CH8700097

SIN-PR-86-10

STICKING IN MUON CATALYZED D-T FUSION

C. Petitjean
Swiss Institute for Nuclear Research
CH-5234 Villigen/Switzerland

W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton
N. Nägele, P. Pawlek, A. Scrinzi, J. Werner, J. Zmeskal
Oesterreichische Akademie der Wissenschaften
A-1090 Vienna, Austria

J. Bistirlich, K.M. Crowe, M. Justice, J. Kurck
University of California and Lawrence Berkeley Lab.
USA-Berkeley, CA 94720

R.H. Sherman
Material Science and Technology
Los Alamos National Laboratory
USA-Los Alamos, New Mexico 87545

H. Bossy, H. Daniel. F.J. Hartmann
W. Neumann, G. Schmidt, T. von Egidy
Physik Departement, Technische Universität München
D-8046 Garching, West Germany

Invited paper, presented to the International Symposium on Muon Catalyzed Fusion, September 1-3, 1986, Tokyo

Swiss Institute
for Nuclear Research

October 1986

CH-5234 Villigen
Switzerland

STICKING IN MUON CATALYZED D-T FUSION

C. Petitjean
Swiss Institute for Nuclear Research
CH-5234 Villigen/Switzerland

W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton,
N. Nägele, P. Pawlek, A.Scrinzi, J. Werner, J. Zmeskal
Oesterreichische Akademie der Wissenschaften
A-1090 Vienna, Austria

J. Bistirlich, K.M. Crowe, M. Justice, J. Kurck
University of California and Lawrence Berkeley Lab.
USA-Berkeley, CA 94720

R.H. Sherman
Material Science and Technology
Los Alamos National Laboratory
USA-Los Alamos, New Mexico 87545

H. Bossy, H. Daniel, F.J. Hartmann,
W. Neumann, G. Schmidt, T. von Egidy
Physik Departement, Technische Universität München
D-8046 Garching, West Germany

Invited paper, presented to the
International Symposium on Muon Catalyzed Fusion
September 1 - 3, 1986, Tokyo
by Claude Petitjean

October 1, 1986

ABSTRACT

The issue of $\mu\alpha$ sticking after muon catalyzed DT fusion is controversial, since a number of theoretical and experimental results came out recently with sticking values ω_s varying over a large range. After a review of this situation, our measurements at SIN and methods of sticking analysis from neutron time structures are presented in detail. The important point is the correct understanding of the experimentally observed time distributions. At high density (liquid DT) we find, after correction for other fusion channels, for DT sticking $\omega_s = (0.45 \pm 0.05)\%$, not dependent on tritium concentration c_t and in accordance with our X-ray observations. At low density (DT gas, $\phi = 3\%$ - 8%) our preliminary result is $0.50 \pm 0.10\%$, giving a ratio 1.1 ± 0.2 in agreement with conventional theories, but strongly disagreeing with the LAMPF experiment of S.E. Jones et al. Our result sets the maximum fusion output per muon to less than 220 ± 20.

1 Introduction

Muon catalyzed fusion (MCF) of deuterium - tritium (DT) isotopes has become a highly discussed issue, since very large rates of the fusion reaction

$$\mu t + d \rightarrow d\mu t \rightarrow \alpha + n + \mu^- + 17.6 MeV \tag{1}$$

were observed in recent experiments [1 - 8]. The reaction kinetics in a DT mixture is shown in Fig.1. Very rapid DT cycles are induced, due to a resonance mechanism in the formation of mesic molecules [9 - 11]. This phenomenon was experimentally first observed in pure deuterium (resonant production of dμd molecules [12 - 14]), but surprisingly it leads (as theoretically predicted [9]) in the DT cycle to even much more enhanced dμt formation rates. Reported DT cycle rates λ_c exceed the muon decay constant λ_o by more than 300 [4,5,8] and show a rising tendency with target temperature [2,3,4,6]. As a consequence, the discussion of future energy applications of MCF is now lively going on [15].

The attainable fusion yield per muon Y_f, however, cannot grow infinitely with the fusion rate, because it is also limited by the sticking factor ω_s, see Fig.1, the probability, that the muon gets trapped after fusion by the emerging α particle:

$$d\mu t \overset{\omega_s}{\rightarrow} \alpha\mu + n + 17.6 MeV \tag{2}$$

Muon sticking interrupts the fusion cycles Fig. 1, and if it cannot be overcome (which is difficult to accomplish, once the $\mu\alpha$ system is at rest) the ultimate limit of fusion output is [16]:

$$Y_f \leq \frac{1}{\omega_s} \tag{3}$$

Theoretical values of ω_s range from the original estimate by Jackson [17] of about 1% down to 0.02% [18]. Recent "canonical" calculations yield 0.5%-0.7% for "final" sticking [19 - 22].

From our experiments at SIN [8] we have evaluated ω_s=(0.45 $\pm$ 0.05)% at high density (liquid) and ω_s = (0.50 $\pm$ 0.10) at low density (gas, preliminary value). The experimental group at Los Alamos by S.E. Jones et al., on the other hand, has reported sticking ω_s to be dependent on tritium density $\phi(c_t)$ [4],on ϕ, $\overline{c_t}$ [5,23] or at least on ϕ [6], with experimental values variing between 0.3% and 1.1%.

Evidently, the issue of sticking is quite controversial, on the theoretical as well as on the experimental side, and needs therefore more clarification. It is the intention of this paper to line out in some detail the present situation concerning expectations, methods of measurement and evaluation of the DT sticking factor, with special emphasis on our experiments, which were performed 1983-85 at SIN, Switzerland, in liquid and gaseous DT mixtures.

2 Theoretical estimates of DT sticking

The probability of $\mu\alpha$ sticking after dμt fusion depends on initial as well as final configurations. The initial scheme (before fusion takes place) is shown in Fig.2. In the resonant formation process, the dμt system is originally formed in a highly excited and weakly bound state with orbital and rotational quantum numbers $(\nu,K)=(1,1)$ [9,10]. It deexcites (mostly by Auger processes) to lower levels, until undergoing fusion from one of the levels. After fusion there is in principle a set of initial sticking probabilities ω_s^n applying to each muonic Helium level n, composed of contribution $\omega_s^{n,i}$ from each dμt state i(see Fig.2):

$$\omega_s^n = \sum_{i=1}^{5} P_i \, \omega_s^{n,i} \tag{4}$$

where P_i are relative probabilities for fusion ($\sum P_i = 1$) calculated from the transition scheme. The overall "initial" sticking value ω_s^o is thus

$$\omega_s^o = \sum_n \omega_s^n \tag{5}$$

The Dubna theory group [24] has calculated the probabilities P_i concluding, that fusion essentially takes place from the J=0 levels (i=2,4). Theoretical work on initial sticking was then mainly concentrated on the calculation of ω_s^o from the (J=0) states [19,20,25,26], see table 1. Only recently Hu [27] considered also the (0,1) p-state of the dμt molecule as starting point and surprisingly obtained a more than three times lower sticking value! Although the contribution from this level to fusion seems to be small, one should keep the scheme of Fig.2 in mind for the case, that some of the transition or fusion rates differ from present theoretical expectations.

Jones [6] has suggested, that subdued electron refilling (after 2 Auger transitions) could impede the last transition (0,1) to (0,0), making sticking dependent on the electron density of the target (dependence assumed to be proportional to $\phi\sqrt{c_t}$). However, such an effect would in the light of Hu's result rather lead to a reduced sticking at low $\phi\sqrt{c_t}$, which is opposite to Jones reported observations [4 -6].

J.Cohen and M.Leon [23] have argued, that a bottleneck state (a side channel, preventing the muon from fast cycling) could lead to a different "effective" sticking ω_s^{eff}, which may then show up in a $\phi\sqrt{c_t}$ dependence of sticking. We clearly reject this argumentation: As long as only one fusion channel is considered open as in Ref. [23], the observable sticking value cannot change due to such a bottleneck state, but rather the cycle rate will be correspondingly reduced. The effect, discussed in Ref. [23], comes from an unphysical definition of ω_s^{eff}, using the cycle rate at time t=0 to muon stop (before the kinetic system is in equilibrium) instead of using the steady state cycle rate. If the experimental analysis is done correctly as described in chapter 3.4, then the effect [23] does <u>not</u> cause any variation of observed sticking.

The "final" sticking value ω_s is defined as the probability, that the $\mu\alpha$ system comes to rest in the 1s state. ω_s is significantly lower than ω_s^o, because the $\mu\alpha$'s have an initial kinetic energy of 3.5 MeV and can by inelastic processes shake off the muon. If R is the "reactivation coefficient", we write

$$\omega_s = \omega_s^o(1 - R) \tag{6}$$

Calculations [21,22] have shown, that muon stripping from higher orbits (n>1) is very likely, while shaking off a muon from the 1s state takes rather place via a multi step process (excitations followed by ionisation).

Although reactivation is expected to be dependent on the target density ϕ (in vacuum R=0!), Takahashi [22] has found little variability for technically accessible densities, the changes between $\phi = 0.1$ and 1.0 being about 3%, while an approximative formula in Ref [21] predicts an 11% effect. It is not clear, wether the theoretical treatment of multistep activation processes has been advanced enough to fully explain experimental observations (see comments in Ref.[21]). Just prior to this conference a new calculation by James Cohen[28] became known, resulting now in a significantly larger reactivation coefficient (R $\sim$ 0.39).

Table 1 summarizes the theoretical work on initial and final sticking. The most accurate calculations yield final sticking factors ω_s between 0.5% and 0.7%, which would limit the maximum DT fusion output to less than 200 fusions per muon.

