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ABSTRACT

Muon catalyzed deuterium-tritium fusion was investigated within a wide range of densities and mixtures in liquid and gas (23K-35K). 5 plastic and a calibrated NE 213 detector measured time and recoil-energy spectra of 14 MeV fusion neutrons. Multiple hits were recorded via fast routing circuits. The observed cycle rates peak at 145 μsec^{-1}, equivalent to 113 fusions per muon. A density dependence increases the normalized cycle rates by ~2. The DT sticking factor is (0.45+-0.05)%.

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In recent years muon catalyzed fusion (MCF) has gained renewed interest due to the observation of resonance effects in dμd 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 reports a systematic experimental investigation of MCF in the low temperature region (23K-35K) using liquid and gas targets at various densities and DT mixtures. Large cycle rates, exhibiting a strong non linear density dependence, and small sticking factors were observed yielding up to 113 fusions per muon.

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 $q_{1s} \leq 1$ describes fast muon transfer during the muonic cascade and strongly depends on the density ϕ and tritium concentration 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 $\phi_o = 4.25 \cdot 10^{22}\text{cm}^{-3}$). Due to the resonance character of mesomolecule formation, the rate $\Lambda_{d\mu t}$ (and also $\Lambda_{d\mu d}$) is expected to consist of strongly different contributions for hyperfine states F [2,12] and for collisions with D_2 and DT molecules[9,10]:

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

While the hyperfine effects have been clarified for dμd formation[2,13], no direct experimental information is available for dμt. 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, non thermalized μt atoms[14,15]. According to theoretical expectations[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.

Because of the large effective rates , a steady state is reached at high density after transient times of a few ns. Then, the observable time distribution of fusion neutrons can simply be described by

$$dN(t)/dt = N_\mu \, \varepsilon_n \, \phi \, \lambda_c \, e^{-(\lambda_0 + w\phi\lambda_c)t} \qquad (2)$$

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 (SIN) 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 cm^3). Time distributions and recoil energy spectra of fusion neutrons and electrons (from muon decay) were measured in 8 consecutive runs with liquid fillings (T=23K, ϕ=1.16-1.24) and in 19 runs with gas (T=30K-35K, ϕ=1%-8%) over a wide range of tritium concentrations (c_t=2%-96%).

As a significant modification to our previous experiments a set of 5 plastic counters was installed to handle large neutron multiplicities. Using fast routing circuits and pulse clipping techniques, up to 4 subsequent neutron hits per detector were recorded. Due to small detector efficiencies

(ε_n = 0.4%) and dead times (50ns), pile up distortions of the time distributions were small and are well understood (Fig. 3). An absolutely calibrated liquid scintillation counter (NE 213) with n-γ pulse shape discrimination was placed at sufficient distances (13, 56 and 113 cm) to keep the occurance of double neutron hits well below 10%. Muonic X-rays were monitored by a Ge(Li) diode to detect any significant muon transfer to impurities.

The trigger for accepting events was a muon stop signal (with beam pile up rejection ± 9μsec) accompanied by at least one neutron or electron signal within 8 μsec. With this simple trigger we obtained undistorted time distributions of neutrons and electrons. Additional constraints (e.g., n-e or n-n correlations) which distort time spectra due to their delayed coincidence characteristics were studied off-line.

For the tritium handling a closed loop high vacuum and gas mixing system was constructed using exclusively metallic components and palladium filters for gas purification[18]. Special filling procedures also provided non equilibrated molecular mixtures. The molecular compositions were monitored with a mass spectrometer connected directly to the target cell.

The time spectra of fusion neutrons were fitted according to Eq. 2, excluding the transient period before the steady state is reached. The requirement of a delayed coincidence with the electrons from muon decay allowed a direct determination of the muon stops N_μ (this method is described in Ref. 2) and it strongly suppressed background events. At liquid densities careful studies of systematic effects associated with the high neutron multiplicities were performed yielding consistent results within ±2%. The comparison between different detectors provided sufficient redundancy to single out counter instabilities or other experimental problems.

