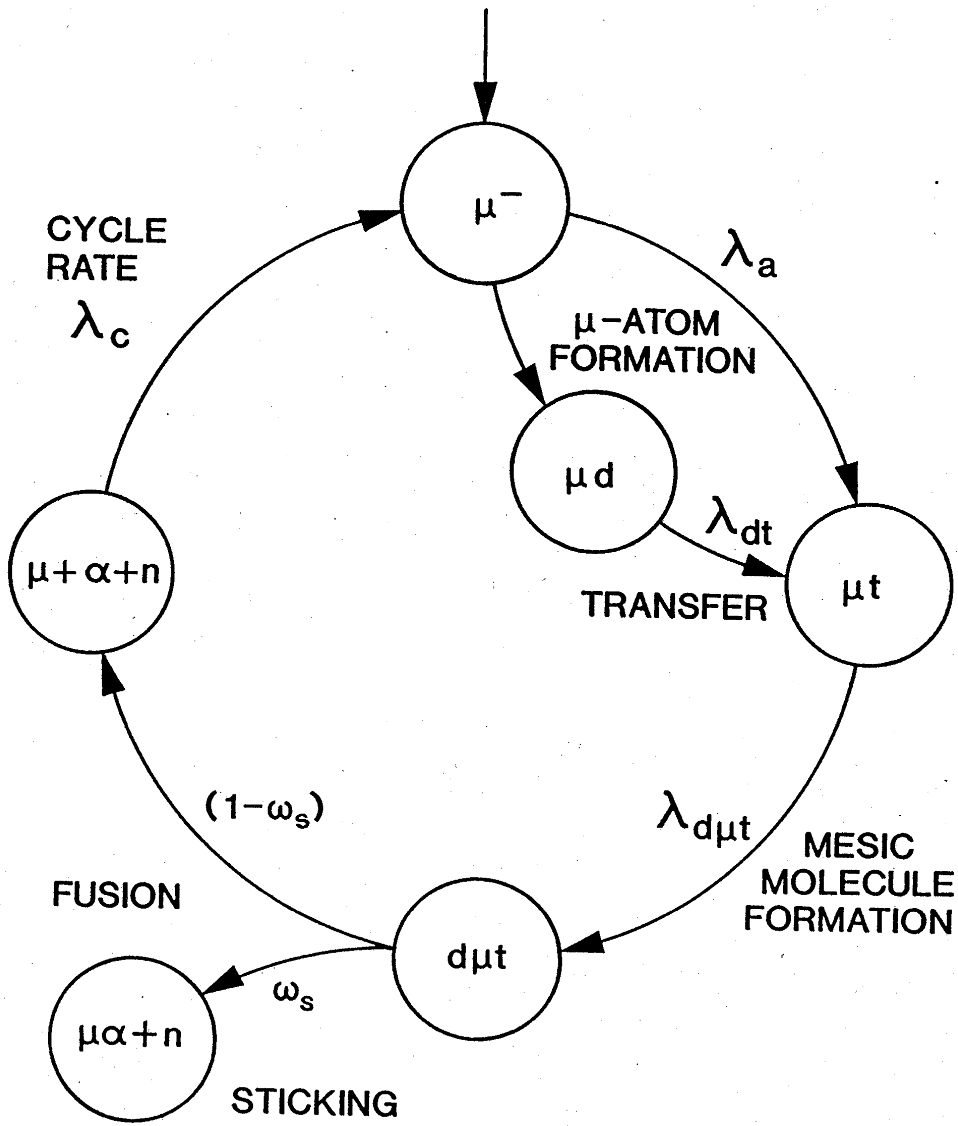
Review of Muon-Catalyzed Deuterium-Tritium Experiments



International Conference on Muon Catalyzed Fusion and Related Topics

MCF-07

Dubna, June 18-21 2007

presented by

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Paul Scherrer Institute

outline of talk

- review of important D-T μCF experiments & results 1979 – 2005
  from DUBNA, LAMPF, PSI, KEK/Tokyo, TRIUMF, RIKEN/RAL
  (presented in historical order)

  (I) cycle & molecular formation rates

  λ_c, $\lambda_{dt\mu}$, etc. are „reduced rates" normalized to
  liquid hydrogen density (φ = 1 ∞ 4.25 10^{22} atoms/cm^3)
  observed rates are defined as $\Lambda_c = \varphi\,\lambda_c$, $\Lambda_{dt\mu} = \varphi\, c_d\, \lambda_{dt\mu}$, etc.

  (II) the μα sticking experiments & methods

  ω_s is the final sticking probability after dtμ fusion
  w is the „effective sticking" = observed muon loss per cycle

- comparison of results & open problems – discussion - conclusions

I. the fast dtμ fusion: discovery

- **1977 Dubna** theorists (S.S.Gerstein, L.I.Ponomarev, Phys Lett. 72B (1977) 80 Vinitskii et al., JETP 47 (1978) 444.) predict existence of dtμ analogue process to resonant ddμ formation:

  $[d\mu t_{(1,1)}dee]$ molecular state with ultra-fast kinetic rates

  $\lambda_{dt\mu} \sim 10^8 s^{-1}$, $\lambda_f \sim 10^{11} s^{-1}$, $\omega_s \sim 1\%$ → $Y_f \sim 100$ fusions/μ

- **1979 Dubna** experimenters (V.P. Dzhelepov, V.M. Bystritsky et al., JETP Lett. 31 (1980) 228, Phys. Lett. 94B (1980) 476.) confirm prediction by first D-T experiment (c_t, φ < 0.1 - T: 93K - 613K):

  mesomolecule formation rate $\lambda_{dt\mu} > 10^8 s^{-1}$

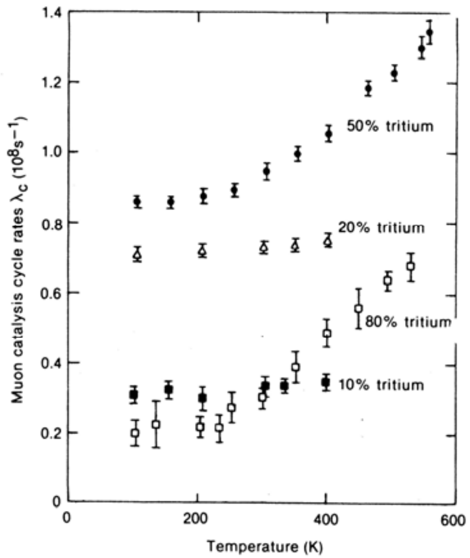
  μd → μt transfer rate $\lambda_{dt} = 2.9 \pm 0.4 \; 10^8 s^{-1}$

- **1981 LAMPF and PSI** laboratories prepare large dtμ experiments

LAMPF 1983: first dtμ fusion results

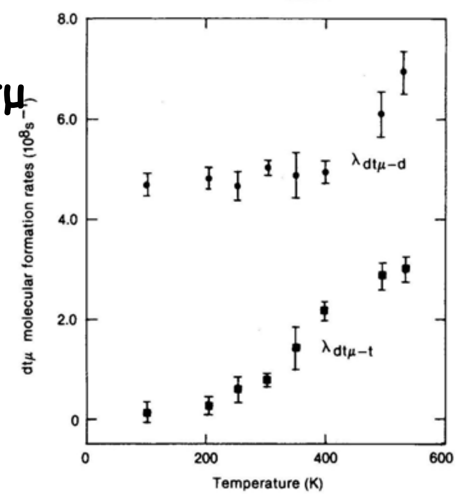
cycle rate

λ_c



molecular formation

$\lambda_{dt\mu}$



temperature T (K)

S.E. Jones et al., PRL 51 (1983) 1757, PRL 56 (1986) 58.

first high yield D-T experiments at
φ = 0.45 - 0.60, T = 100-540 K

strong temperature effects observed!

cycle rates: $\lambda_c^{max} = 1.4\ 10^8\ s^{-1}$

effective sticking: $w = 0.77 \pm .08\ \%$

projected max. fusion yield (φ=1, 540K) :

$Y_f \sim 90$ fusions/μ

meso-molecular formation rates on

D_2 molecule: $\lambda_{dt\mu-d}(T)$ 4 → 7 $10^8 s^{-1}$

DT molecule: $\lambda_{dt\mu-t}(T)$ 0 → 3 $10^8 s^{-1}$

PSI 1983: first dtμ fusion results

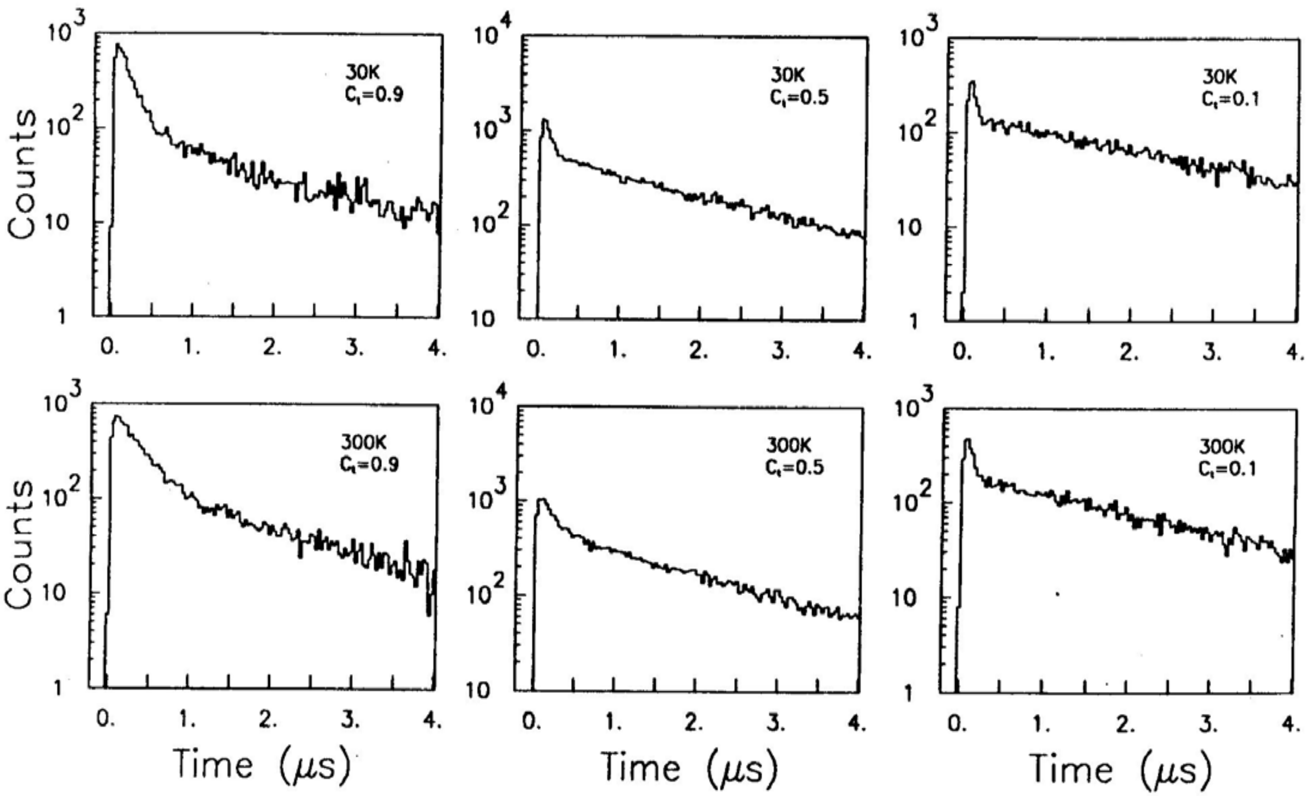
fusion rates at low density $\varphi = 0.01$, $T = 30\text{-}300$ K

W.H. Breunlich et al., PRL 53 (1984) 1137, MCF 1 (1987) 67.

M. Jeitler et al., Phys. Rev. A51 (1995) 2881.

steady state: $\lambda_c^{max} = 0.55\ 10^8\ s^{-1}$ $\lambda_{dt\mu-d} = 1.0\text{-}1.3\ 10^8 s^{-1}$

initial peaks: $\lambda_{dt\mu} \gg 10^8\ s^{-1}$ at epithermal μt energies ($\varepsilon_{\mu t} \sim$ eV)



time spectra of dt fusion neutrons

with

steady state slopes and initial peaks due to thermalisation during first μs!