3 Experimental methods of sticking measurement

Various methods have been used or are proposed to investigate sticking:

1. direct detection of the $\mu\alpha$ systems
2. measurement of muonic X-rays from excited $\mu\alpha^*$ systems
3. measurement of the yield reduction after first fusion
4. measurement of the fusion disappearance rate.

We discuss here all methods, but will concentrate on method (4), which has resulted so far in the most precise sticking values.

(1) The direct detection of $\mu\alpha$ systems is a straight foreward method, if proper monitoring and distinction from α's can be made. The discrimination from α's can be achieved by making use of the different range and/or energy loss characteristics (singly versus doubly charged ions!). This method was successfully applied in Gatchina (Leningrad) to determine sticking after dμd fusion [29]. For the dμt case there is the drawback of much smaller yields and of the enormous beta activity from tritium, inducing large background radiations in detectors placed near or in the tritium target. Nevertheless, attempts are under way to do such measurements also in dμt fusion [29,30].

(2) The measurement of muonic X-rays from excited $\mu\alpha^*$ atoms is also a direct observation of "sticking" muons, though only of the fraction ending up in orbits above the 1s groundlevel. A full assessment of sticking needs therefore detailed calculations of the initial occupation of $\mu\alpha$ orbits and the successive processes during the $\mu\alpha$ slow down and the muonic cascade. On the other hand, absolute and relative X-ray yields can be compared with theoretical calculations, allowing tests of the validity of theoretical models.

X-ray measurements have been successfully performed at SIN by our collaboration, first in pμd and dμd fusion [31], later in dμt fusion [32]. An absolute precision of 20% was reached for the dμt case. Our results indicate, that higher $\mu\alpha$ orbits (n>1) get mostly depleted by ionisation during the slow down. The agreement with theoretical expectations [22] is not yet satisfactory but with the newest calculation [28] is very good ($Y_x(2-1) = 0.25\%$ per dμt fusion).

X-ray measurements in DT targets also suffer from Bremsstrahlung induced by the tritium radioactivity. The Japaneese group has proposed to perform X-ray experiments at KEK with the pulsed beam technique [33].

(3) The measurement of yield reduction makes use of the fact, that after a fusion only the fraction (1-w) of muons is free to start another fusion cycle:

$$Y_{ff} = Y_{\mu f}(1 - w) \tag{7}$$

where $Y_{\mu f}$ and Y_{ff} are the fusion yields, measured after a muon stop and after a fusion, respectively. This method was successfully applied in our experiments at high tritium concentrations (c_t=96%) to determine tμt sticking ω_{tt} [34]. It is independent of absolute counter sensitivities, but relies on an accurate measurement of the number of "good" muon stops (muons stopping in the DT mixture are usually less than electronic triggers!). Using the coincidence method [13] (measurement of single and coincident time spectra of fusion events and of electrons from muon decay), we have achieved experimental accuracies better than 2%. For the determination of ω_s this method is not yet precise enough.

The method of determining the fusion parameters from the analysis of experimental time distributions of consecutively detected fusion events has been treated in a general way in a paper by Filchenkov et al. [35], claiming also independence from absolute calibrations.

(4) The measurement of fusion disappearance rates

Fusion events disappear due to sticking faster than the muon decay constant λ_o. For a cycling system (Fig.1), that has reached steady state equilibrium, one can describe the time distribution of fusion events simply by

$$N_f(t) = \phi\,\lambda_c\,e^{-\lambda_n t} \tag{8}$$

where $\phi\lambda_c$ is the cycle rate (see Ref. [8]),

$$\lambda_n = \lambda_o + w\,\phi\,\lambda_c \tag{9}$$

is the fusion or (in our case) the neutron disappearance rate and w the "raw" sticking factor. w is not identical with ω_s, because several fusion channels are present in DT, each contributing to the observed disappearance rate. If impurities x are present, there may be more terms in Eq.9 describing the muon transfer to x, e.g. $\Lambda_x = c_x \phi\,\lambda_x$. The measurement of λ_n in dμt fusion is extremely sensitive to the value of w because of the large cycle rates (we have observed $\lambda_n \sim 2.5\,\lambda_o$ in liquid DT mixtures). It should however be pointed out, that a proper evaluation of DT sticking ω_s from λ_n requires:

- knowledge of the absolute cycle rate (and as an ingredient knowledge of the absolute detector efficiency),
- correction for other fusion channels such as dμd, tμt with sticking $\tilde{\omega}_{dd}, \omega_{tt}$ and (in the presence of protium) pμd, pμt (with ω_{pd}, ω_{pt}) and for transfers to impurities.

If the cycle rate λ_c is split up into rates for each fusion channel:

$$\lambda_c = \lambda_c^{dt} + \lambda_c^{dd} + \lambda_c^{tt} + \lambda_c^{pd} + \lambda_c^{pt} \tag{10}$$

then one gets for raw sticking

$$w\lambda_c = \omega_s\lambda_c^{dt} + \tilde{\omega}_{dd}\lambda_c^{dd} + \omega_{tt}\lambda_c^{tt} + \omega_{pd}\lambda_c^{pd} + \omega_{pt}\lambda_c^{pt} \tag{11}$$

Since sticking values of other channels than dμt are much larger, corrections to w are more significant than to λ_c, and an accurate knowledge of the kinetic system in its steady state becomes essential. Denoting $a_{\mu d}$ and $a_{\mu t}$ the (normalized) steady state populations, the cycle rates can be expressed in terms of mesomolecular formation rates [7], e.g.

$$\phi\lambda_c^{dt} = a_{\mu t}\,\Lambda_{d\mu t} = a_{\mu t}\,\phi[2c_{D_2}\,\lambda_{d\mu t}^{D_2} + c_{DT}\,\lambda_{d\mu t}^{DT}] \tag{12}$$

(note, that the hyperfine structure in principle splits up resonant rates into contributions from each hyperfine level. Such effects have so far only been experimentally verified in resonant dμd formation [13,14].)

On the other hand, the DT cycle rate can also be expressed in terms of rates and parameters of the kinetic scheme given in Fig.1 [7]:

$$\frac{1}{\phi\lambda_c^{dt}} = \frac{P_{1s}}{\Lambda_{dt} + (1 - P_{1s})\Lambda_{d\mu d}} + \frac{1}{\Lambda_{d\mu t}} \tag{13}$$

For the evaluation of DT sticking from w we finally derive:

$$\omega_s = w - \omega_{tt}\frac{\Lambda_{t\mu t}\lambda_f^{tt}}{\Lambda_{d\mu t}(\lambda_f^{tt} + \Lambda_{t\mu t})} - \frac{P_{1s}(\tilde{\omega}_{dd}\Lambda_{d\mu d} + \omega_{pd}\Lambda_{p\mu d})}{\Lambda_{dt} + (1 - P_{1s})\Lambda_{d\mu d}} - \omega_{pt}\frac{\Lambda_{p\mu t}}{\Lambda_{d\mu t}} \tag{14}$$

In conclusion, we have described several (independent) methods of how to investigate sticking. For DT sticking (ω_s) method (4), the analysis of fusion disappearance rates, presents a very promising approach, but requires good calibration and knowledge of the complete cycling system including side channels.

4 Setup of the SIN experiment

Fig. 3 shows the experimental setup used in our DT fusion experiments at SIN and previously described in Refs. [3,7,8]. High density measurements were done with liquid DT mixtures (V=20 cm^3,T=23K) at density $\phi \simeq 1.2$ (ϕ is always given in units of liquid protium $4.25 \cdot 10^{22}/cm^3$). At low density (ϕ=0.005-0.08) gas targets with V=100-1000cm^3 were used at temperatures from 30K to 300K. Tritium concentrations c_t ranged from 2% to 96%.

The main features of event detection were:

- A muon beam telescope ($M_1\,M_2\bar{3}\,\bar{4}\,\overline{ET}_1\,\overline{ET}_2$) defining electronic muon stops. The ratio ϵ_r of real muon stops (in DT) to electronic stops was 64% to 68% in liquid and 6%-40% in gas. It was evaluated using the time spectra of electrons from muon decay. A pileup circuitry rejected events with a second particle hitting counter M_1 + 9 μsec with respect to the muon stop.

- 2 electron telescopes ET_1, ET_2 detecting electrons from muon decay. The overall sensitivity was ϵ_e=38%, but also a small, but significant sensitivity for fusion neutrons of ϵ^n=0.08% was encountered. The time distributions were measured in an 8 μsec wide time range (see Figs.4-6).

- A NE213 liquid scintillation detector with pulse shaping cuircuit for n-γ discrimination (PSD), positioned far enough from the target (up to 113cm) to keep the probability of double neutron hits within the integration time (0.5μsec) at a negligible level (few percent). The proton recoil energy, the PSD signal and the time spectrum were recorded. This detector was previously carefully calibrated in an absolutely monitored 15 MeV neutron beam at GSF (Gesellschaft für Strahlenforschung) Munich and acted as our main calibration instrument. The effects of neutron absorptions and scatterings were carefully studied with Monte Carlo simulations. The absolute precision (including all experimental and electronic uncertainties) was ±8%.

- 5 plastic detectors equipped with a fast routing electronics to handle multiple signals acted as fast neutron detectors (deadtime 50 nsec). The time and proton recoil spectra of up to 4 succeeding hits were recorded (see spectrum Fig.7). The efficiency ϵ_n for detection of a DT fusion neutron was 0.4% per detector, small enough to prevent significant distortions due to dead-time or pileup effects.