The experimental results are presented in Fig. 4a (normalized cycle rates λ_c) and Fig. 4b (raw sticking w, derived from the neutron disappearance rates Eq. 2). The large differences between liquid and gas data show a significant density dependence over the whole range of investigated tritium concentrations. At low c_t this effect is predicted to be caused by the behavior of q_{1s}, describing the fast muon transfer[11]. However, this density dependence is even more pronounced at larger c_t, where $\Lambda_{d\mu t}$ dominates λ_c. According to very recent calculations[19], this enhancement can be explained by triple collisions. Density effects are also expected from non thermal contributions to the dμt formation rate[14,15].

A detailed analysis of the λ_c distribution (Fig. 4a) in liquid DT has been performed in terms of basic kinetic parameters, (i) assuming no hyperfine effects to be present in dμt formation, (ii) including the dμt hyperfine effects, but assuming only the F=0 state to be resonant[16]. A simple parametrization of $q_{1s}=(1+ac_t)^{-1}$ was chosen, roughly describing the theoretical curves[11]. 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 this analysis are given in Table 1 and Fig. 4. The solid line in Fig.4a is calculated for molecular concentrations at high temperature equilibrium ($c_{D_2}:c_{DT}:c_{T_2} = c_d^2:2c_dc_t:c_t^2$) using our fit results (Table 1). The data points above the curve belong to fillings, where the D_2 concentration was larger than the equilibrium values (up to 40%). The higher cycle rates seen for these points are direct evidence, that dμt formation on D_2 molecules dominates at liquid conditions.

We note: 1) Different assumptions (i) and (ii) on the presence of hyperfine effects are both consistent with our liquid DT results, but influence the determination of the basic parameters (Table I). This ambiguity may be resolved in careful studies of the transient period before the steady state is reached. 2) The q_{1s} dependence on c_t is significantly stronger for assumption (ii) [$a=6.5\pm3$ for (i), whereas $a=15\pm4$ for (ii)], but still smaller than the most recent calculation[11]. 3) A comparison with experiment[8] shows qualitative agreement for cycle rates and density effect, but considerable disagreement for the c_t dependence of λ_c in liquid DT (our observed cycle rates peak at smaller c_t). As a direct consequence, the resulting values for $\lambda_{d\mu t}^{D_2}$ differ by ~2 (see Table I). We also evaluate a stronger q_{1s} effect. The assumptions of model[20], proposed to explain data[8], are inconsistent with the purely exponential time distributions seen after a few ns in our liquid data.

With the parameters obtained from the λ_c fit the raw sticking values w (Fig. 4b) were corrected for contributions from $d\mu d$, $t\mu t$, $p\mu d$ and $p\mu t$ fusion[17]. (The latter 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 Table I) nearly independent of the choice of kinetic rates. Stringent limits of $<2\cdot10^{-4}$ per cycle were derived experimentally for muon losses to impurities and to ^{3}He originating from tritium decay. Our values ω_s (Fig. 4b) show no significant variation with c_t, resulting in an average DT sticking $\omega_s = (0.45\pm0.05)\%$, (the experiment at LAMPF[8,20] reports a $\phi\sqrt{c_t}$ dependence with ω_s as low as 0.35%). Our result is somewhat lower than the most recent theoretical calculations which include reactivation of the muon [0.58%[21] and 0.67%[22] using initial sticking values $\overset{o}{\omega}_{s}$ = 0.848%[23] and 0.895%[24], respectively].

Our maximum observed cycle rate $\phi\lambda_c$ is 145±12 μsec^{-1}, the corresponding fusion yield per muon $\phi\lambda_c/(\lambda_o+w\phi\lambda_c)$ 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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TABLE CAPTION

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

TABLE I

	λ_{dt}	D_2 $\lambda_{d\mu t}$	DT $\lambda_{d\mu t}$
Bystritskii et al.[5]	290 ± 40	>100	—
Jones et al.[8] (T<130K)	284 ± 40	746 ± 67	26 ± 6
This work (T=23K): analysis (i)	280 ± 50	326 ± 40	11^{+6}_{-11}
analysis (ii)	350 ± 50	373 ± 50	7 ± 7

FIGURE CAPTIONS

Fig. 1: Simplified scheme of muon catalyzed fusion cycles in DT mixtures.