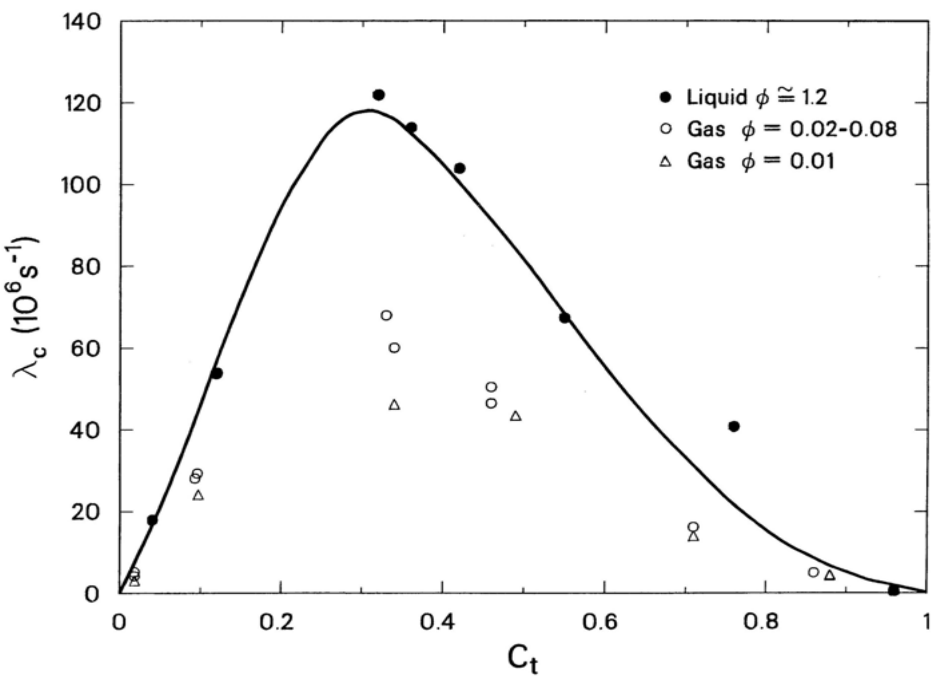
PSI 1984: first high yield data in D-T liquid & gas

W.H. Breunlich et al., PRL 58 (1987) 329, MCF 1 (1987) 67
P. Ackerbauer et al., Nucl. Phys. A 652 (1999) 311

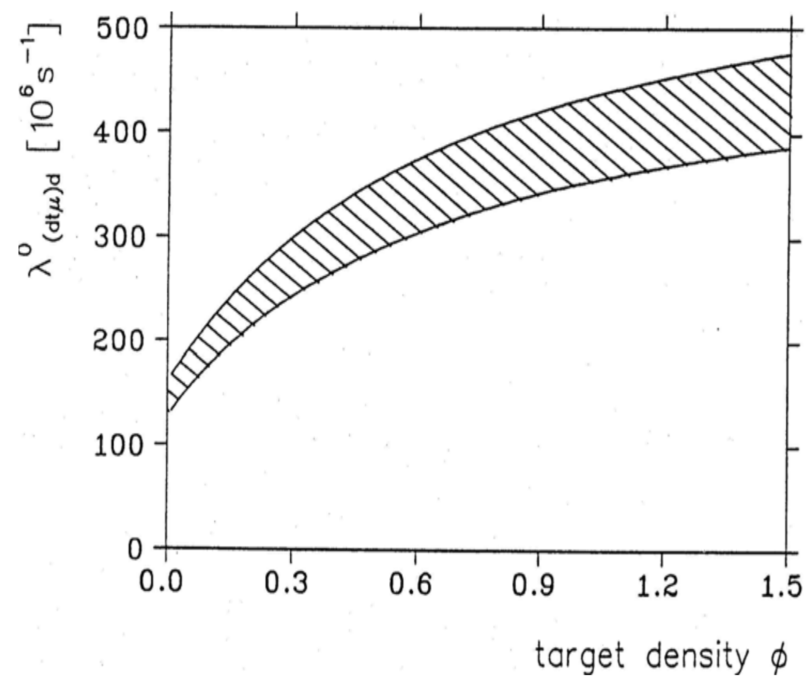
strong density effects at low temperature observed

in liquid D-T at 20K, density φ = 1.2: $\lambda_c^{max} = 1.2\ 10^8\ s^{-1}$

Y_f = 113 fusions/μ $\lambda_{dt\mu\text{-}d}(\varphi) = 1.5 - 4\ 10^8 s^{-1}$



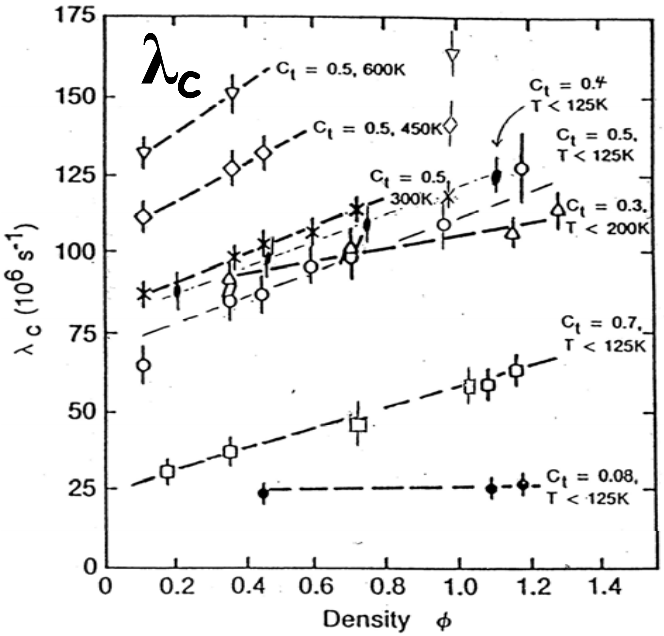
λ_c vs. c_t at various φ

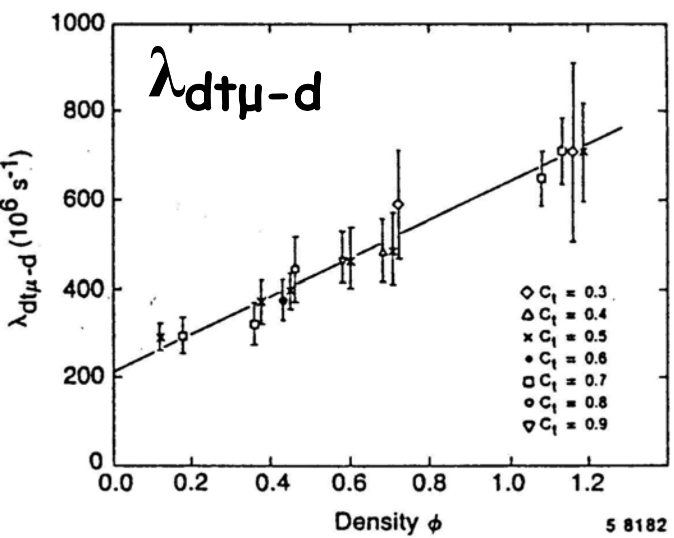


$\lambda_{dt\mu\text{-}d}$ vs. φ

LAMPF 1985/86: S.E.Jones reports new surpsises

record cycle rates & yields S.E. Jones et al., PRL 56 (1986) 588.





φ: 0.1 → 1.2, T: 20 K → 600 K

strong temperature & density effects seen

λ_c^{max} = 1.5 10^8 s^{-1} (600K)

$\lambda_{dt\mu-d}$ (φ) = 2 - 7 $10^8 s^{-1}$

highest observed yield published:

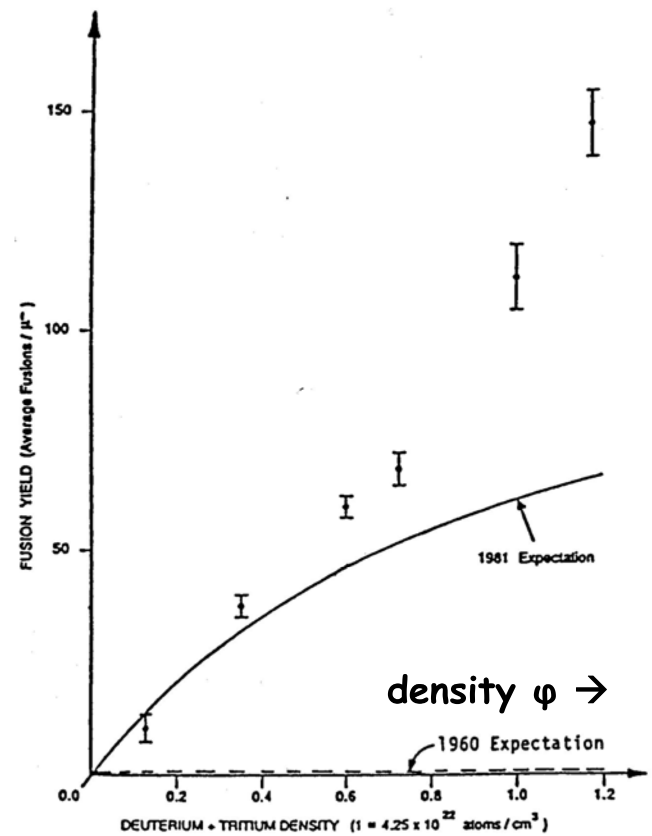
Y_f ~ 150±20 f/μ

in liquid D-T with φ = 1.2, c_t= 0.3

λ_c = 1.1 $10^8 s^{-1}$

w = 0.35 % (?)

start of sticking controversy!