- A Ge(Li) diode placed below the target (not shown in Fig.3) detected X-rays from muons stopped in the target walls or transfered from the DT mixture to higher Z impurities. The energy and time spectra were registered.

Various trigger conditions were applied for each target mixture, using simple conditions (e.g. an electron or any neutron signal within an 8 μsec time gate with respect to the muon stop) as well as more complicated schemes (e.g. neutron events delayed to muon stop or in coincidence with an electron signal). Purely accidental events were collected by triggering the electronics without a muon stop. The simple triggers yielded electronically undistorted time distributions, while the special triggers allowed the collection of "precleaned" spectra at high statistics, by taking some electronic distortions into account (see chapter 5). For certain trigger schemes and experimental conditions an appropriate reduction factor was applied for data recording.

5 Analysis of time distributions

The investigation of sticking from disappearance rates necessitates a detailed understanding of experimental time distributions. Although the real time structures are given by simple exponentials $e^{-\lambda_n t}$, see Eq.8, and $e^{-\lambda_0 t}$ (muon decay), the experimentally observed spectra may be more complicated for several reasons:

- After a particle has hit a detector and triggered its electronics, the system is "dead" for a period that may be long on the scale of event rates or muon decay. The detector thus kills itself from detecting further events with a rate

$\epsilon_n \phi \lambda_c$. In the presence of event routing this effect is avoided, but a deadtime Δt has to be considered. This effect is illustrated in Fig.4.

- The electron telescopes - although primarily designed for electron detection as a charged particle coincidence - are also a little bit sensitive to neutrons from fusion. This leads due to the large neutron multiplicities in DT fusion to significant distortions of electron and correlated neutron-electron (ne) spectra. In fact we found experimentally a much larger neutron sensitivity ϵ^n than expected from proton recoils. Only for cycle rates $\lambda_c < 1\mu sec^{-1}$ the observed effects were negligible (for illustrations, see Fig.5).

- Neutron time distributions generated in correlation with an electron signal are usually distorted, because the probability of a (ne) coincidence varies as function of the time after muon stop. A method (adopted by us) to avoid this problem is to collect fusion events by individually requesting for each event a delayed (ne) coincidence in a constant time delay bin with respect to the fusion event (not the muon stop!). Still an additional term $e^{-\epsilon^n \phi \lambda_c t}$ remains due to the "dying out" of the electron detector (unless it is also routed for multiple events). Fig. 6 shows some of the distortion effects due to limited time bins.

Taking into account these effects we derived the following expressions for observable time spectra (which also were carefully checked with Monte Carlo simulations):

Electron time distribution (1. hit), per muon (simple trigger):

$$e_1(t) = \epsilon_r \epsilon_e \lambda_o [\frac{w}{\epsilon^n + w} e^{-\lambda_o t} + \frac{\epsilon^n}{\epsilon^n + w} e^{-\lambda_n' t}] + \epsilon_r \epsilon^n \phi \lambda_c e^{-\lambda_n' t} \tag{15}$$

with

$$\lambda_n' = \lambda_n + \epsilon^n \phi \lambda_c = \lambda_o + (w + \epsilon^n) \lambda_c \tag{16}$$

The same expression holds for an electron time spectrum, that is triggered by a fusion neutron (ne). The time scale is: t = t(e)-t(n).

Neutron time distribution (1. hit), per muon (simple trigger):

$$n_1(t) = \epsilon_r \epsilon_n \phi \lambda_c e^{-(\lambda_n + \epsilon_n \phi \lambda_c) t} \tag{17}$$

Neutron time distribution (k-th hit), per muon (simple trigger):

$$n_k(t) = n_1(t) \frac{[(1-w)\epsilon_n \phi \lambda_c (t - [k-1]\Delta t)]^{k-1}}{(k-1)!} e^{+\epsilon_n \phi \lambda_c \Delta t (k-1)} \tag{18}$$

Neutron time distribution per muon (1. hit) with delayed (ne) correlation:

$$n_1^c(t) = [\int_{\Delta t_{ne}} e_1(t)dt]\, \epsilon_r \epsilon_n \phi \lambda_c \, e^{-[\lambda_n + (\epsilon_n + \epsilon'')\phi\lambda_c]t} \quad (19)$$

In the presence of accidental background some small additional terms are necessary to describe the observations. Fig.5 shows some observed electron time spectra. While in the liquid case (a) all 3 terms of Eq.15 are significant, its in gas (b) the first 2 terms (due to the smaller cycle rates). At t=0 there is an additional component due to muon stops in the target walls, however dying out quickly. This component can be easily avoided by using the (ne) time distributions.

Figures 4, 6 and 7 show neutron time spectra applying to expressions (17) to (19).

6 Results and Discussion

Normalized DT cycle rates λ_c have been evaluated for all experimental conditions, see Refs. [7,8]. From the observed neutron disappearance rates λ_n a set of raw sticking values was extracted by fitting the observed time distributions to the formulas Eq.15 - 19. Different analysis methods were applied, (a) using non coincident spectra (1. hit), (b) coincident spectra, (c) fitting the full set of spectra, separated according to hit number (see Fig.7) and (d) using high discrimination levels (to check for effects of accidental events). All methods yielded for our liquid data raw sticking factors w with a relative consistency of better than 2%. The resulting averaged values for w are displayed in figure 8 (open circles).

The sticking analysis of gas data, on the other hand, is much more difficult for reasons of smaller cycling rates (ϕ dependence, enhanced by density effect!). The effect of sticking $w\phi\lambda_c/\lambda_o$ is reduced from typically 100% (liquid data) to 5% or less for gas data. Distortions of the type discussed above or due to backgrounds become large. Also the time after muon stop, when the kinetic system reaches equilibrium, becomes significantly enlarged (e.g. more than 1 μsec transient times were observed at ϕ=1%), which narrows the time bin of meaningful analysis. At too low density the system may even never reach equilibrium!

For these reasons we have restricted the sticking analysis to the cases of gas data with highest cycle rates and density ($\lambda_c \sim 2 - 5/\mu sec, \phi = 3\% - 8\%$). Preliminairy results are shown in figure 9.

From the w values DT sticking ω_s was obtained by correcting for other fusion channels dμd, tμt, pμd and pμt (the pμd and pμt channels are present, because the mass spectrometer determined about 0.9% protium content in our samples). Expression (14) was taken using kinetic parameters, determined from a fit to the cycle rate distribution [8]. Different fit assumptions in Ref. [8] did not alter the corrections significantly. No corrections were necessary for muon transfers to impurities, because the Ge(Li) spectra yielded upper limits $\delta w < 0.02\%$. The results for ω_s are also given in figures 8 and 9 (closed circles).

As can be seen from the figures, we find no significant dependence of sticking ω_s neither on concentration c_t nor on density ϕ. For the liquid data ($\phi \cong 1.2$) we obtain an average value

$$\omega_s^{LQ} = (0.45 \pm 0.05)\% \tag{20}$$

and for gas ($\phi = 3\%$ - 8%)

$$\omega_s^{GAS} = (0.50 \pm 0.10)\% \tag{21}$$

The given errors include uncertainties from statistics, absolute calibration and from corrections to w. In our liquid data the systematical uncertainties (calibration and corrections) dominate, while in the gas data it is statistics.

From the results (20) and (21) we can form the ratio, to study the ϕ dependence:

$$r = \frac{\omega_s^{GAS}}{\omega_s^{LQ}} = 1.1 \pm 0.2 \tag{22}$$

This expression is independent of most systematical errors, because all data were measured with the same detectors, geometry and method. It agrees well with theoretical expectations [21,22,28].

The dependencies of sticking ω_s on density ϕ and/or concentration c_t, previously reported from the LAMPF experiment [4-6,23] are in disagreement with our results. Especially there is no $\phi\sqrt{c_t}$ dependence in our data. Also the ratio $\omega_s(\phi = 0.12)/\omega(\phi = 1.2) = 3.1 \pm 0.5$ extracted from Ref. [6] disagrees with our observation Eq. (22) by many standard deviations.

In comparison to theoretical expectations [19-22,28] (see table I) our result for ω_s is somewhat lower, setting the maximum fusion output per muon (Eq. 3) to less than 220 ± 20. Our results are in accordance with our X-ray observations [32]. Further work will be necessary on the experimental and on the theoretical side, to clear up present controversies.

Support by the following institutions is gratefully acknowledged: the Austrian Academy of Science, the Austrian Science Foundation, the Swiss Institute for Nuclear Research, the German Federal Ministry for Science and Technology, and the U.S. Department of Energy under Contract No DE-AC03-76SF00098 and AT03-81ER40004. We are indebted to Professors J.P. Blaser and K. Lintner for their continuous support and encouragement. We thank Dr. L. Hansen for the calculation of neutron detector efficiencies at the Lawrence Livermore Laboratory. We thank Drs. Hietl, Schulz and Schraube for providing us an absolutely calibrated neutron beam at GSF Munich. We especially thank the SIN technical staff and the workshop of H. Oschwald for their excellent work and expert assistance.

References

1. V.M.Bystritsky, V.P. Dzhelepov, Z.V. Ershova, V.G. Zinov, V.K. Kapyshev, S.Sh. Mukhamet-Galeeva, V.S. Nadezhdin, L.A. Rivkis, A.I. Rudenko, V.I. Satarov, N.V. Sergeeva, L.N. Somov, V.A. Stolupin, V.V. Fil'chenkov, Phys. Lett. 94B,476 (1980) and JETP 53, 877 (1981).

2. S.E. Jones, A.N. Anderson, A.J. Caffrey, J.B. Walter, K.D. Watts, J.N. Bradbury, P.A.M. Gram, M. Leon, H.R. Maltrud, M. A. Paciotti, Phys. Rev. Lett. 51, 1757 (1983).

