Muon-Catalyzed D-T Fusion at Low Temperature

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Muon-catalyzed deuterium-tritium fusion was investigated within a wide range of mixtures in liquid and gas (23–35 K) by detection of fusion neutrons. Our improved analysis includes hyperfine effects and allows a clear separation of intrinsic *dt* sticking ω_s from kinetic effects. Strongly density-dependent cycle rates with values up to 1.45×10^8 s^{-1}, yields of 113 fusions per muon, and $\omega_s=(0.45\pm0.05)\%$ are found. In comparison with previous experiments we confirm that ω_s in liquid is lower than theoretically predicted, but do not find a strong dependence on either tritium concentration or density.

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In recent years muon-catalyzed fusion (MCF) has gained renewed interest due to the observation of resonance effects in $d\mu d$ formation[1,2] and the predictions of extremely fast rates in deuterium-tritium (DT) mixtures.[3,4] First experiments[5–8] found high yields of the fusion reaction $d\mu t \rightarrow \alpha+n+\mu^-+17.6$ MeV and a surprisingly rich physics of muon-induced processes. This paper presents a systematic experimental investigation of MCF at low temperatures in liquid and gas of various densities ϕ and tritium concentrations c_t. Large and strongly ϕ-dependent cycle rates, yields up to 113 fusions per muon, and low *dt* sticking factors ω_s, with no strong dependence on either c_t or ϕ, are reported.

The reaction-kinetics of muons in DT[9,10] is shown in Fig. 1. The initial population of μd atoms in their ground state is $P_{1s}=c_d q_{1s}$, where $q_{1s}\leqq 1$ strongly depends on ϕ and c_t.[11] In the ground state, isotopic transfer takes place with an effective rate $\Lambda_{dt}=\phi c_t \lambda_{dt}$ (the collisional rates Λ_x depend on the target density ϕ; the rates λ_x are always normalized to liquid-hydrogen density $\phi_0=4.25\times10^{22}$ cm^{-3}). Because of the resonance character of mesonic molecule formation, the rate $\Lambda_{d\mu t}$ (and also $\Lambda_{d\mu d}$) is expected to consist of strongly different contributions from different hyperfine states F[2,12] and from collisions with D_2 and DT molecules[9,10]:

$$\Lambda_{d\mu t}^{F}=\phi[2c_{D_2}\lambda_{d\mu t}^{F,D_2}+c_{DT}\lambda_{d\mu t}^{F,DT}]. \quad (1)$$

While the hyperfine effects have been clarified for $d\mu d$ formation,[2,13] no direct experimental information is available for $d\mu t$. Fast transients, first seen in our DT experiments at low density and originally interpreted as evidence for hyperfine effects,[7] can more likely be explained as due to fast, nonthermalized μt atoms.[14,15] According to theoretical prediction,[16] only $\lambda_{d\mu t}^{0,D_2}$ is resonant at low temperatures. Sticking to the helium products interrupts the fusion cycles with probabilities $\tilde{\omega}_d$, ω_s, or ω_t

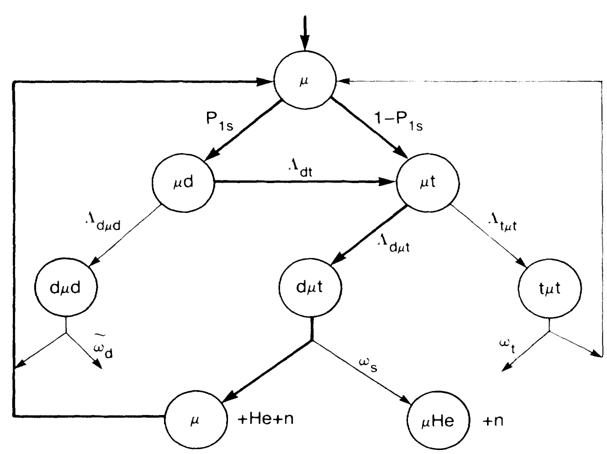

FIG. 1. Simplified scheme of muon-catalyzed fusion cycles in DT mixtures.