Fig. 2: Experimental set-up: 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 of the plastic detectors (c_t = 36%, liquid DT). Solid curve demonstrates agreement with analytical expressions derived from Eq.(2).

Fig. 4: Experimental results. (a) Normalized DT cycle rates λ_c versus 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).

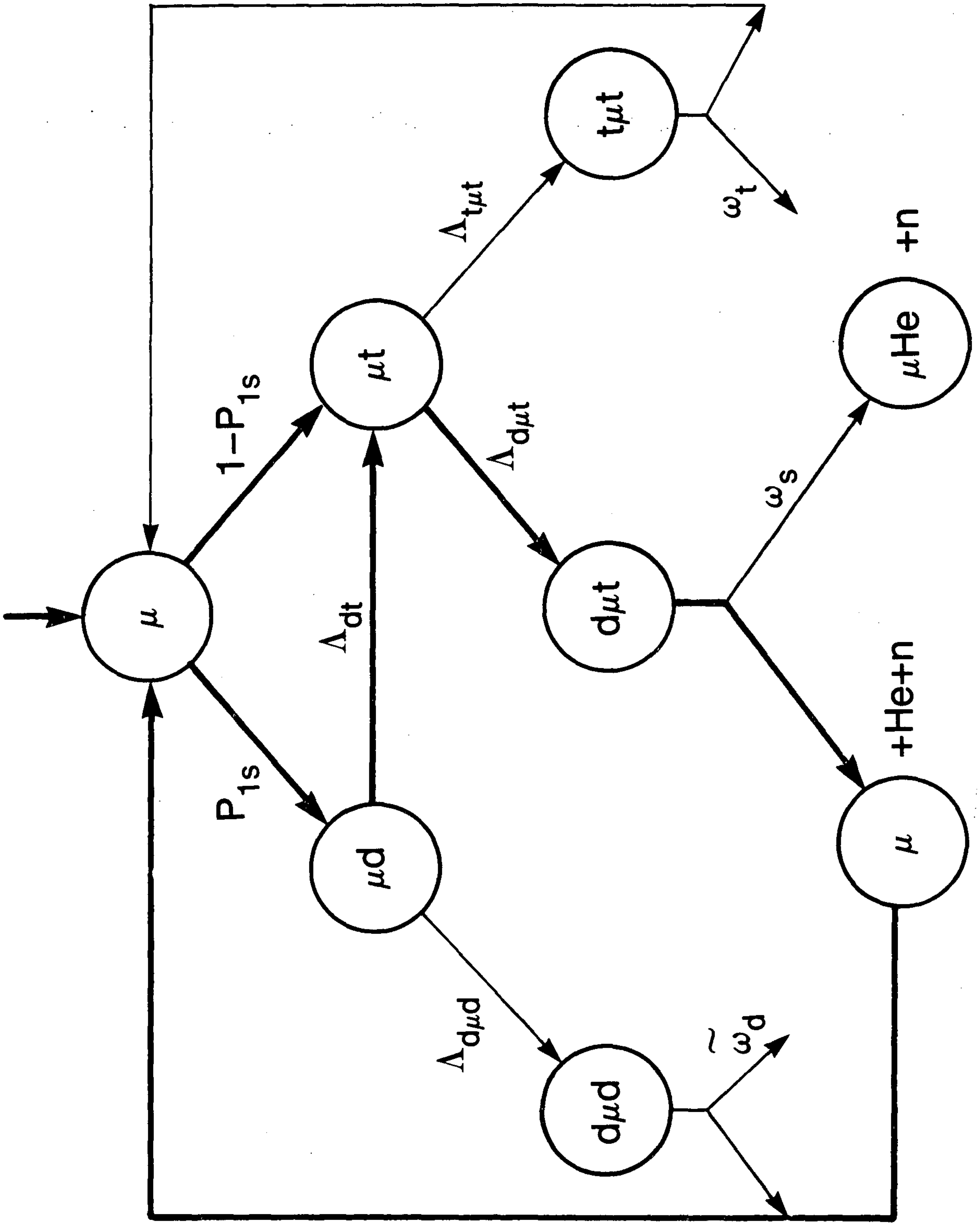