3. W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton, P. Pawlek, J. Werner, J. Zmeskal, K.M. Crowe, J. Kurck, A. Janett, C. Petitjean, R.H. Sherman, H. Bossy, W. Neumann, Phys. Rev. Lett. 53, 1137 (1984).

4. S.E. Jones, "Some surprises in muon-catalyzed fusion", presented at the Nineth int. Conference on Atomic Physics, Seattle, Washington, USA, 23 -27 July 1984.

5. S.E. Jones, A.N. Anderson, A.J. Caffrey, C.DeW. Van Siclen, K.D. Watts, J.N. Bradbury, J.S. Cohen, P.A.M. Gram, M. Leon, H.R. Maltrud, M.A. Paciotti, Phys. Rev. Lett. 56,588 (1986).

6. S.E. Jones, "Muon-induced fusion: experiments at LAMPF", proc. Los Alamos Workshop on Fundamental Muon Physics, Jan. 20 - 22, 1986, LA-10714-C, p.157 and progress report presented by A.J. Caffrey to this conference.

7. W.H. Breunlich, M. Cargnelli, J. Marton, N. Nägele, P. Pawlek, A. Scrinzi, J. Werner, J. Zmeskal, J. Bistirlich, K.M. Crowe, M. Justice, P. Kammel, J. Kurck, C. Petitjean, R.H. Sherman, H. Bossy, H. Daniel, T.v. Egidy, J. Hartmann, W. Neumann, H. Schmidt, LBL-Rep. 21174 (1986), proc. Los Alamos Workshop on Fundamental Muon Physics, Jan. 20 - 22, 1986, LA-10714-C, p. 165.

8. W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton, N. Nägele, P. Pawlek, A. Scrinzi, J. Werner, J. Zmeskal, J. Bistirlich, K.M. Crowe, M. Justice, J. Kurck, C. Petitjean, R.H. Sherman, H. Bossy, F.J. Hartmann, W. Neumann, G. Schmidt, LBL-Rep. 21366 (1986), subm. to PR Letters and progress report presented by P. Kammel to this conference.

9. S.S.Gerstein, L.I. Ponomarev, Phys. Lett. 72B, 80 (1977).

10. S.I. Vinitskii, L.I. Ponomarev, I.V. Puzynin, T.P. Puzynina, L.N. Somov, M.P. Faifman, JETP 47, 444 (1978).

11. L.I. Ponomarev, Atomkernenergie 43, 175 (1983).

12. V.M. Bystritskii, V.P. Dzhelepov, V.I. Petrukhin, A.I. Rudenko, L.N. Somov, V.M. Suvorov, V.V. Fil'chenkov, G. Hemnitz, N.N. Khovanskii, B.A. Khomenko, D. Horvath, JETP 49, 232 (1979).

13. P. Kammel, W.H. Breunlich, M. Cargnelli, H.G. Mahler, J. Zmeskal, W.H. Bertl, C. Petitjean, W.J. Kossler, Phys. Lett. 112B, 319 (1982) and

P. Kammel, W.H. Breunlich, M. Cargnelli, H.G. Mahler, J. Zmeskal, W.H. Bertl, C. Petitjean, Phys. Rev. A28, 2611 (1983).

14. J. Zmeskal, W.H. Breunlich, M. Cargnelli, H. Fuhrmann, P. Kammel, J. Marton, P. Pawlek, J. Werner, W.H. Bertl, C. Petitjean, Atomkernenerie 43, 193 (1983) and contribution to this conference.

15. Yu.V. Petrov, Nature 285, 466, (1980),

Yu.V. Petrov, E.G. Sakhnovsky, Atomkernenergie 46, 25 (1985) and

Yu.V. Petrov, contribution to this conference.

16. S.S. Gershtein, Yu. V. Petrov, L.I. Ponomarev, L.N. Somov, M.P. Faifman, JETP 51, 1053 (1980).

17. J.D. Jackson, Phys. Rev. 106, 330 (1957).

18. S.K. Kauffmann, B. Müller, J. Rafelski, UCT-TP 16, (1984) (unpublished).

19. D. Ceperly and B.J. Alder, Phys. Rev. A31, 1999 (1985).

20. L.N. Bogdanova, L. Bracci, G. Fiorentini, S.S. Gerstein, V.E. Markushin, V.S. Melezhik, L.I. Menshikov, L.I. Ponomarev, Nucl. Phys. A454, 653 (1986).

21. L.I. Menshikov, L.I. Ponomarev, Pis'ma Zh. Eksp. Teor. Fiz. 41, 511 (1985) [Sov. Phys. JETP Lett.41, 623 (1985)].

22. H. Takahashi, BNL Preprint BNL 37714 (1986), Fusion Technology 9, 328 1986, Phys. Lett. B174, 133 (1986) and contribution to this conference.

23. J.S. Cohen, M. Leon, Phys. Rev. A33, 1437 (1986).

24. L.N. Bogdanova, V.E. Markushin, V.S. Melezhik, L.I. Ponomarev, Zh. Eksp. Teor. Fiz. 83, 1616 (1982) [Sov. Phys. JETP 56, 931 (1982)].

25. S.S.Gerstein, Yu.V. Petrov, L.I. Ponomarev, N.P. Popov, L.P. Presnyakov, L.N. Somov, Zh. Eksp. Teor. Fiz. 80, 1960 -1699 (1981)[Sov. Phys. JETP 53, 872 (1981)].

26. L. Bracci, G. Fiorentini, Nucl. Phys. A364, 383 (1981).

27. Chi-Yu Hu, UCRL preprint 94504, Livermore, April 1986.

28. J.S. Cohen, private communication and contribution to this conference.

29. D.V. Balin, A.I. Ilyin, E.M. Maev, A.A. Markov, V.I. Medvedev, E.M. Orishchin, G.E. Petrov, L.B. Petrov, V.I. Poromov, G.L. Sokolov, g.G. Semenchuk, Yu.V.Smirenin, N.A. Timofeev, A.A. Vorobyov, Yu.K. Zalite, Leningrad preprint 895 (1983).

D.V. Balin, E.M. Maev, V.I. Medvedev, G.G. Semenchuk, Yu.V. Smirenin, A.A. Vorobyov, An.A. Vorobyov,Yu.K. Zalite, Phys. Lett. 141B, 173 (1984).

30. A.N. Anderson, S.E. Jones, M. Leon, Los Alamos Research Proposal, (1985).

31. H. Bossy, H. Daniel, F.J. Hartmann, W. Neumann, G. Schmidt, T. von Egidy, W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton, N. Nägele, J. Zmeskal, C. Petitjean, Phys. Rev. Lett. 55, 1870 (1985).

32. H. Bossy, H. Daniel, F.J. Hartmann, W. Neumann, H. Pendl, G. Schmidt, T. von Egidy, W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton, N. Nägele, A. Scrinzi, J. Werner, J. Zmeskal, C. Petitjean, contribution to this conference.

33. K. Nagamine, private communication and contribution to this conference.

34. W.H. Breunlich, M. Cargnelli, P. Kammel, J. Marton, N. Nägele, J. Werner, J. Zmeskal, C. Petitjean, J. Bistirlich, K.M. Crowe, J. Kurck, R.H. Sherman, H. Angerer, H. Bossy, F.J. Hartmann, W. Neumann, G. Schmidt, "Muon Catalyzed tt-Fusion", contribution to this conference.

35. V.V. Filchenkov, L.N. Somov, V.G. Zinov, Nucl. Instr. and Meth. 228, 174 (1984)

36. J. Rafelski, B. Müller, Phys. Lett. 164B, 223(1985)

37. M. Danos, B. Müller, J. Rafelski, ANR 302L-3 (1986), submitted to Phys. Rev. A

Table Captions

Table I List of theoretical values for "initial" DT sticking ω_s^o, reactivation R and final DT sticking ω_s.

Table I

	ω_s^o [%]	R	ω_s [%]	
J.D. Jackson,[17](1957)	∼ 1	0.22	∼ 0.8	B.O. approx.
S.S. Gerstein et al.,[25](1980)	1.12	0.23	0.86	"
L. Bracci and G. Fiorentini,[26](1981)	1.2 ± 0.1	0.24^{+}	0.91	"
S.K. Kauffmann et al.,[18](1981)	0.02 %			method questioned[21]
D. Ceperly and B. Alder,[19](1985)	0.895 (4)*			MC method
L. Bogdanova et al.,[20](1985)	0.848 (25)*		0.58	B.O. + S. approx.
L. Menshikov and L. Ponomarev, [21](1985)		0.32^{+}		incl. multistep ionis.
H. Takahashi,[22](1986)		0.24^{+}		" " "
J. Rafelski and R. Müller, [36](1985)	0.33 - 0.9			incl. res. doorway state
M. Danos et al.,[37](1986)	0.5 - 0.9			incl. sens. to dt-res. par.
Chi-Yu Hu,[27](1986)	0.897 * 0.25 ++			MC method dμt s states " " dμt (1,0) p states
J.S. Cohen, [28] (1986)	(0.87)	0.393	0.53	ϕ = 1.2

* $\omega_s^{i,n}$ separately listed

+ density dependence given

Figure Captions

Figure 1 Kinetic cycles of muon catalyzed fusion in DT mixtures (simplified scheme). $P_{1s} = c_d\, q_{1s}$[11] and Λ_{dt} determine the muon transfer. $\Lambda_{d\mu d}, \Lambda_{d\mu t}$ and $\Lambda_{t\mu t}$ are the effective rates for mesomolecule formation. $\tilde{\omega}_{dd}, \omega_s$ and ω_{tt} are the sticking probabilities after fusion. For a more detailed discussion see Refs. [7,8].