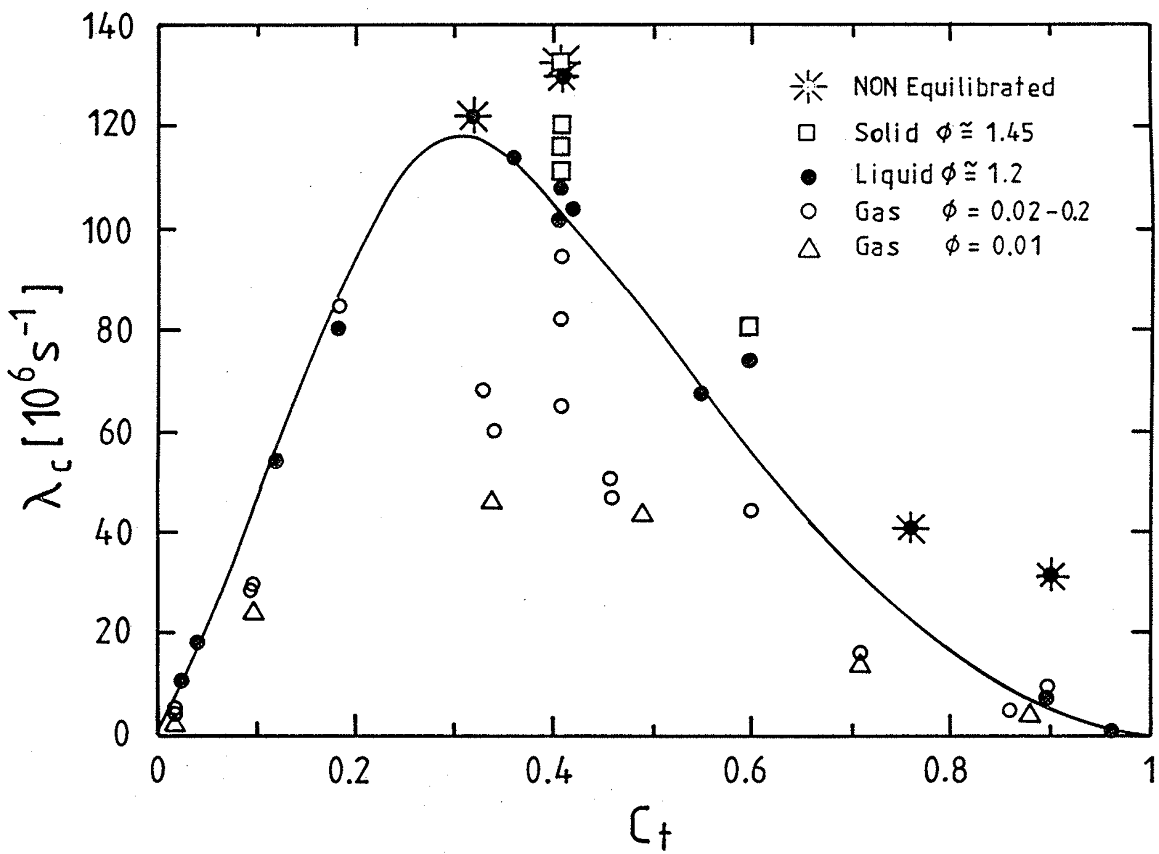


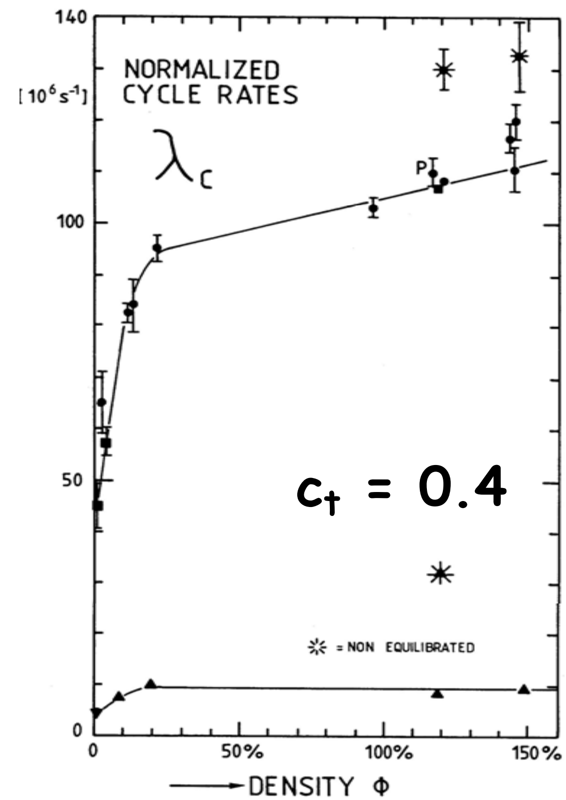
PSI 1987: new survey in solid, liquid & gaseous D-T

φ = 0.1-1.45, T = 12-30 K, non-equilibrated D_2+T_2

C. Petitjean et al., MCF 2 (1988) 37, Hyp.Int.82 (1993) 273,
P. Ackerbauer et al., Nucl. Phys. A 652 (1999) 311.

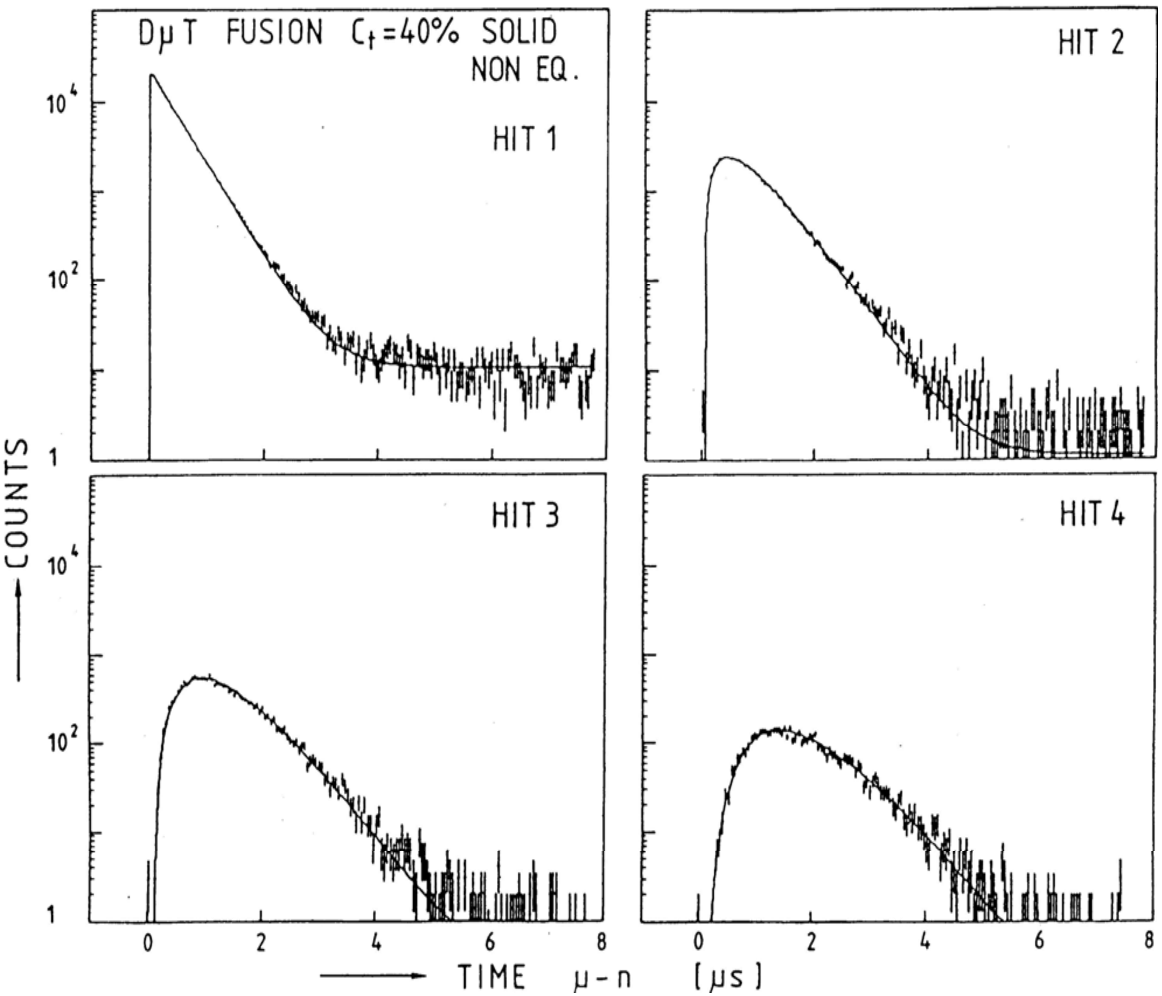
λ_c^{max} = 1.3 10^8 s^{-1} strong density effects confirmed!
Y_f = 124 fusions/μ in solid non-equilibrated mixture





PSI 1987: the highest observed fusion yield

14-MeV neutron spectra from ultra-fast dμt cycle



multi-hit time distributions after μ stop

solid D_2-T_2 at 12K
non-equilibrated
40%-60% mixture

Λ_c = 1.95 $10^8 s^{-1}$

φ = 1.45

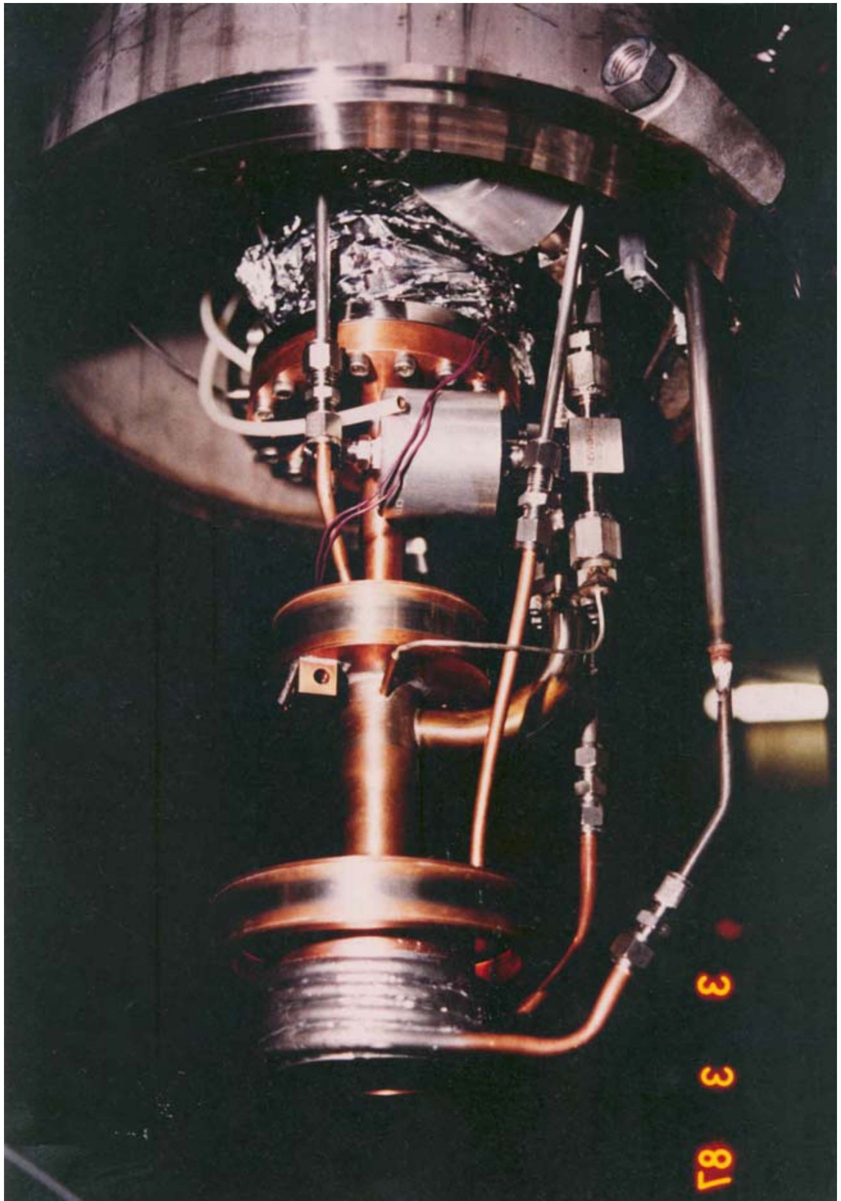
w = 0.568 %

ω_s = 0.48(4) %

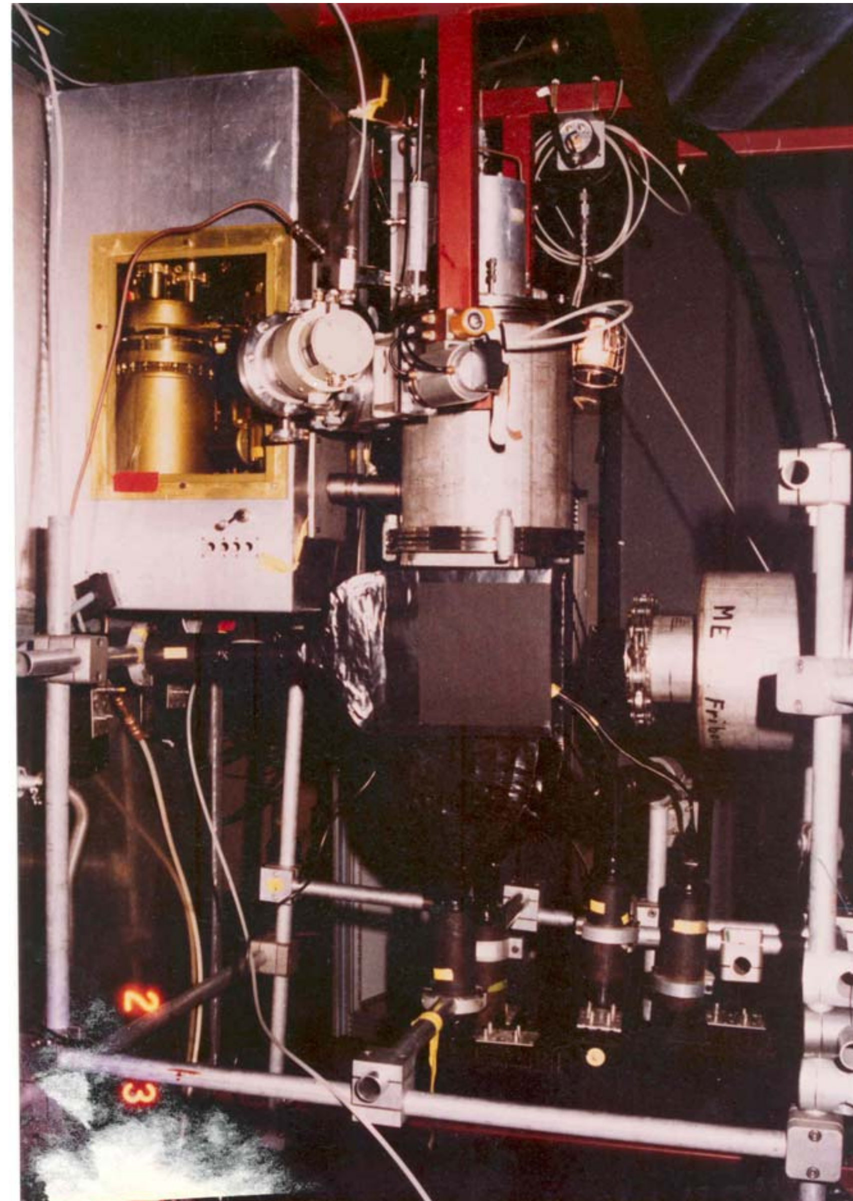
Y_f = 124 ± 10

(presented 1987 at Gatchina μCF conference)