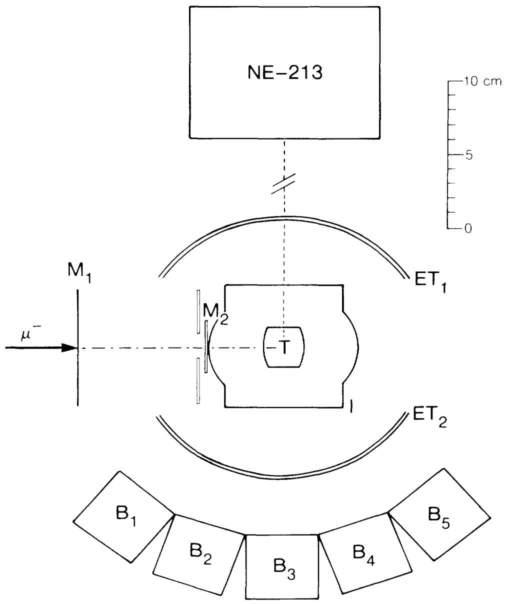

FIG. 2. Experimental setup: Target (T), insulation vacuum (I), μ telescope (M1,M2), n detectors (B1-B5, NE213), e telescopes (ET1,ET2).

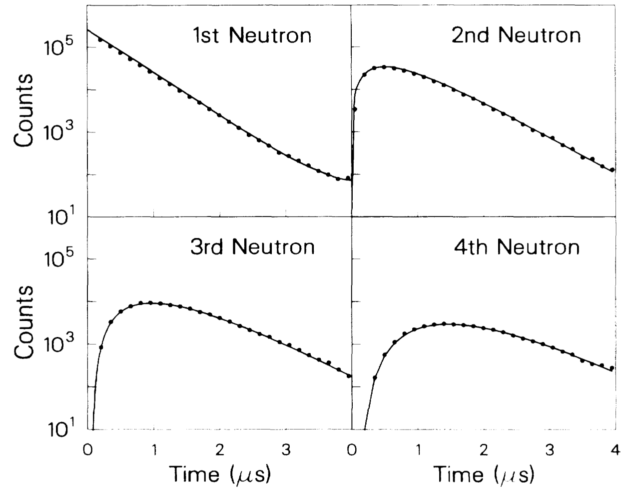

FIG. 3. Time spectra of fusion neutrons observed subsequently in one of the plastic detectors ($c_t=36\%$, liquid DT, $\varepsilon_n=0.4\%$, deadtime 50 nsec). Solid curve demonstrates agreement with analytical expressions derived from Eq. (2).

(see Fig. 1).

After a steady state is reached the observable time distribution of fusion neutrons can simply be described by

$$dN(t)/dt = N_\mu \varepsilon_n \phi \lambda_c \exp[-(\lambda_0 + w\phi\lambda_c)t], \qquad (2)$$

where N_μ is the number of muon stops in DT, ε_n the neutron detection efficiency, λ_c the normalized cycle rate, λ_0 the muon decay constant (0.455×10^6 s^{-1}), and w the mean loss per cycle (raw sticking). In terms of the basic kinetic rates (Fig. 1) λ_c can be written as[6,17]

$$(\phi\lambda_c)^{-1} = P_{1s}\Lambda_{dt}^{-1} + \Lambda_{d\mu t}^{-1}. \qquad (3)$$

The measurements were performed at the Swiss Institute for Nuclear Research with the experimental setup shown in Fig. 2. The fraction of good muon stops in liquid DT was 64%–68% (target volume $V=20$ cm^3), and 6%–40% in gas ($V=100$–1000 cm^3). Time distributions and recoil energy spectra of fusion neutrons and electrons (from muon decay) were measured in eight consecutive runs with liquid fillings ($T=23$ K, $\phi=1.16$–1.24) and in nineteen runs with gas ($T=30$–35 K, $\phi=1\%$–8%) over a wide range of tritium concentrations ($c_t=2\%$–96%).