Figure 2 Level scheme and transition rates of the dμt mesic molecule (from Ref. [24]) leading to fusion. Initial sticking factors ω_s^o are from Refs.[20,27].

Figure 3 Experimental setup used in liquid and gaseous DT measurements: Target (T), insulation vacuum (I), muon telescope (M_1, M_2,3,4), neutron detectors B_1-B_5, (plastic, sizes 25 cm x 5 cm x 5 cm) and NE 213 (liquid, Ø x d = 12.7 cm x 10 cm), electron telescopes (ET_1, ET_2).

Figure 4 Time spectra of neutron disappearance from one of the fast plastic detectors, measured with liquid DT.

a) sum of first 4 neutron hits ($\lambda \sim \lambda_n = \lambda_o + w\phi\lambda_c$, see Eqs. 17 and 18)

b) first neutron hit only ($\lambda = \lambda_n + \epsilon_n\phi\lambda_c$, see Eq. 17)

c) first neutron hit with delayed (ne) correlation (Eq. 19).

Figure 5 Time spectra of electrons from muon decay, measured

a) in liquid DT ($\phi = 1.2$, $c_t = 36$ %)

b) in gaseous DT ($\phi = 7.8$ %, $c_t = 34$ %)

Figure 6 Time spectra of neutrons from one of the gas runs

a) all neutron hits, simple trigger ($\lambda = \lambda_n$). The spike at t=0 is due to muon stops in the target wall.

b) neutrons with delayed (ne) coincidence [0.3 - 3 μsec] ($\lambda = \lambda_n + \epsilon^n\lambda_c$)

c) accidental background, measured with a fake trigger.

Figure 7 Time spectra of fusion neutrons, observed subsequently in one of the plastic detectors (1.-4. hit) and fitted curves using Eqs. 17 and 18.

Figure 8 Experimental results of observed "raw" sticking w (open circles) and corrected DT sticking ω_s (closed circles) in liquid DT mixtures at densities $\phi \cong 1.2$.

Figure 9 Preliminary experimental results for raw sticking w (open circles) and corrected DT sticking ω_s (closed circles) obtained in gaseous DT at densities $\phi = 3\% - 8\%$.

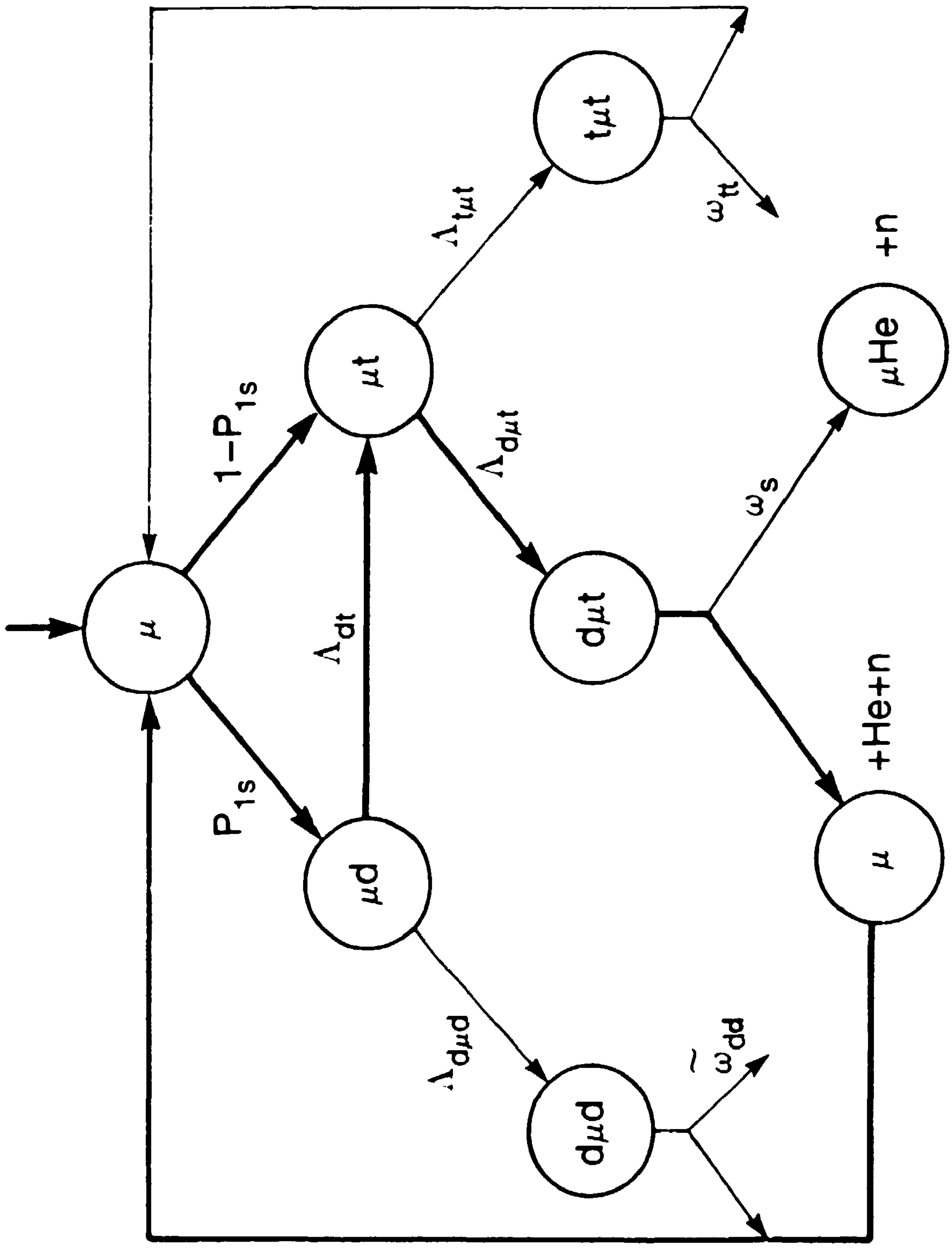
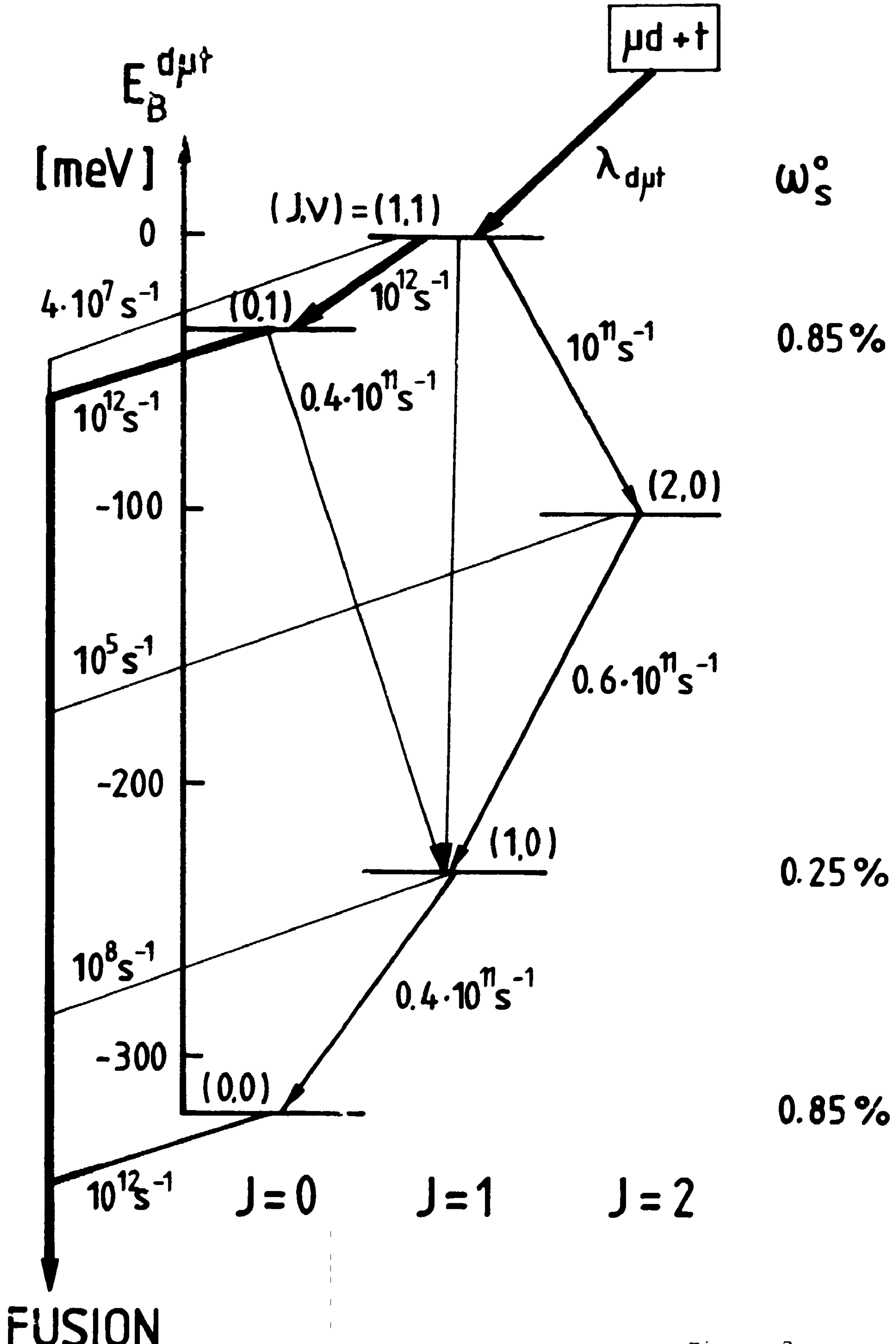