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Figure 1

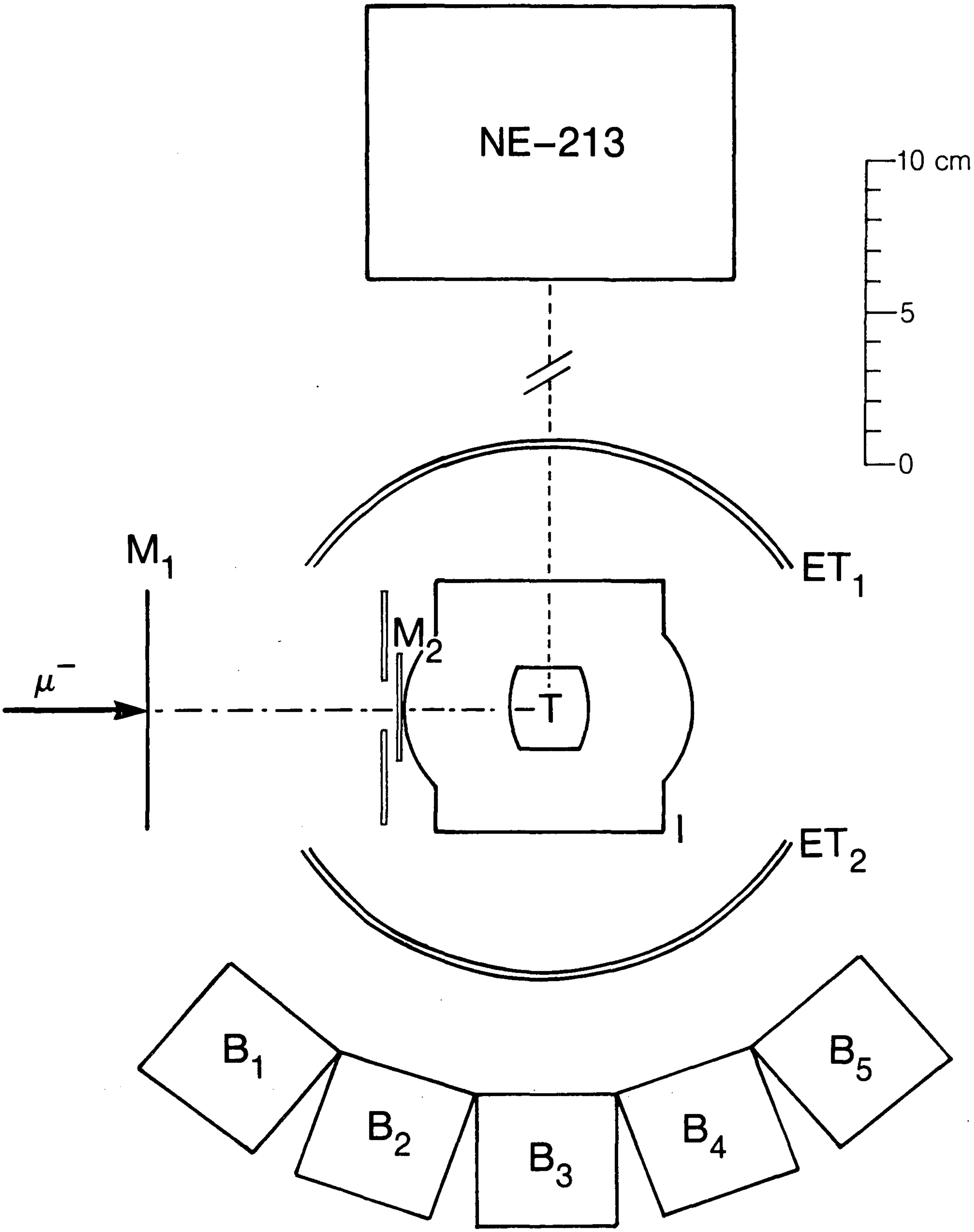

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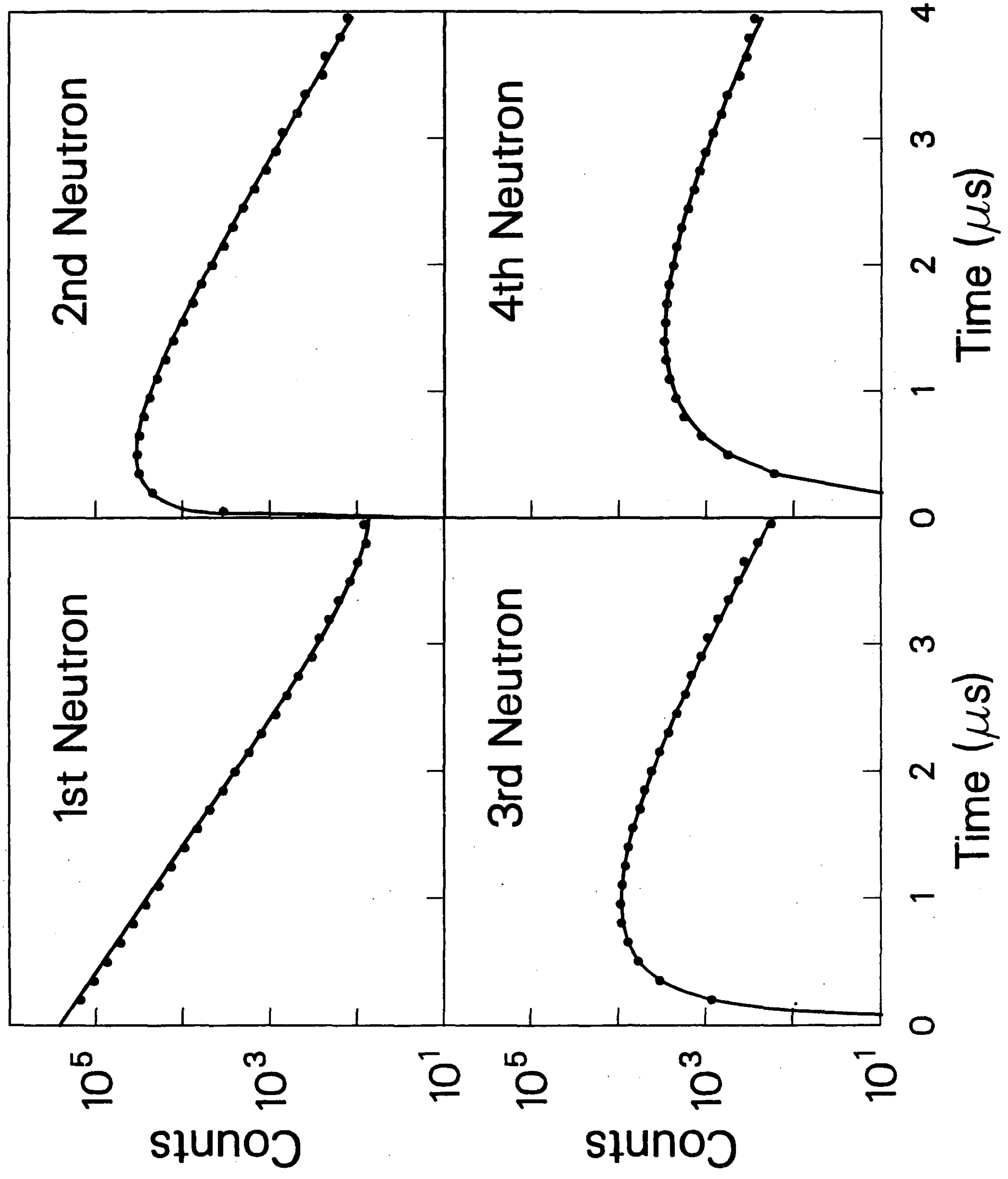
Figure 2

