda_{pd\mu}C_p\omega_{pd} + \lambda_{d\rm He}C_{\rm He}) + \frac{1}{\lambda_{dt\mu}C_d}(\lambda_{tt\mu}C_t\omega_t + \lambda_{pt\mu}C_p\omega_{pt} + \lambda_{t\rm He}C_{\rm He}) + C_{\rm He}\omega_{\rm He} + \omega_s^{\rm eff}, \quad (2)$$

where $\lambda_{dd\mu}, \ldots,$ are the rates for $dd\mu, \ldots,$ molecular formation, $\lambda_{d\rm He}$ and $\lambda_{t\rm He}$ are the rates for transfer to ^{3}He from the $d\mu$ and $t\mu$ ground states, and $\omega_{\rm He}$ is the probability for initial capture by ^{3}He. $\omega_s^{\rm eff}$ is then the *effective*

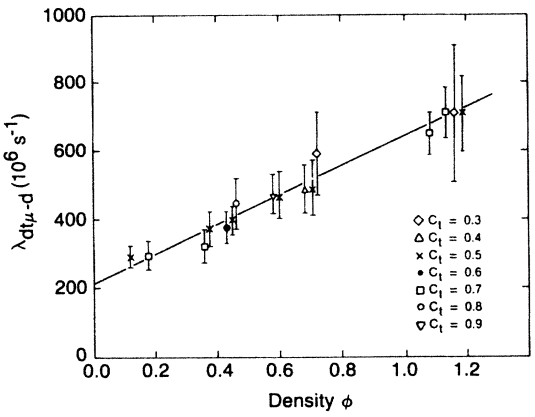

FIG. 3. Density dependence of the normalized molecular formation rate $\lambda_{dt\mu\text{-}d}$ for $T < 130$ K, assuming that $\lambda_{dt\mu\text{-}t}$ is density independent. The solid line is a fit to the data (see Table I).

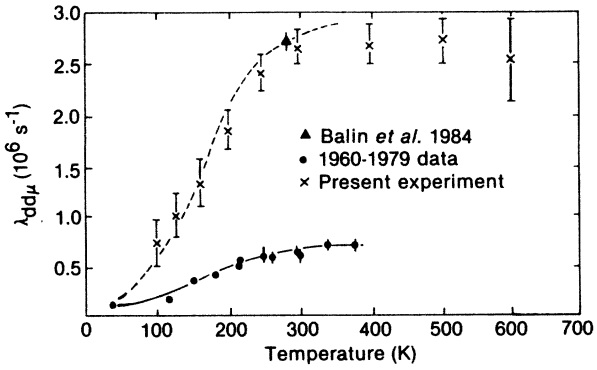

FIG. 4. Temperature dependence of the $dd\mu$ formation rate $\lambda_{dd\mu}$ (with $\omega_d = 0.122$ from Ref. 18), from data with $C_t < 13\%$. The solid line is a theoretical fit (Ref. 8) to earlier data (circles); renormalization yields the dashed curve.

sticking probability for the $dt\mu$ fusion reaction.

It follows from Eq. (2) that $dd\mu$ fusion shows up in our experiment as an increase in w for low-C_t targets, permitting us to evaluate the product $\lambda_{dd\mu}\omega_d$ at different temperatures. Since ω_d has been measured independently,[18] we are able to extract $\lambda_{dd\mu}$ as a function of temperature as shown in Fig. 4. Our results agree well with the room-temperature measurement of $\lambda_{dd\mu}$ of Balin *et al.* and, except for normalization, with earlier data over the range 100–400 K.[18] Similarly, assuming that the observed temperature dependence of w for high-C_t targets is due to the temperature dependence of $\lambda_{dt\mu}$, we evaluate the corresponding product for $tt\mu$ fusion: $\lambda_{tt\mu}\omega_t = (0.40 \pm 0.1) \times 10^6$ s^{-1}. Furthermore, from targets with large amounts of protium, we find that the $pd\mu$ and $pt\mu$ losses can adequately be expressed by $w_p = (C_p/\lambda_c)(6.0 \pm 0.6) \times 10^{-6}$ s^{-1}. Muon losses due to scavenging by ^{3}He are evaluated by noting the increase in w with time as ^{3}He builds up from tritium decay.