μ
1−P1s
P1s
μt
μd
Λdt
Λtμt
Λdμt
Λdμd
tμt
dμt
dμd
ωtt
ωs
ω̃dd
μHe
+n
+He+n
μ

Figure 1



μd + t
$E_B^{d\mu t}$
[meV]
$\lambda_{d\mu t}$
ω_s^o
(J,v) = (1,1)
0
$4\cdot10^7 s^{-1}$
(0,1)
$10^{12} s^{-1}$
$10^{11} s^{-1}$
0.85 %
$10^{12} s^{-1}$
$0.4\cdot10^{11} s^{-1}$
(2,0)
-100
$10^5 s^{-1}$
$0.6\cdot10^{11} s^{-1}$
-200
(1,0)
0.25 %
$10^8 s^{-1}$
$0.4\cdot10^{11} s^{-1}$
-300
(0,0)
0.85 %
$10^{12} s^{-1}$
J = 0
J = 1
J = 2
FUSION

Figure 2

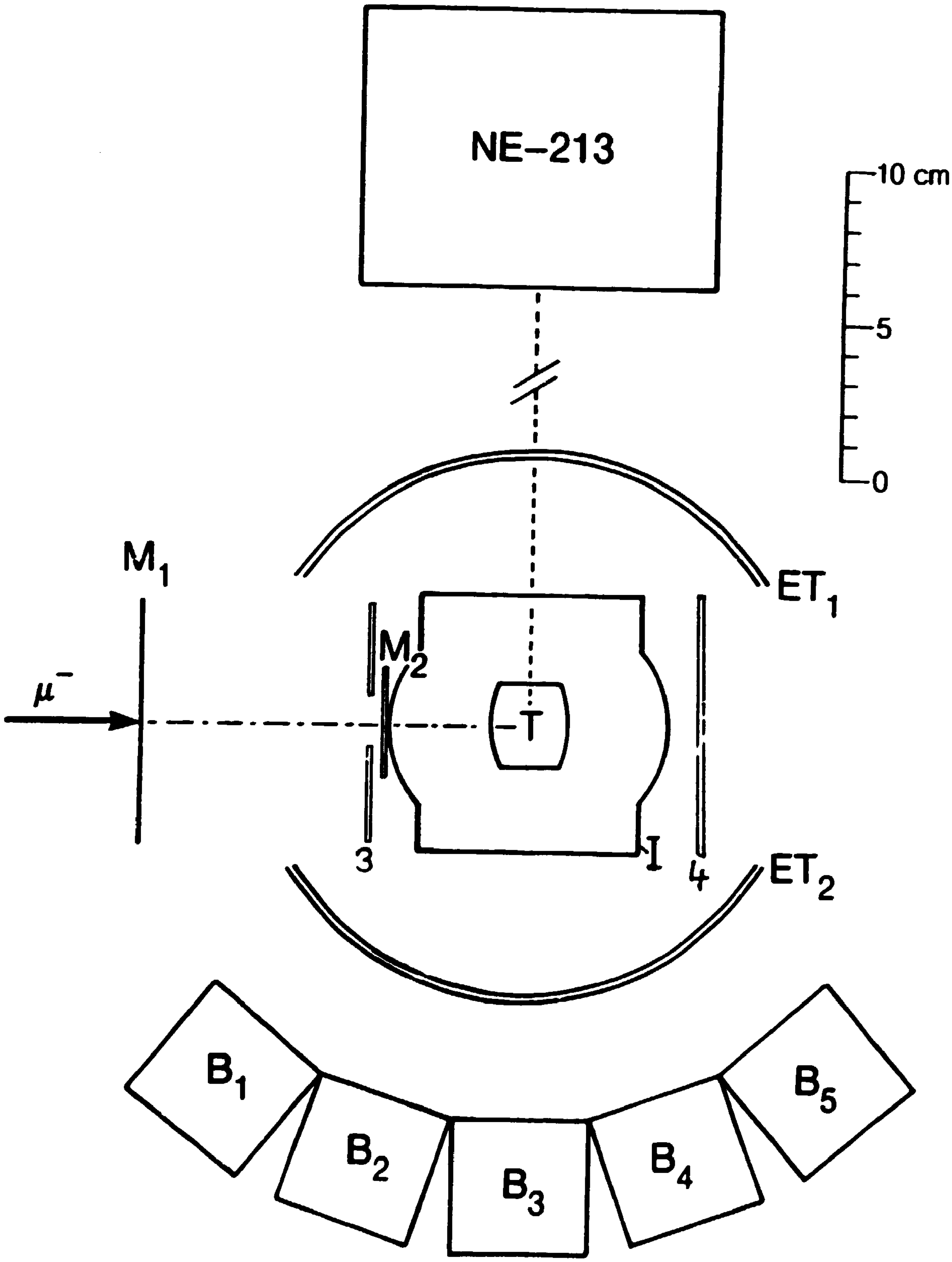


Figure 3

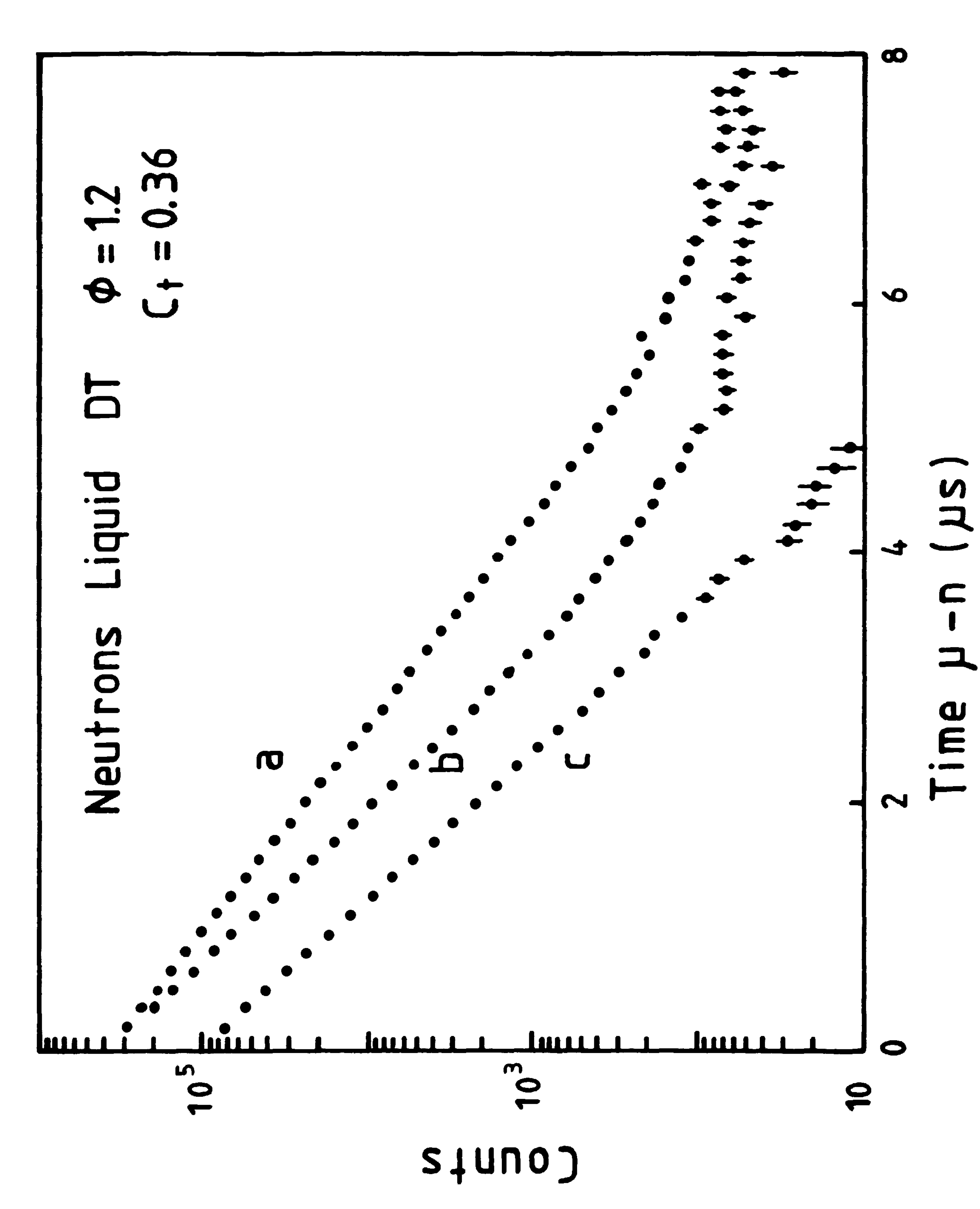

Neutrons Liquid DT
Φ = 1.2
Ct = 0.36
a
b
c
Time μ-n (μs)
0
2
4
6
8
Counts
10^5
10^3
10