For the correct and separate determination of λ_c and w [Eq. (2)] the full understanding of systematic effects (e.g., dead-time effects, neutron sensitivities of all counters) associated with the high multiplicity of fusion neutrons is essential. In our experiment the complete time distribution of neutrons and electrons (up to 8 μs after muon stop) were recorded. This allowed a careful off-line study of spectral distortions resulting from delayed n-e and n-n requirements. Spectra of subsequent fusion neutrons were obtained with small and well-understood dead-time corrections (Fig. 3) by use of five fast plastic scintillators (operated with fast routing circuits). For the absolute calibration an experimentally calibrated NE213 detector with n-γ discrimination was placed at sufficient distances to the target (up to 113 cm) to keep double hits well below 10%. The purity of the DT mixture was achieved by filling of the target[18] through a palladium filter and checked experimentally (muonic x rays were monitored to exclude muon transfer to impurities).

The time spectra of fusion neutrons were fitted according to Eq. (2), excluding the transient period before the steady state is reached. Additional independent analysis methods yielded consistent results within 2%. The requirement of a delayed coincidence with the electrons from muon decay allowed a direct determination of the muon stops N_μ (see Ref. 2). The experimental results are presented in Fig. 4(a) (normalized cycle rates λ_c) and Fig. 4(b) (raw sticking w). The large differences between λ_c in liquid and gas show a *significant density dependence* over the whole range of investigated tritium concentrations. At low c_t this effect is expected from the ϕ dependence of the fast muon transfer q_{1s}.[11] At large c_t, where $\Lambda_{d\mu t}$ dominates λ_c, this enhancement with ϕ is even more pronounced and can be explained qualitatively by triple collisions.[19]

A detailed analysis of the λ_c distribution [Fig. 4(a)] in liquid DT has been performed in terms of basic kinetic parameters, (i) with the assumption of no hyperfine effects to be present in $d\mu t$ formation, (ii) including the

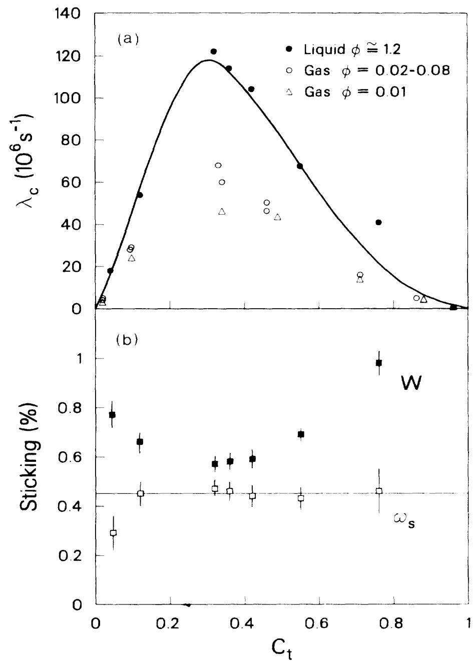

FIG. 4. Experimental results. (a) Normalized DT cycle rates λ_c vs c_t showing pronounced density effects. Relative errors ~2% (liquid) and < 10% (gas), absolute calibration error ± 8% (whole data set). (b) Raw sticking w and DT sticking ω_s (from liquid data).

$d\mu t$ hyperfine effects, with the assumption that only the $F=0$ state is resonant.[16] A simple parametrization of $q_{1s}=(1+ac_t)^{-1}$ was chosen, sufficiently general to describe roughly the theoretical[11] and experimental[8] results. λ_{dt} was evaluated from the preliminary analysis of our low-ϕ, low-c_t data, where $q_{1s} \cong 1$ and thus $\Lambda_{dt} \cong \phi\lambda_c$ [see Eq. (3)]. The results of the fit of all liquid data points (including their molecular and atomic compositions as measured on site with a mass spectrometer) are given in Table I. Note that special liquid fillings were prepared (e.g., at $c_t=0.76$) where the relative D_2 concentration was much larger than for the other points, which were approximately at high-temperature equilibrium ($c_{D_2}:c_{DT}:c_{T_2}=c_d^2:2c_dc_t:c_t^2$). The corresponding data points significantly exceed the solid line in Fig. 4(a) which is calculated for high-temperature equilibrium with use of our fit results (Table I). This observation shows directly that $\lambda_{d\mu t}^{D_2}$ dominates at low temperatures.