Figure 3



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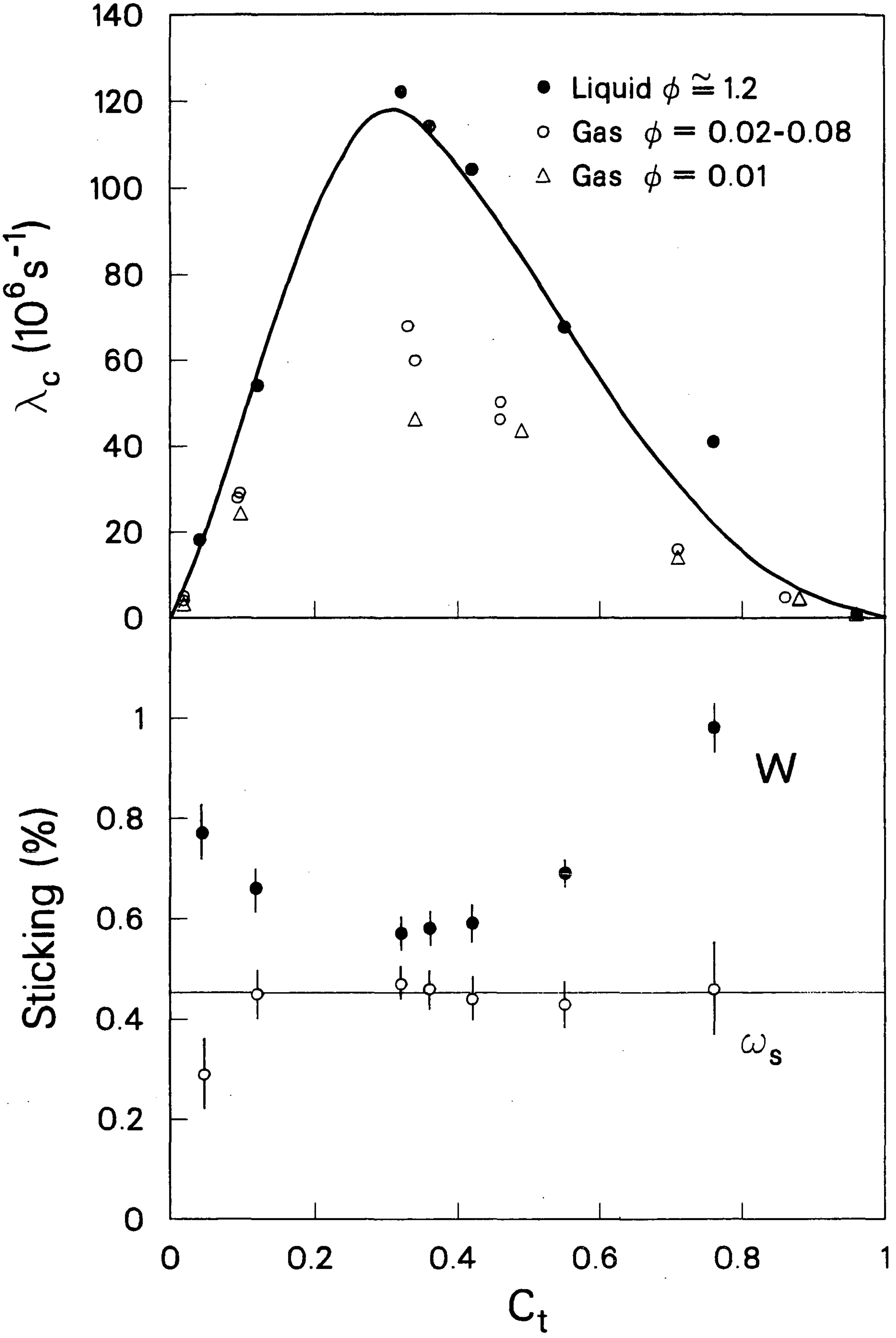

Figure 4 XCG 865-7224

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