PSI apparatus in 1987



tritium cryotarget (20 cm^3)



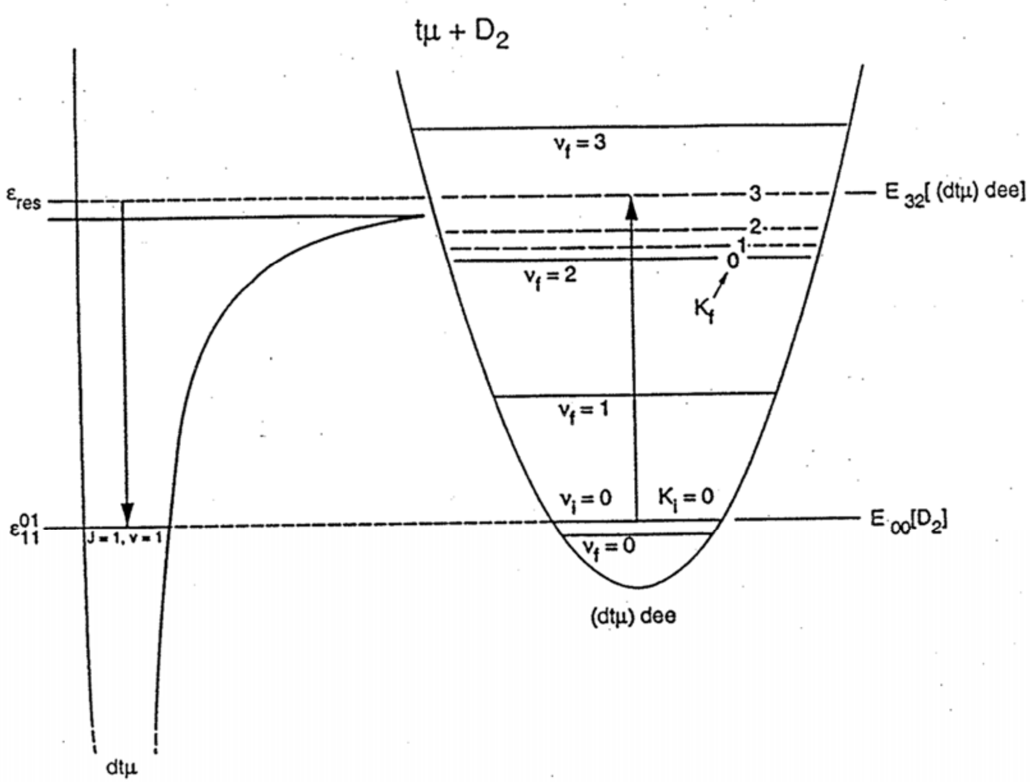
scint-counters & gas system (part)

interpretation of $\lambda_{dt\mu-d}$ - $\lambda_{dt\mu-t}$ behaviour

main $\nu_f=2$ resonances $t\mu + D_2 \rightarrow [d\mu t_{(1,1)}dee]$ are just below threshold (-14 meV, -4.3 meV)

→ increased in non-equilibrated D_2+T_2 mixtures
→ density dependence due to triple collisions
→ $\lambda_{dt\mu-d}$ large at low temperature

on the other hand: $t\mu + DT \rightarrow [d\mu t_{(1,1)}tee]$ $\nu_f=3$ resonant at +164 meV
→ $\lambda_{dt\mu-t}$ large at high temperatures (~ 1000 K)



level schemes showing Vesman mechanism in the $t\mu + D_2$ system

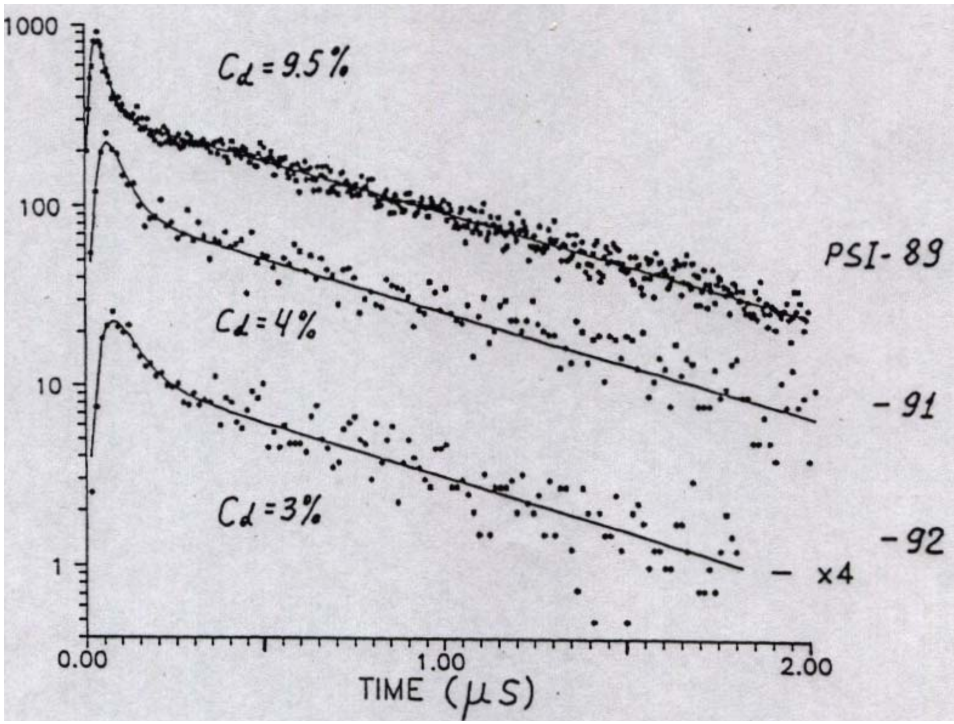
← ε_{11} = -596 meV (Faifman)

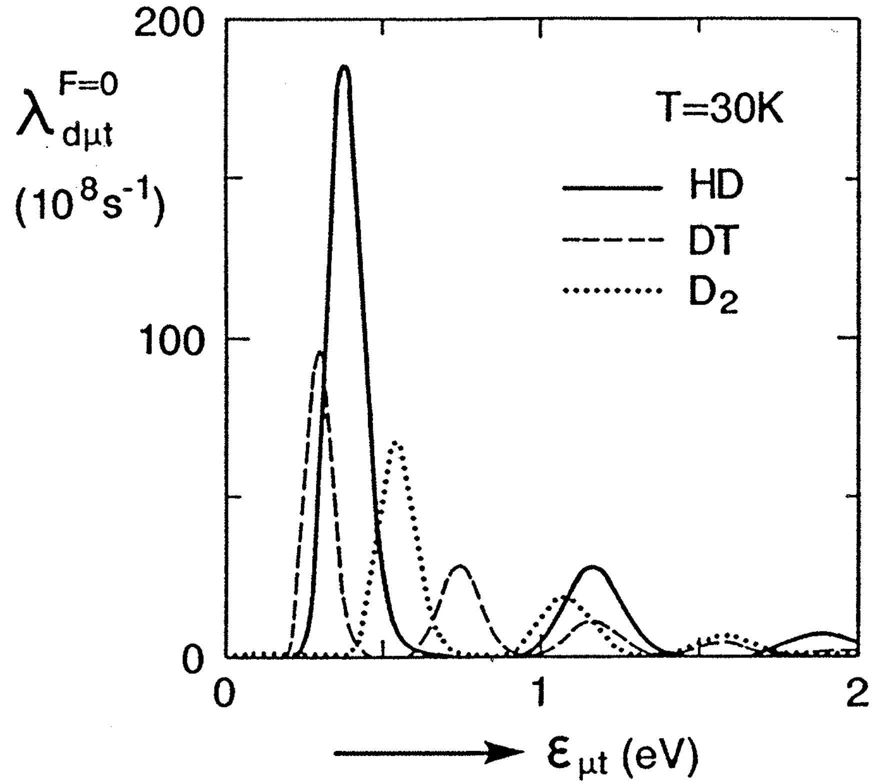
(figure by Cohen, LEMS'93)

PSI 1989: epithermal resonances in HDT-mixtures

experiment: T. Case et al., MCF 5/6 (1990/91) 327

theory: M.P. Faifman and L.I. Ponomarev, Phys. Lett. B (1991) 201





PSI experiments 1989-92 using Gatchina ionisation chamber:

fusion time distribution in H-D-T gas with φ=0.17, c_p=0.9-0.97, c_t=0.036% shows initial peak from epithermal μt

theory 1991:

plot of $\lambda_{dt\mu}$ vs. μt energy

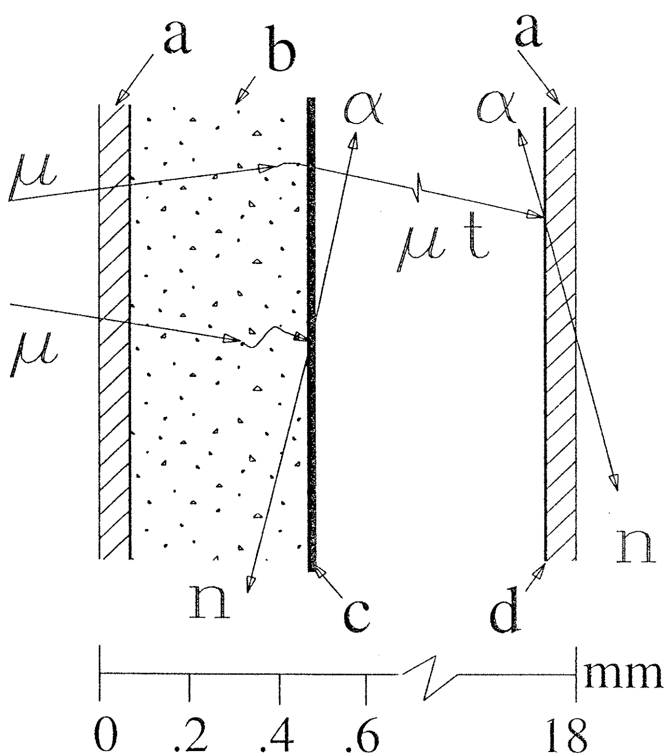
$\lambda_{dt\mu}^{max} \sim 10^{10}\ s^{-1}$!