In comparison to the experiment of Jones *et al.*[8] our experiment is quite complementary, as it provides a complete coverage of a low and well-defined temperature region (within the range 23–35 K, temperature effects are small) and extends to lower gas densities ($0.01 < \phi < 0.08$). Thus, it is interesting that the two experiments agree qualitatively on the magnitude of the observed cycle rates and density effects. In the overlap region of the two experiments (liquid conditions) we find significantly smaller λ_c values for $c_t > 0.4$ than reported in Ref. 8. As a direct consequence the resulting values for $\lambda_{d\mu t}^{D_2}$ disagree by ~2 (Table I). Our analysis also proves the importance of hyperfine effects even at high densities. Different assumptions (i) and (ii) are both consistent with our data, but have distinct influence on the determination of basic rates (Table I) and q_{1s} [$a=6.5\pm3$ for (i), whereas $a=15\pm4$ for (ii) resulting in a stronger c_t dependence, but still much weaker than predicted[11]]. This ambiguity may be resolved in careful studies of the transient period at high densities (where thermalization occurs already during the muonic cascade[15]).

TABLE I. Comparison of experimental results for muon transfer and normalized $d\mu t$ formation rates (in units of 10^6 s^{-1}) (Ref. 8 quoted for $\phi=1.2$).

	λ_{dt}	$\lambda_{d\mu t}^{D_2}$	$\lambda_{d\mu t}^{DT}$
Bystritskii *et al.*[a]	290 ± 40	>100	
Jones *et al.*[b] ($T<130$ K)	284 ± 40	746 ± 67	26 ± 6
This work ($T=23$ K)			
Analysis (i)	280 ± 50	326 ± 40	11^{+6}_{-11}
Analysis (ii)	350 ± 50	373 ± 50	7 ± 7

[a]Reference 5.
[b]Reference 8.

With the parameters obtained from the λ_c fit, the raw sticking values w [Fig. 4(b)] were corrected for contributions from $d\mu d$, $t\mu t$, $p\mu d$, and $p\mu t$ fusion.[17] (The last two fusion channels had to be included because there was about 1% protium in our samples.) Calculations verified that these corrections were (within the parameter range of Table I) nearly independent of the choice of kinetic rates. Stringent limits of $<2\times10^{-4}$ per cycle were derived experimentally for muon losses to impurities and to ^3He originating from tritium decay. The corrected sticking values ω_s obtained in liquid DT [Fig. 4(b)] show *no significant variation with* c_t, resulting in an average DT sticking $\omega_s=(0.45\pm0.05)\%$. This result is somewhat larger than reported by Jones *et al.*,[8] but still lower than the most recent theoretical calculations (0.58%[20] and 0.67%[21] using initial sticking values 0.848%[22] and 0.895%,[23] respectively). In DT gas ($\phi=3\%$–8%) we evaluate $\omega_s=(0.5\pm0.1)\%$ as a preliminary result. This value allows only a *weak* ϕ *dependence of* ω_s, in accordance with theory,[20,21] but in strong disagreement with experiment.[8]

This work contains the first evaluation of ω_s over the full c_t range and presents important information about the controversial situation concerning sticking. Since 1984 preliminary results from Clinton P. Anderson Meson Physics Facility have indicated small values as well as c_t and ϕ dependence of ω_s,[8,24] triggering models about hidden kinetic effects ("bottleneck" models)[25] to explain these surprising findings. Our improved analysis allows a clear separation of the intrinsic stricking from these kinetic effects. Since we extract ω_s from the slope of the steady-state distribution [Eq. (2)], the sticking definition of Ref. 25 is not relevant for our method and our sticking values are *not affected by the existence of bottleneck states.* Though unimportant for our analysis, at liquid conditions we can even exclude any significant existence of such states in the MCF cycle, which would lead to deviations from the purely exponential time distributions seen after a few nanoseconds in our experiment.

Our maximum observed cycle rate $\phi\lambda_c$ is 145 ± 12 μs^{-1}; the corresponding fusion yield per muon $\phi\lambda_c/(\lambda_0 + w\phi\lambda_c)$ is 113 ± 10. At conditions with even larger cycle rates the yield could exceed 200. Indeed, such promising conditions are anticipated at high temperatures, since the fast transients in our gas data[7,17] indicate extremely high molecular formation rates for hot μt atoms.[14,15]

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