Figure 4

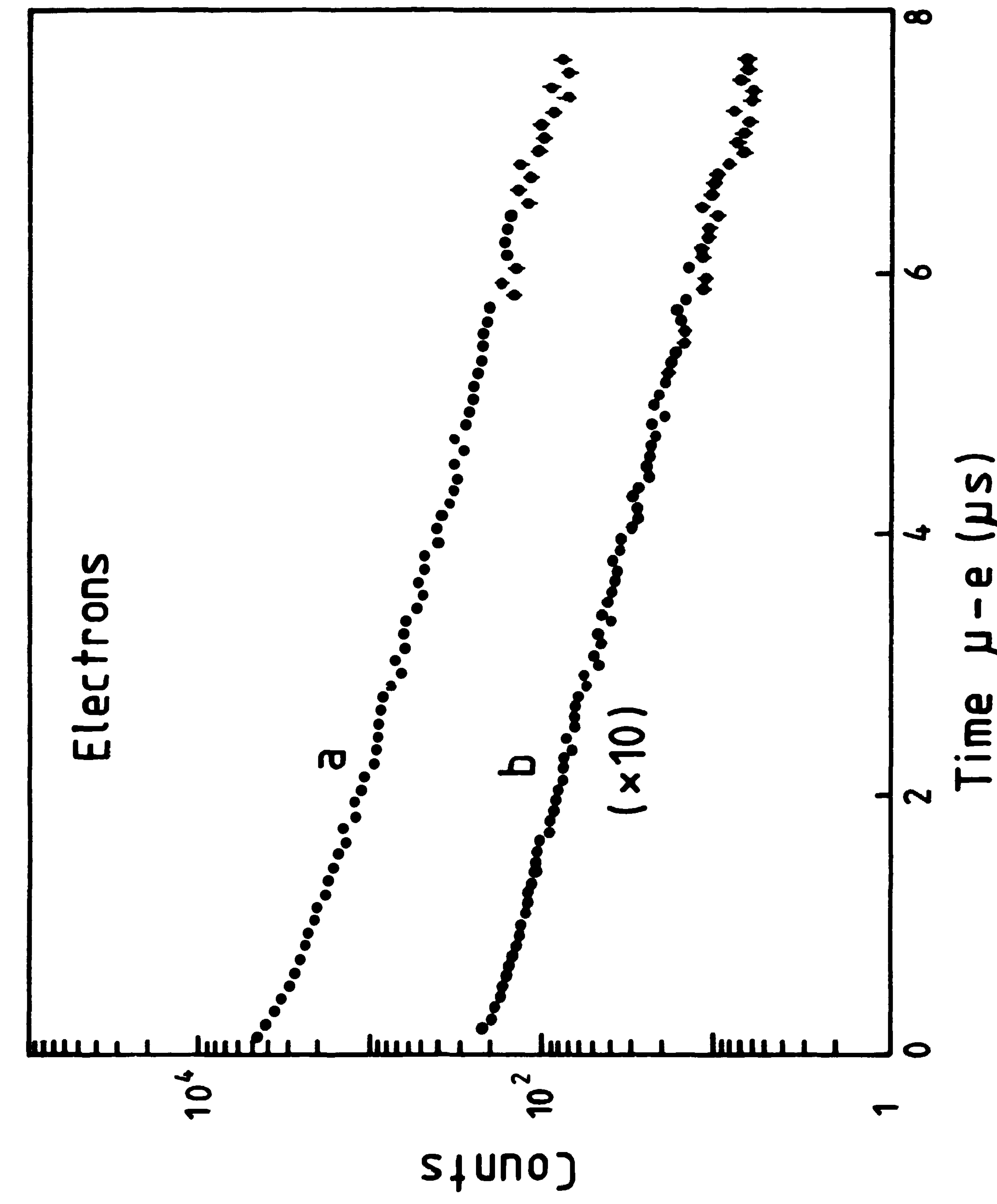
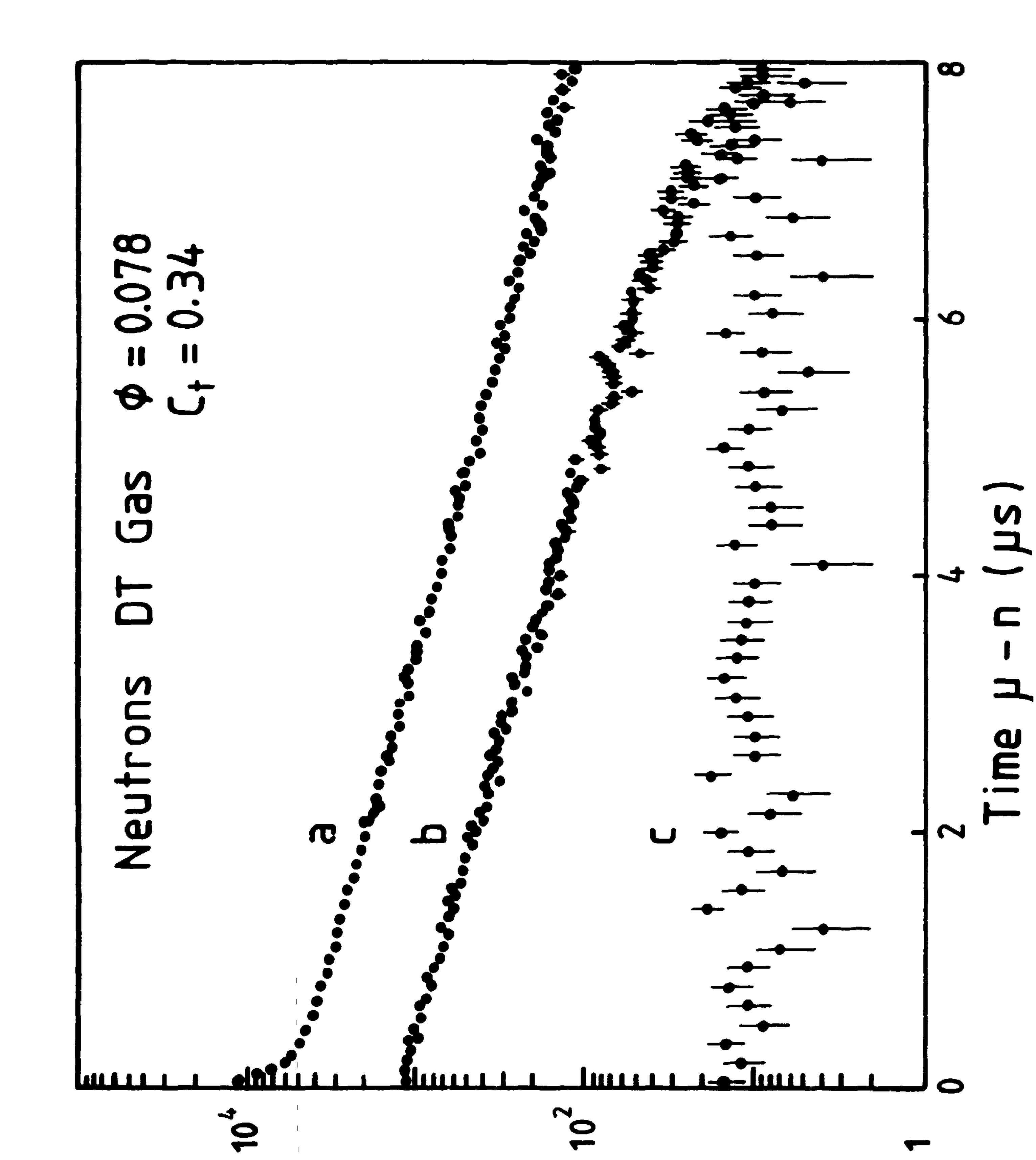
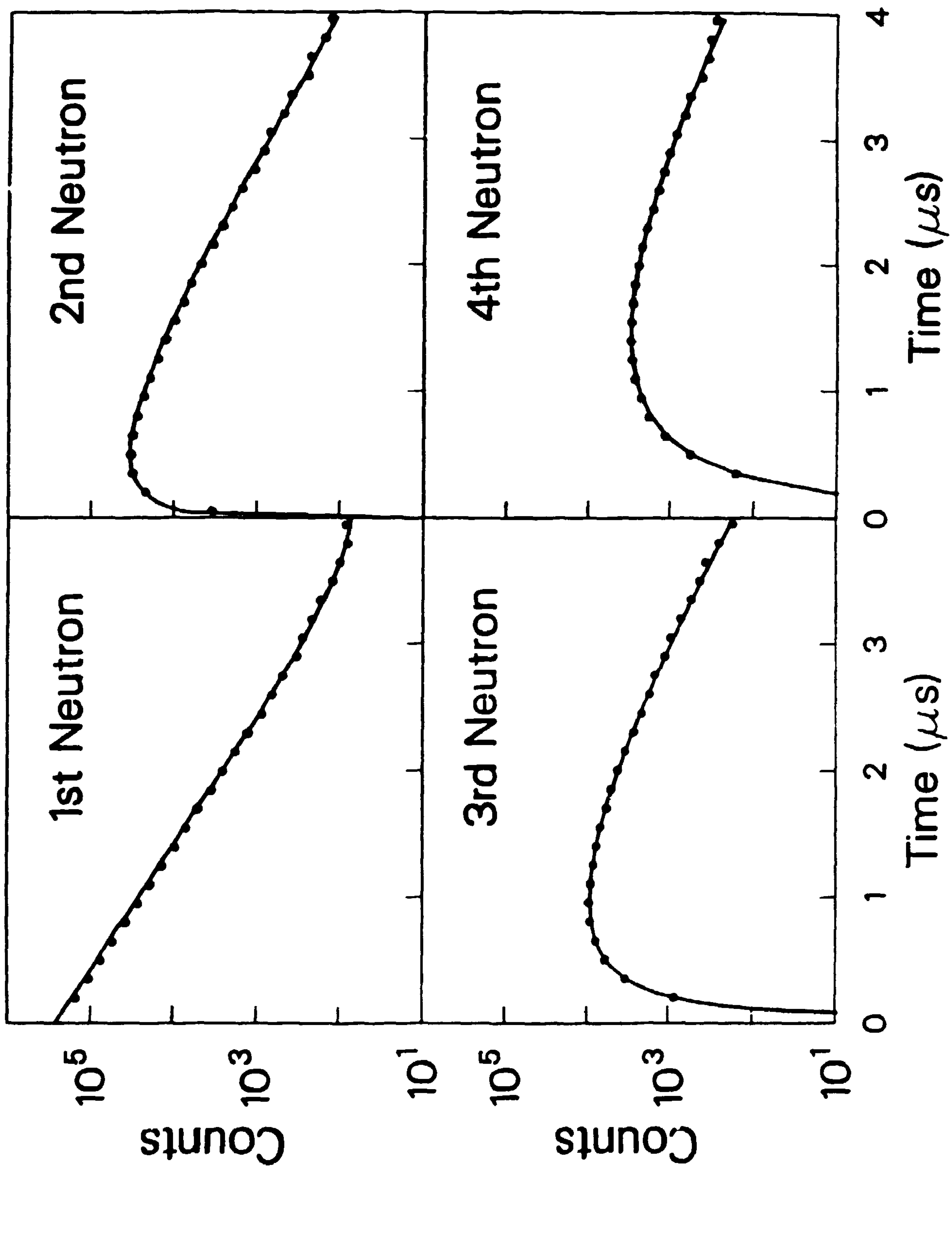