TRIUMF 1990th: experiments in T-doped solid H_2

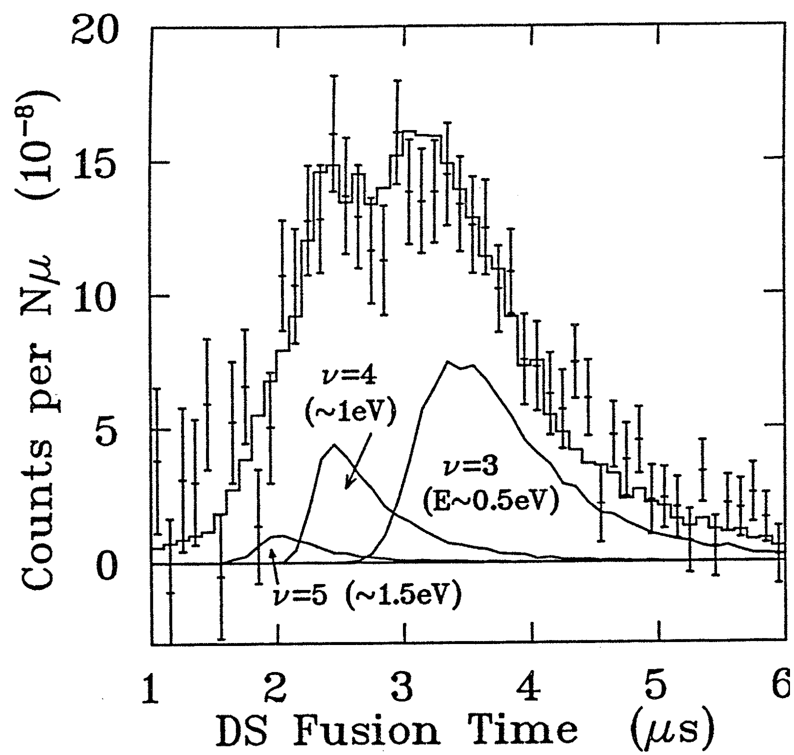
M.C. Fujiwara et al., PRL 85 (2000) 1642,
G.M. Marshall et al., Hyp.Int. 138 (2001) 203.

diffusion of epithermal μt atoms due to Ramsauer-Townsend effect!

→direct observation of reactions with epithermal μt atoms on D_2 or HD



setup of solid H_2(T) target for μt TOF measurement detecting α & n from dtμ fusion in D_2,HD

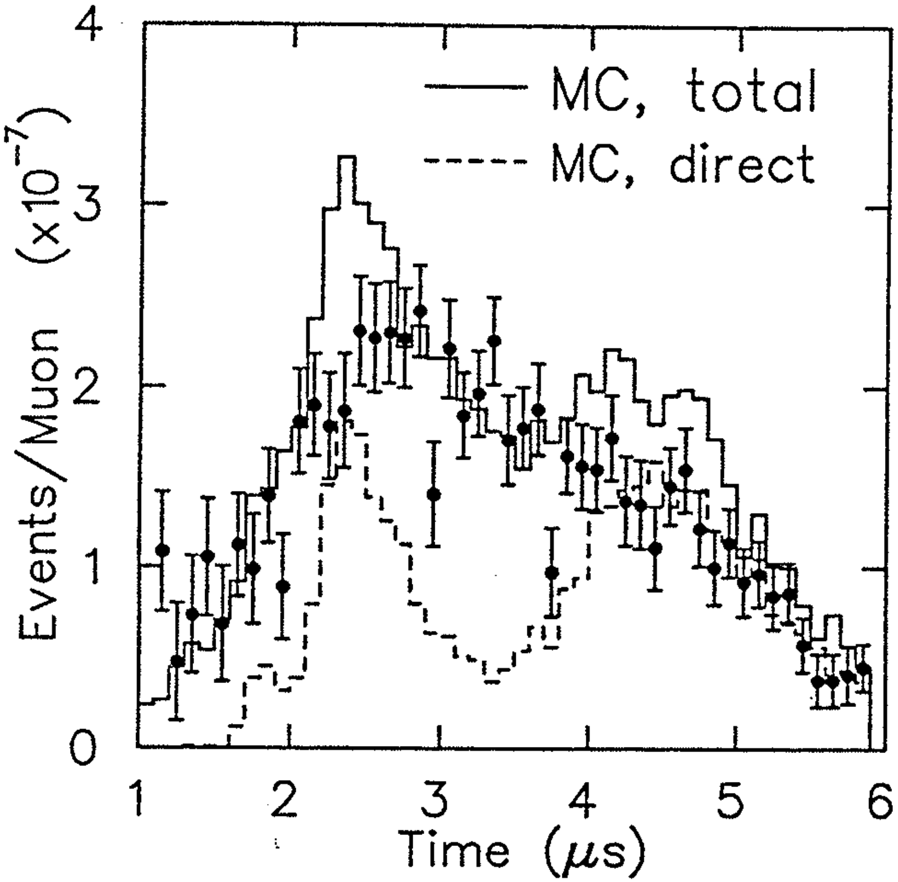


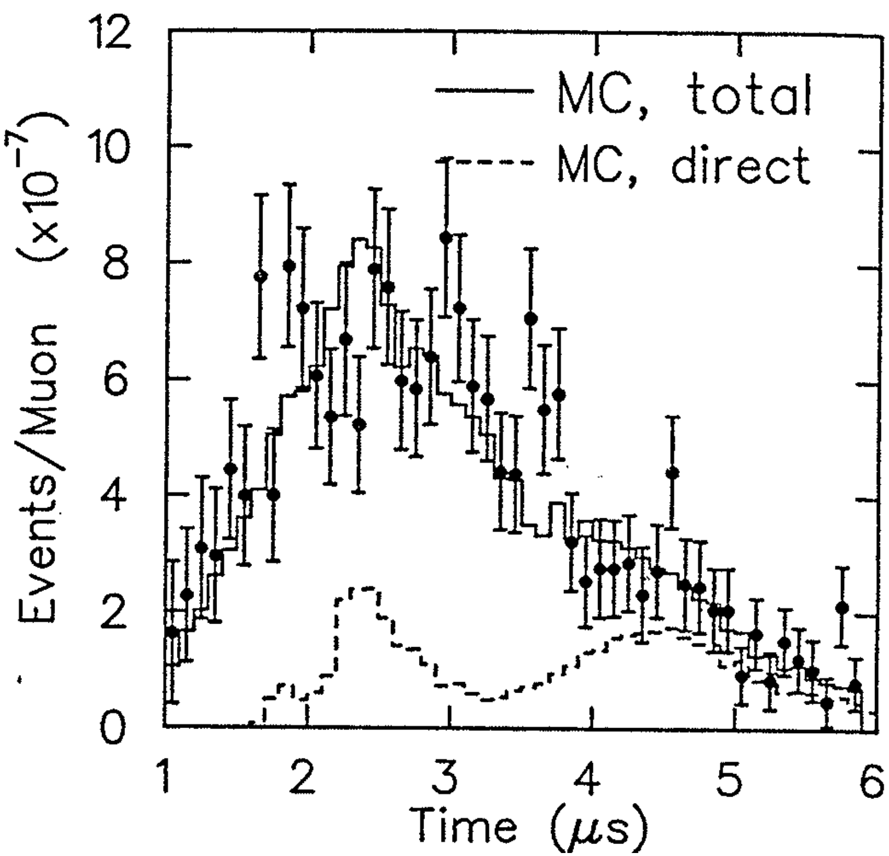
μt + D_2 → [dtμ-dee]
showing epithermal resonances

TRIUMF run on μt + HD → $[dt\mu_{(1,1)}p2e]$

T.A.Porcelli et al., PRL 86 (2001) 3763.

qualitative agreement with Faifman-Ponomarev theory of epithermal resonances



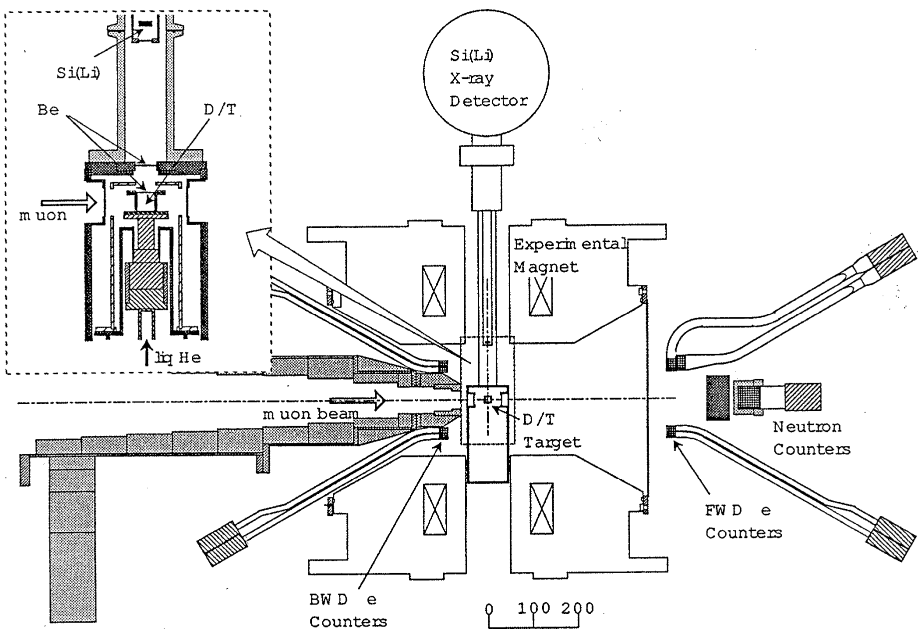


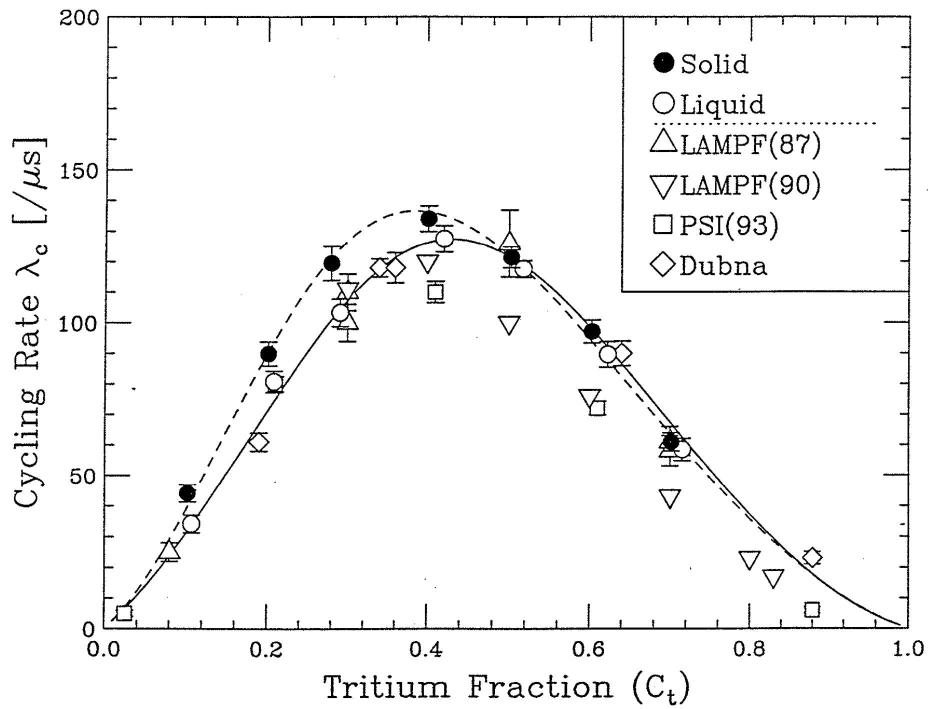
RIKEN-RAL 1990th dtμ fusion in solid & liquid D-T