Subtracting from w the contributions discussed above yields ω_s^{eff}, which depends on density and tritium fraction as shown in Fig. 5. (The evidence for the $\sqrt{C_t}$ dependence used is much weaker than that for the ϕ dependence.) The striking variation with ϕ was completely unexpected. Furthermore, the observed value of ω_s^{eff}, as small as 0.35% and still decreasing at high density, is much smaller than the calculated value[19] of 0.9% for α sticking accepted before the present experiment. (The calculated sticking fraction is the product of the probability that the muon is initially captured by the recoiling fusion α particle, $\omega_s^0 \simeq 1.2\%$, by the conditional probability that the muon is *not* subsequently stripped, $1 - R \simeq 0.75$.) More accurate calculations[20] of initial sticking have very recently reduced this estimate by 25% to 33% but the resulting values still significantly exceed our high-density ω_s^{eff} results.[21]

The variation of ω_s^{eff} could come from events (a) preceding or (b) following the nuclear fusion. Under (b) the most likely origin is the muon-stripping process. Although the value of R is somewhat uncertain, it is not expected[22] to have nearly as much dependence on density as implied by Fig. 5. Under (a), a certain fraction of the muons may be delayed *after* molecular

TABLE I. Fitted contributions to the $dt\mu$-formation rate (Ref. 12) (in units of 10^6 s^{-1}) assuming $\lambda_{dt\mu} = C_d(\lambda^{(1)}_{dt\mu\text{-}d} + \lambda^{(2)}_{dt\mu\text{-}d}\phi) + C_t\lambda^{(1)}_{dt\mu\text{-}t}$.

T (K)	$\lambda^{(1)}_{dt\mu\text{-}d}$	$\lambda^{(2)}_{dt\mu\text{-}d}$	$\lambda^{(1)}_{dt\mu\text{-}t}$	$\lambda^{(2)}_{dt\mu\text{-}t}$
< 130	206 ± 29	450 ± 50	26 ± 6	· · ·
300	306 ± 43	286 ± 67	92 ± 19	· · ·
400–500	347 ± 52	275 ± 120	225 ± 21	· · ·

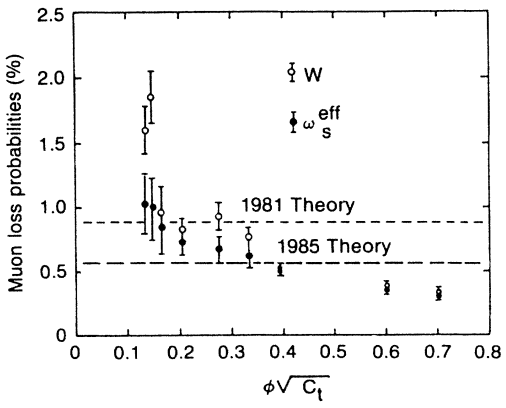

FIG. 5. Dependence of ω_s^{eff} on $\phi\sqrt{C_t}$ for $C_t \leq 0.3$. The uncorrected values w are also shown.

formation but *before* fusion, thus increasing ω_s^{eff} above a small initial sticking value.[23] The $dt\mu$ system, initially formed in the excited $J=1$, $v=1$ state, needs to cascade via Auger transitions to a $J=0$ state for fusion to be rapid. Possibly this cascade may be facilitated by electrons supplied by ionization induced by tritium decay.[24] The sensitivity to ϕ and C_t could then come from the ion-electron recombination process, whose rate is proportional to $\phi\sqrt{C_t}$. This model also encounters some difficulties.[23] Clearly, further study is needed to determine which, if either, of these ideas can explain the observed dependence of ω_s^{eff}.

With the experimental ω_s^{eff} well below predicted values, 300 or more fusions per muon might be possible. We have already detected an average value of $150 \pm 4(\text{stat.}) \pm 20(\text{syst.})$ fusions per muon, releasing about 3 GeV of energy, in a liquefied d-t target with $C_t = 0.3$.

In summary, we have discovered some completely unexpected target-density dependences in both the $dt\mu$ molecular formation rate $\lambda_{dt\mu\text{-}d}$ and the effective sticking probability ω_s^{eff}. The former is presumably due to three-body contributions to resonant mesonic-molecule formation. The origin of the latter remains much less clear.

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