Figure 5



Neutrons DT Gas
Φ = 0.078
C_t = 0.34
a
b
c
Counts
10^4
10^2
1
0
2
4
6
8
Time μ-n (μs)

Figure 6



1st Neutron
2nd Neutron
3rd Neutron
4th Neutron
Counts
Counts
10^5
10^3
10^1
10^5
10^3
10^1
0
1
2
3
4
Time (μs)
Time (μs)

Figure 7

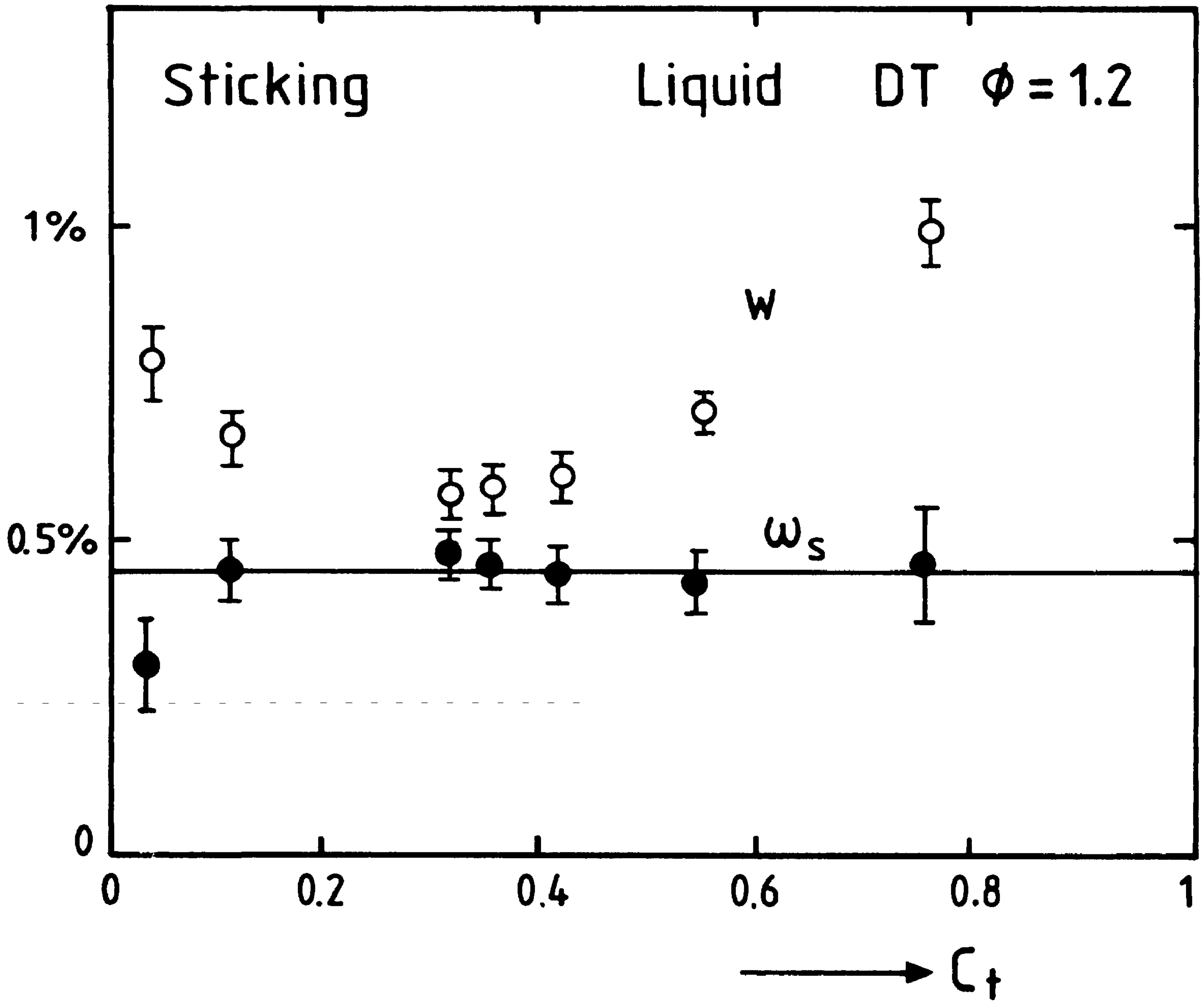


Figure 8

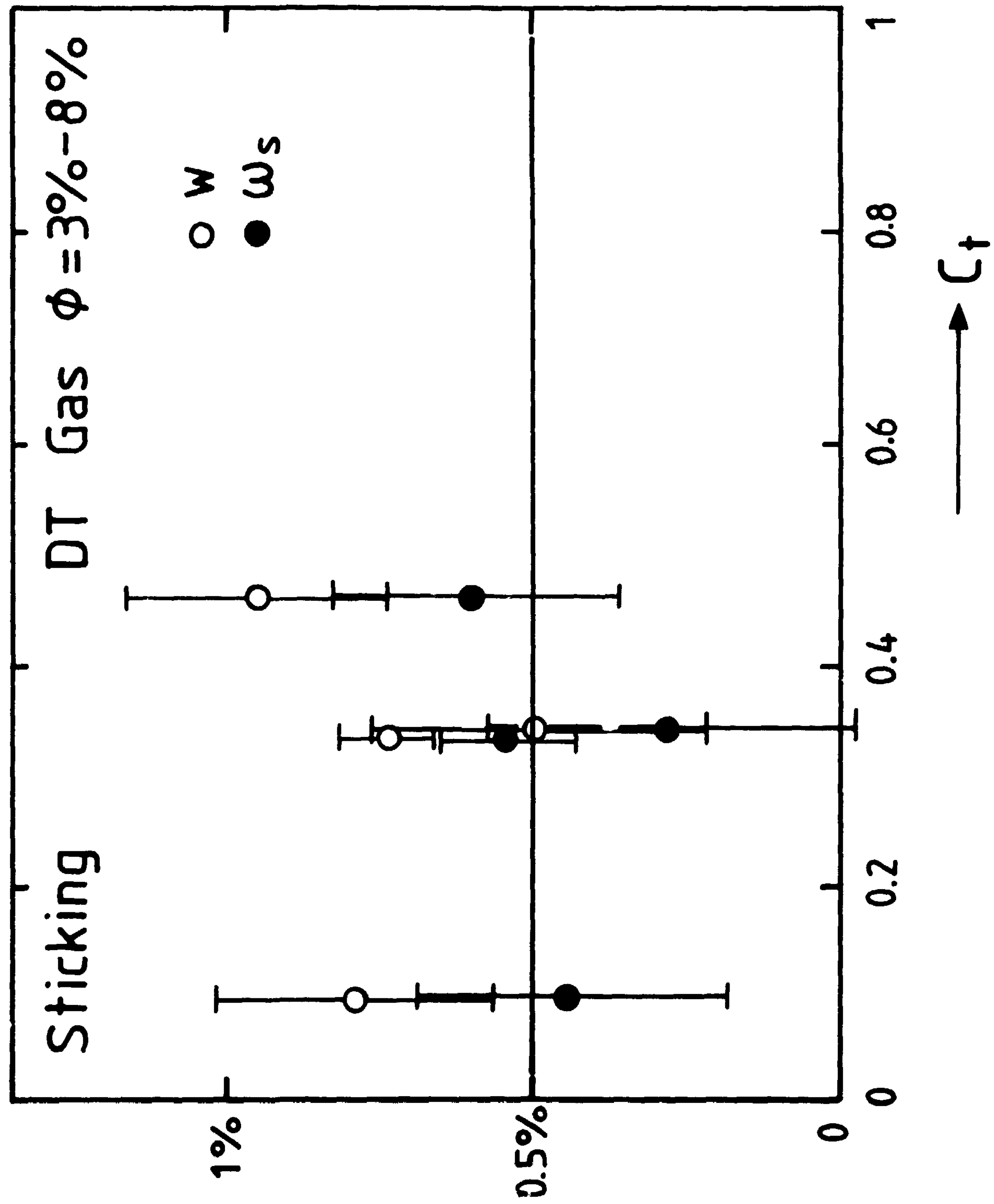


Figure 9