K. Ishida et al., Hyp.Int.118 (1999) 203

φ: 1.2 – 1.45, T: 16K / 20 K

$\lambda_c^{max} = 1.3\ 10^8$





RIKEN-RAL apparatus for neutron & X-ray measurements in D-T targets

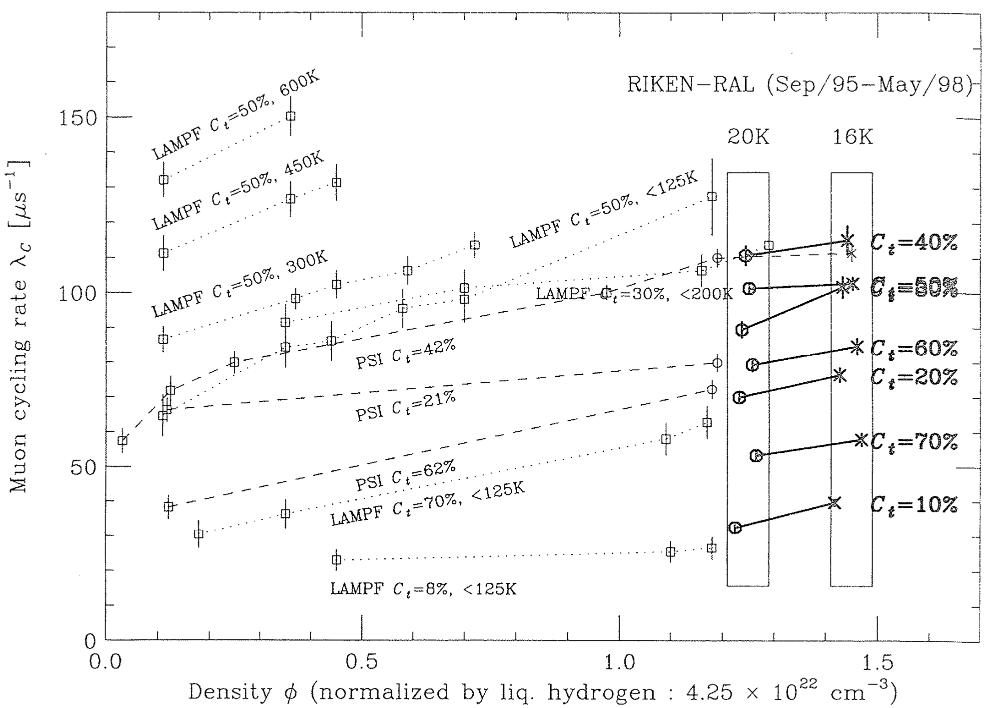
cycle rates λ_c in solid & liquid D-T

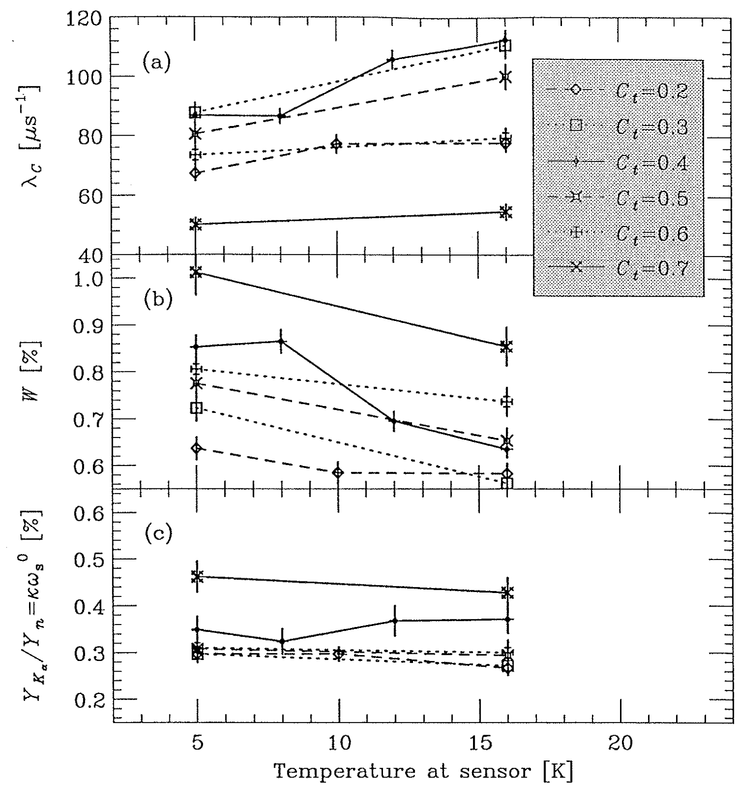
RIKEN-RAL 1995/96: temperature and density effects in solid D-T mixtures

K. Nagamine, Hyp.Int. 138 (2001) 5, N. Kawamura et al., ibid. p. 235.

φ: 1.2 - 1.45,

T: 5K - 20 K





density effects at low temperature
comparison with LAMPF & PSI data

explained by ε_{res} < 0

temperature effects in solid D-T

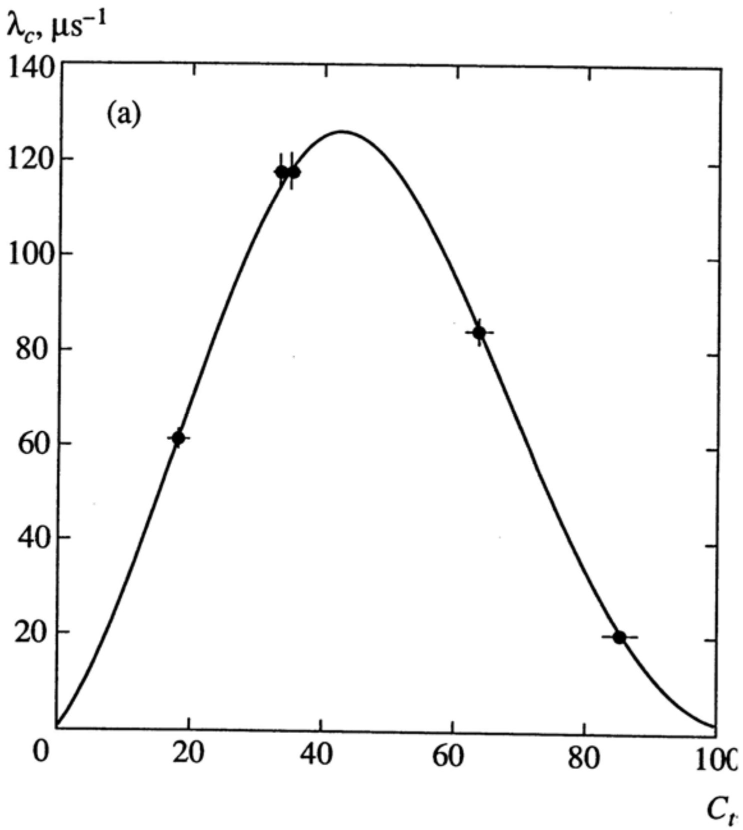
unexplained! - due to solid state?

Dubna 1997-2005: new dμt experimental survey

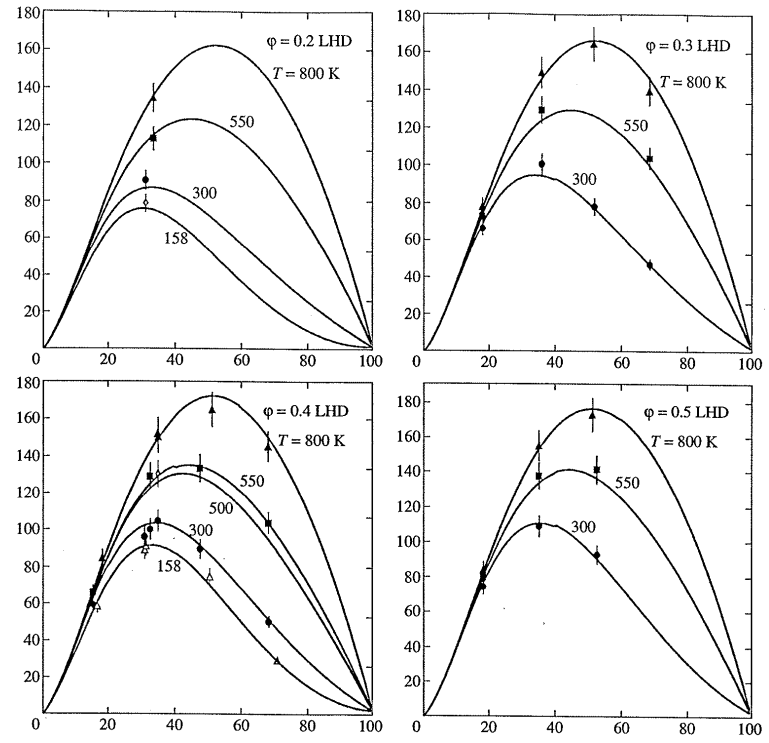
Yu.P. Averin et al., Hyp.Int.118 (1999) 101 V.R.Bom et al., Hyp.Int.118 (1999) 103, Hyp.Int. 138 (2001) 213, JETP 127 (2005) 752

φ: 0.2-1.2 T: 22K - 800K 81 λ_c - data points

λ_c^{max} = 1.25 $10^8 s^{-1}$ (liquid DT) - 1.73 $10^8 s^{-1}$ (T=800K)



λ_c in liquid D-T

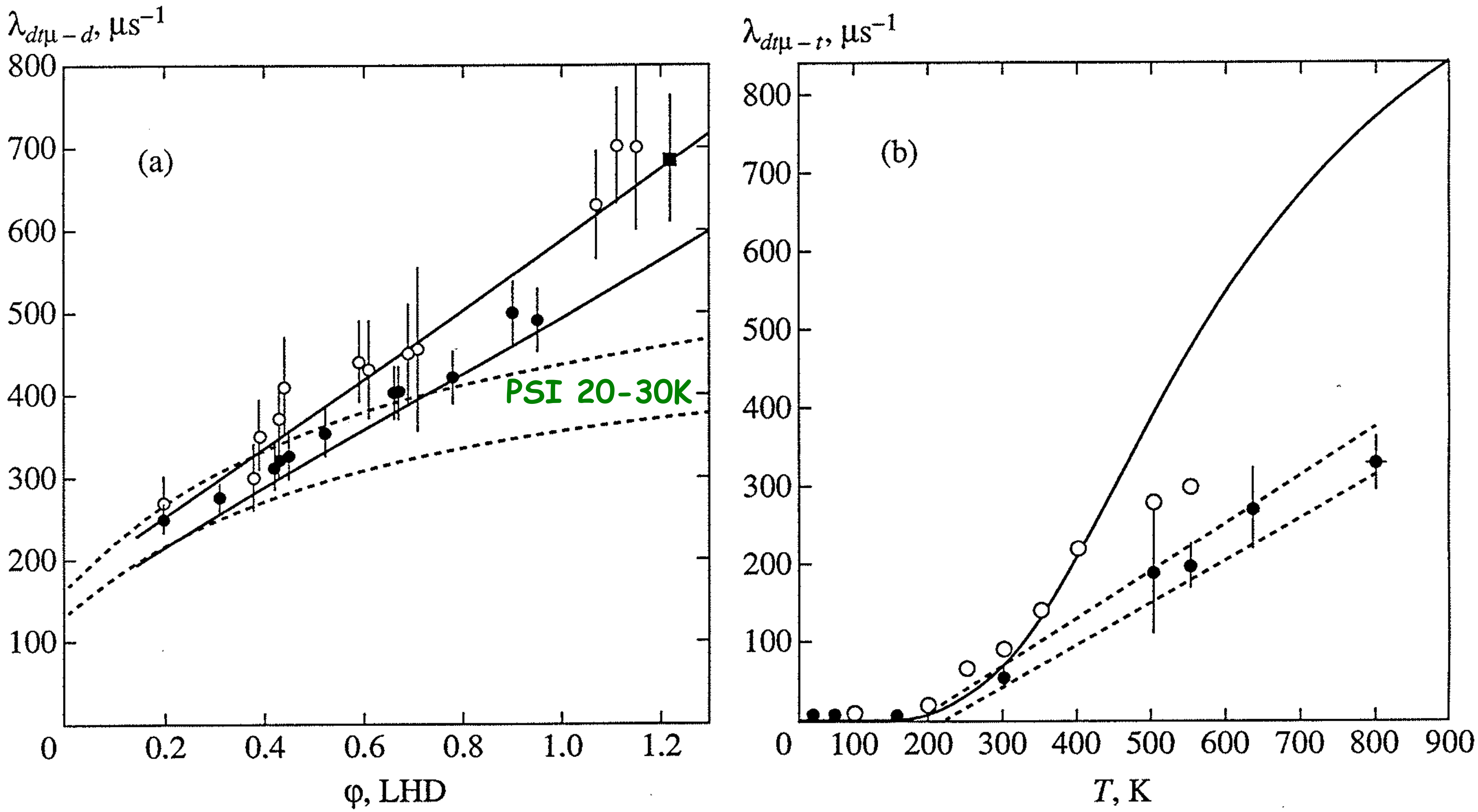


sample in D-T gas T = 158K-800K

Dubna 2005 vs. LAMPF 1986

comparison of mesomolecule formation rates (open circles Dubna full circles LAMPF)

$\lambda_{dt\mu-d}(\varphi)$ on D_2 $\lambda_{dt\mu-t}(T)$ on DT



density effect of $\lambda_{dt\mu-d}$ (T<300K) temperature effect of $\lambda_{dt\mu-t}$

Dubna 91: can the D-T fusion yields get enhanced in triple mixture H-D-T?

Yu.P. Averin et al., Hyp. Int. 138 (2001) 249

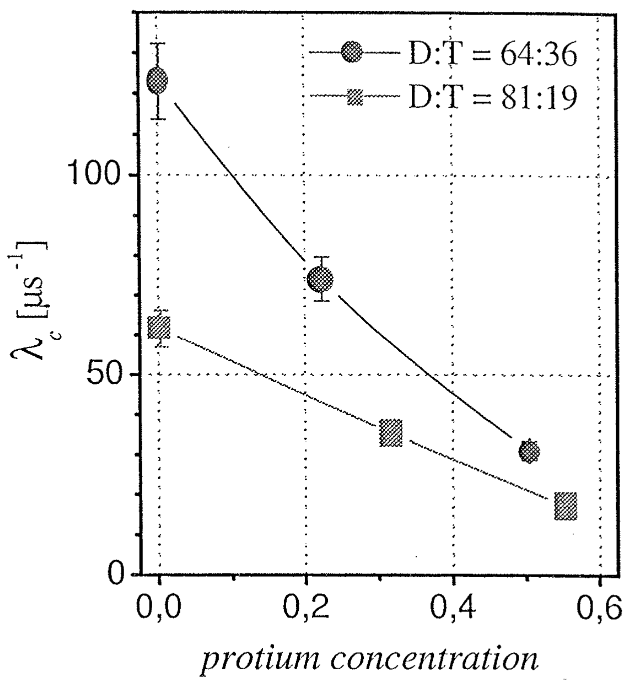
favorable: more epithermal μt near the big mmf resonances due to Ramsauer-Townsend effect

disfavorable: reduced c_t & c_d concentrations and $pt\mu$ formation ($\lambda_{pt\mu} \sim 6\ 10^6 s^{-1}$) cut the $dt\mu$ cycle

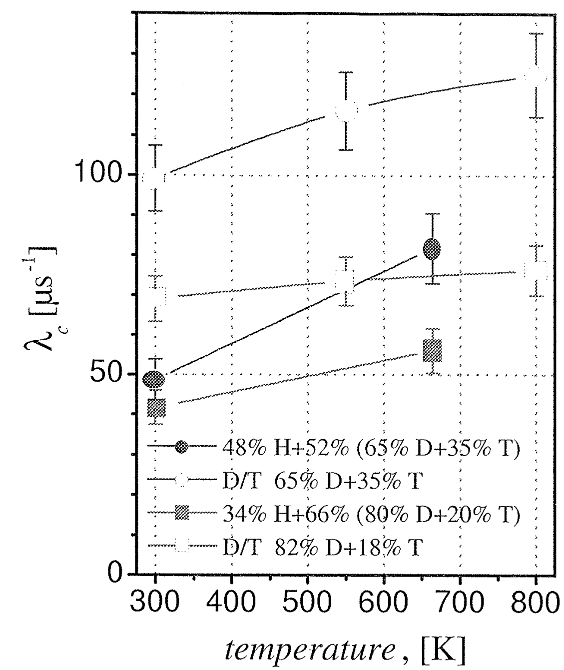
Dubna result:

H^1 admixture reduces λ_c

in liquid phase and as well at higher Temp.!



liquid phase 20K



gaseous phase 300-800K

conclusions I on μCF rates

- exp. cycle & molecule formation rates agree ±10% among all labs
  (Dubna – LAMPF - PSI - RIKEN/RAL)

  e.g. λ_c^{max} (liquid D-T) = $(1.2 \pm 0.1)\ 10^8\ s^{-1}$

- low temperature resonance is μt+D_2 ($\lambda_{dt\mu-d}$); density effects due to sub-threshold resonances are corroborated (LAMPF-PSI-Dubna)

- epithermal resonances (Faifman, Ponomarev) confirmed by all measurements sensitive to it (Dubna-PSI–TRIUMF–LAMPF)

μt+D_2 ($\lambda_{dt\mu-d}$): good agreement with theory (TRIUMF TOF, PSI low φ)

μt+HD ($\lambda_{dt\mu-p}$): qualitative agreement with theory (TRIUMF & PSI)

μt+DT ($\lambda_{dt\mu-t}$): smaller rate increase with T than predicted by theory (LAMPF & Dubna)

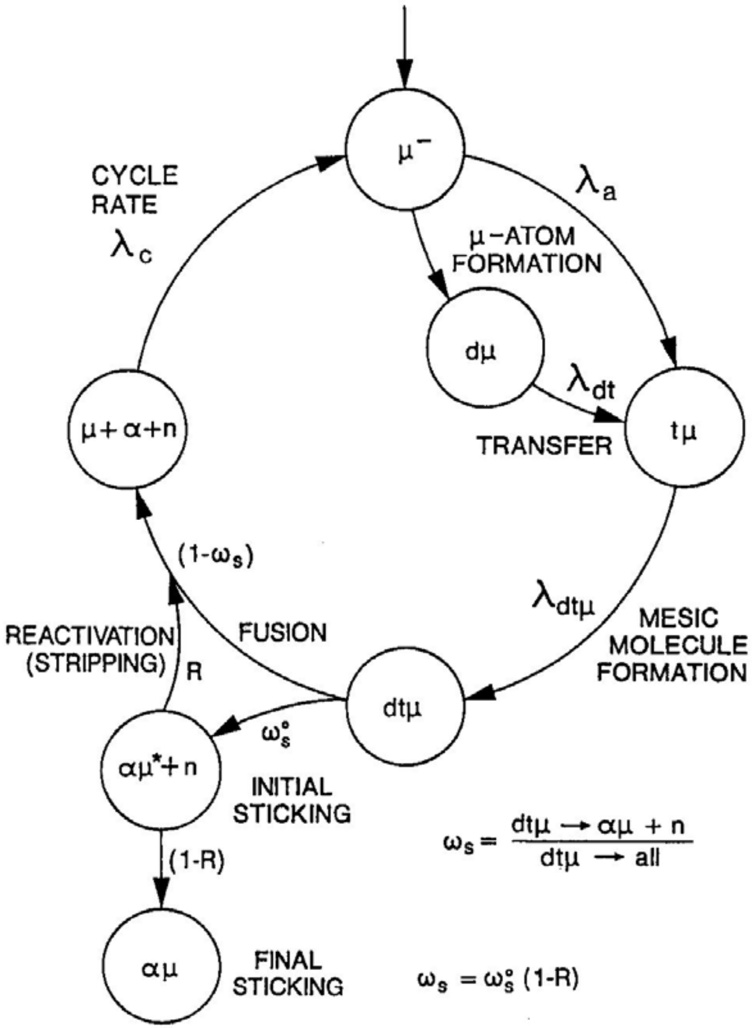
- μCF in solid D-T: rates ~ same as in liquid (RIKEN/RAL- PSI), cf. solid state theory by A. Adamczak, Hyp.Int. 119 (1999) 23.

  The RIKEN/RAL experiment has reported strange temperature effects (16 K → 5K) K. Nagamine, Hyp.Int. 138 (2001) 5.

II μα – sticking

$d\mu t \rightarrow \mu\alpha^* + n \rightarrow \mu\alpha + n$

ω_s^o (1-R)



theory

ω_s^o initial sticking ~ 0.92%

R reactivation (μα-stripping) 0.30-0.36

slightly density dependent!

$\omega_s = \omega_s^o(1-R)$ final sticking 0.59-0.65%

w „effective sticking"

= ω_s + other muon loss terms

e.g. dd, hd, tt, ht channels, μ transfers

fusion time curve & yield:

$$N_f(t) = \Lambda_c\, e^{-[(\lambda_\mu + w\Lambda_c) * t]}$$

$$Y_f = \int N_f = \Lambda_c/(\lambda_\mu + w\Lambda_c) < w^{-1} < \omega_s^{-1}$$

Gerstein et al., JETP 51 (1981) 1053

theory: $Y_f^{th} < 170$ D-T fusions/muon

methods of sticking measurements

1) neutron time spectra

$N_n(t) = \varepsilon_n \Lambda_c e^{-(\lambda_n * t)}$ neutron time distribution

$\lambda_n = \lambda_\mu + w \Lambda_c$ neutron disappearance rate

λ_μ muon decay rate

$w = \omega_s$ + other loss channels = muon loss per cycle

$\Lambda_c = \varphi \lambda_c$ effective cycle rate

$Y_f = \Lambda_c / (\lambda_\mu + w\Lambda_c)$ fusion yield per muon

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

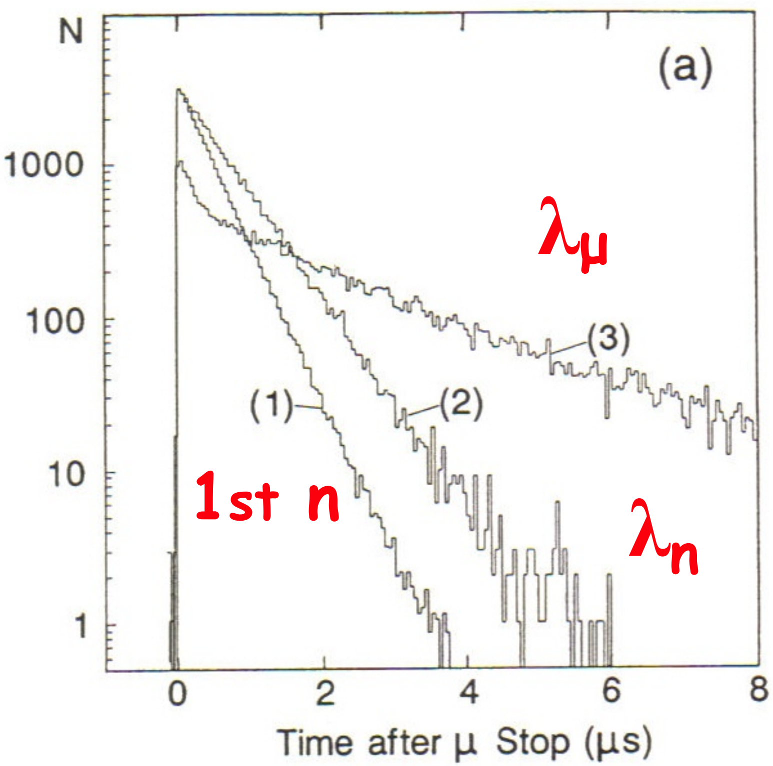
slope of neutron time spectra

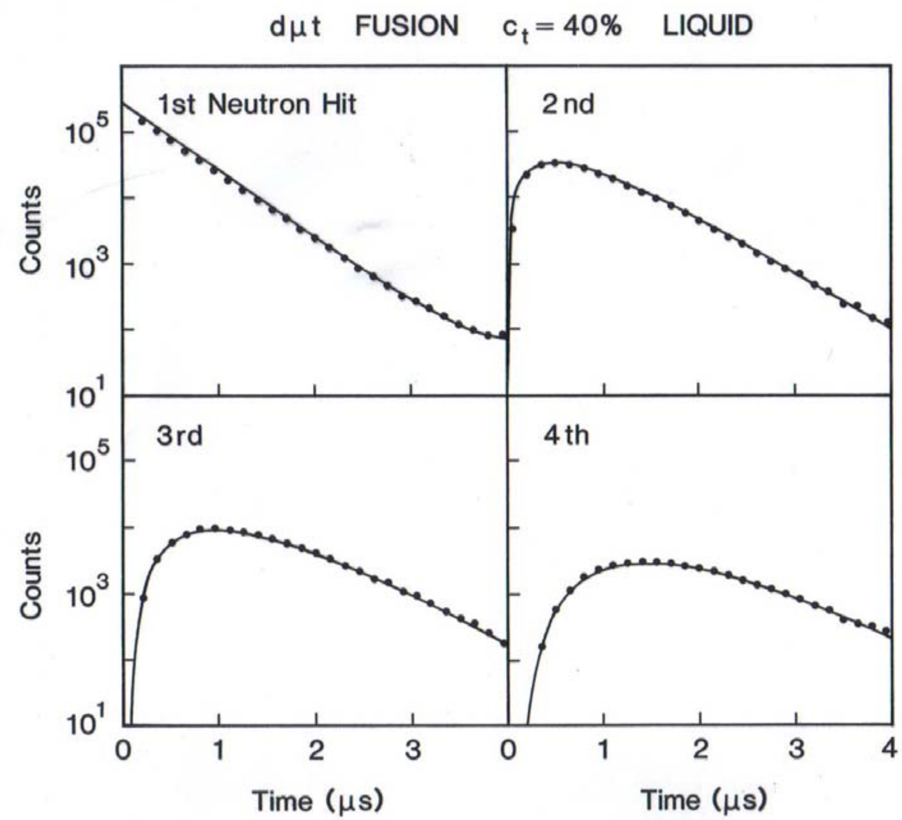
disappearance rate $\lambda_n = -(\lambda_\mu + w\,\Lambda_c)$

→ w most sensitive to large Λ_c ($\gg \lambda_\mu$)

all observed in liquid and solid D-T mixtures !

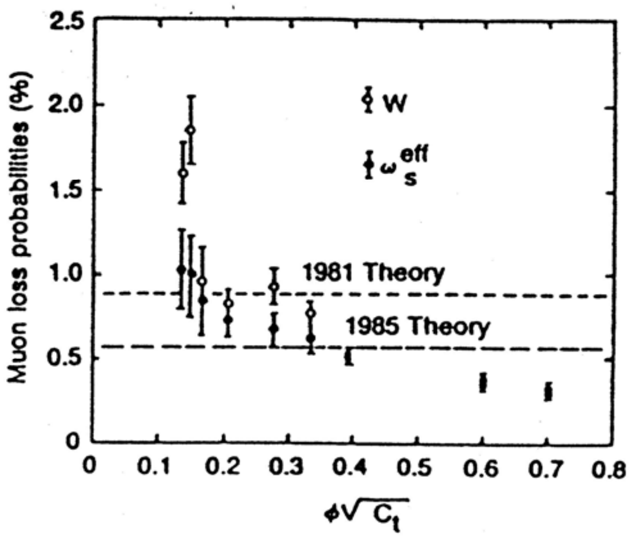
solid non-eq DT $\Lambda_c = 2 * 10^8\ s^{-1}$ liquid DT $\Lambda_c = 1.5 * 10^8\ s^{-1}$



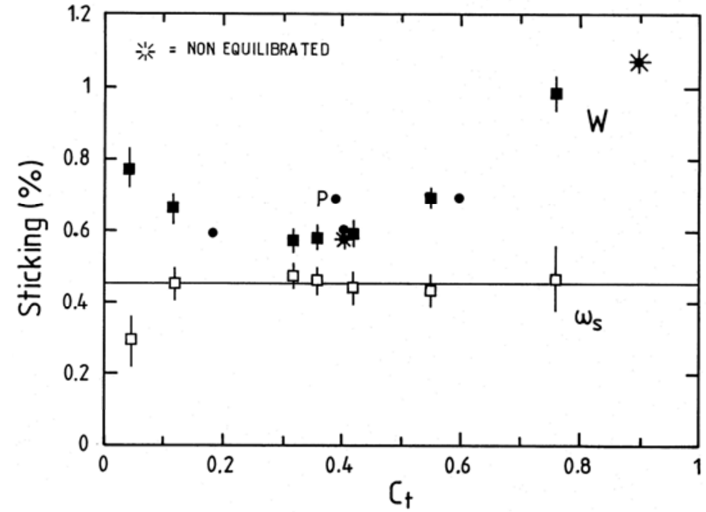


world results on w from high-yield n-disappearance data

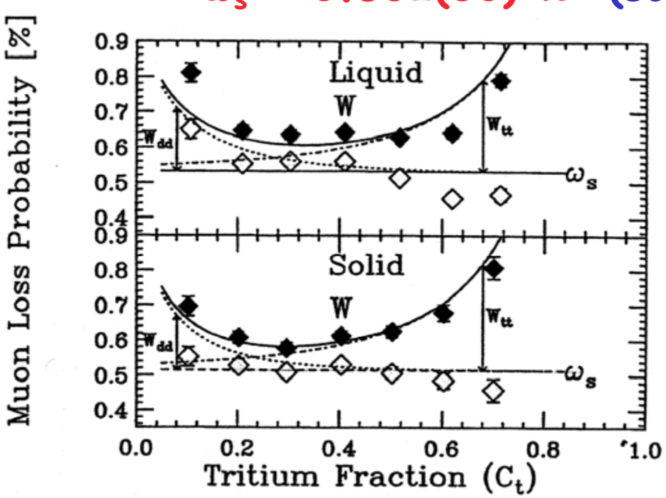
LAMPF 1986: ω_s = 0.32(3) %
(liquid D-T)



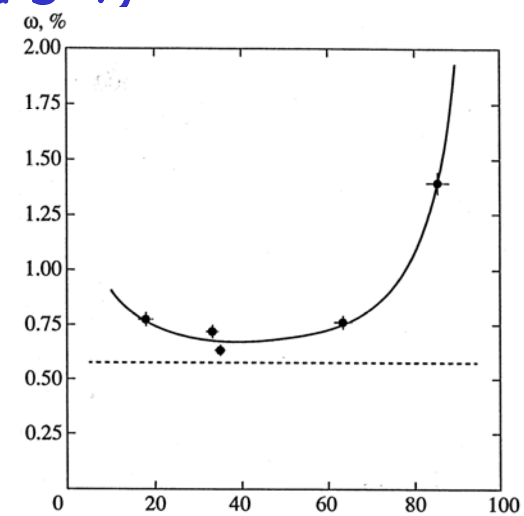
PSI 1987/93: ω_s = 0.485(17) %
(liquid & solid D-T)



RIKEN-RAL: 2001 ω_s = 0.515(30) % (liquid D-T)
ω_s = 0.532(30) % (solid D-T)



Dubna 2005: ω_s = 0.574(22) %
(liquid D-T)



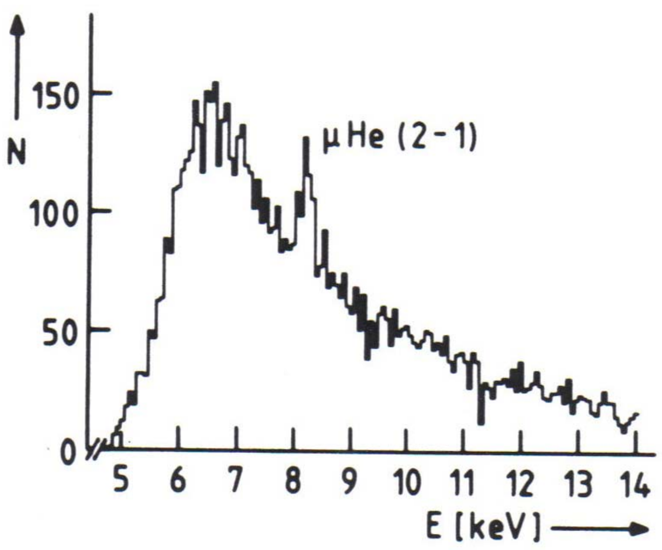
summary table of w & ω_s from neutron slope data
(the worlds high-yield data in liquid & solid D-T)

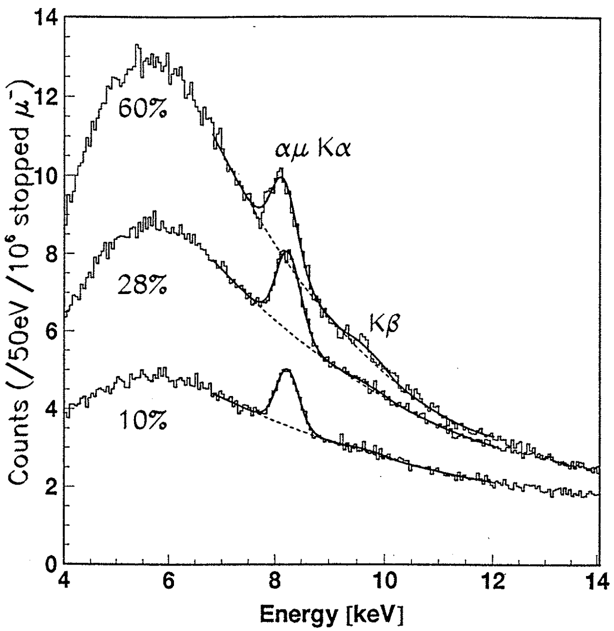
Lab	references	condition	c_t	λ_c	Λ_c	w	Y_f	ω_s	comments
LAMPF 1984	S.E. Jones et al. PRL 56 (1986) 558	liquid $\varphi=1.2$	0.3	120	144	0.35(3)	150	0.32(3)	inconsistent!
	Hyp.Int.82(1993)303	liquid $\varphi=1.14$ non eq.	0.7	102	117	0.70(3)	92	0.43(5)	
PSI 1984	W. Breunlich et al. PRL 58 (1987) 329	liquid 23K $\varphi=1.20$	0.32	122	145	0.57(3)	113	0.45(5)	global fit
1987	C. Petitjean et al. Hyp.Int.82(1993) 273	solid 12K $\varphi=1.45$ non eq.	0.41	134	195	0.568(12)	124	0.485(17)	8% calib.
		liquid 23K $\varphi=1.21$ non eq.	0.41	134	162	0.554(14)	120	0.466(21)	8% calib
RIKEN -RAL 1996	K.Nagamine et al. & K. Ishida et al.	solid 16K $\varphi=1.45$	0.3	~100	~145	0.57(3)	~113	0.515(30)	global fit
	Hyp.Int.138(2001) 5 & Hyp.Int.138(2001)225	liquid 20K $\varphi=1.25$	0.3	~110	~137	0.62(3)	~105	0.532(30)	global fit
JINR Dubna 2003	V.R. Bom et al. JETP 100 (2005) 663	liquid 22K $\varphi=1.20$	0.334	118	141	0.72(6)	97	0.574(22)	global fit
			0.352	118	140	0.63(5)	103		

2) X ray method

$$dt\mu \rightarrow \mu\alpha^* \rightarrow \mu\alpha + X$$

Lab	ref.	c_t	K_α-yield	sticking	
PSI	H. Bossy et al. PRL 59 (1987) 2864	0.0004	0.19(5)%	0.42(14)%	
RIKEN-RAL	K. Ishida et al. Hyp.Int.138(2001) 225	0.1-0.7	0.273(17)	(0.532 %)	liquid D-T
		0.1-0.7	0.279(17)	(0.515 %)	solid D-T



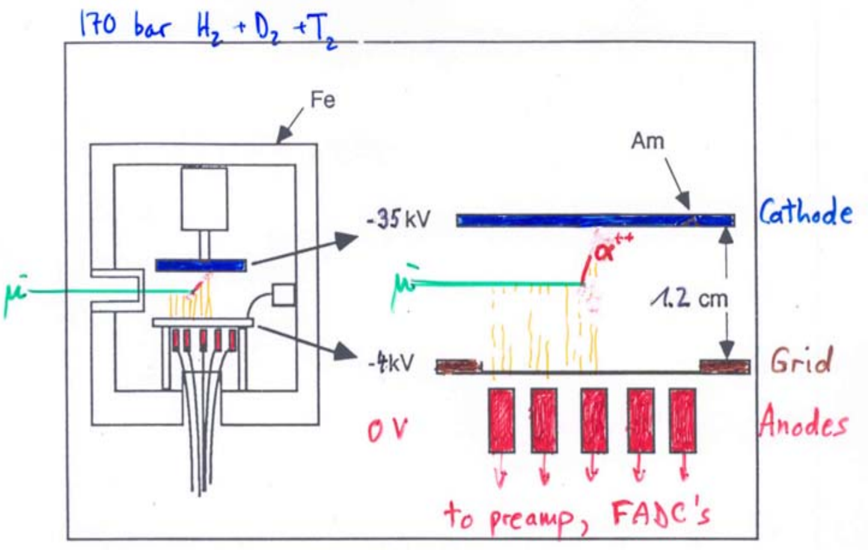


3) direct observations of sticking

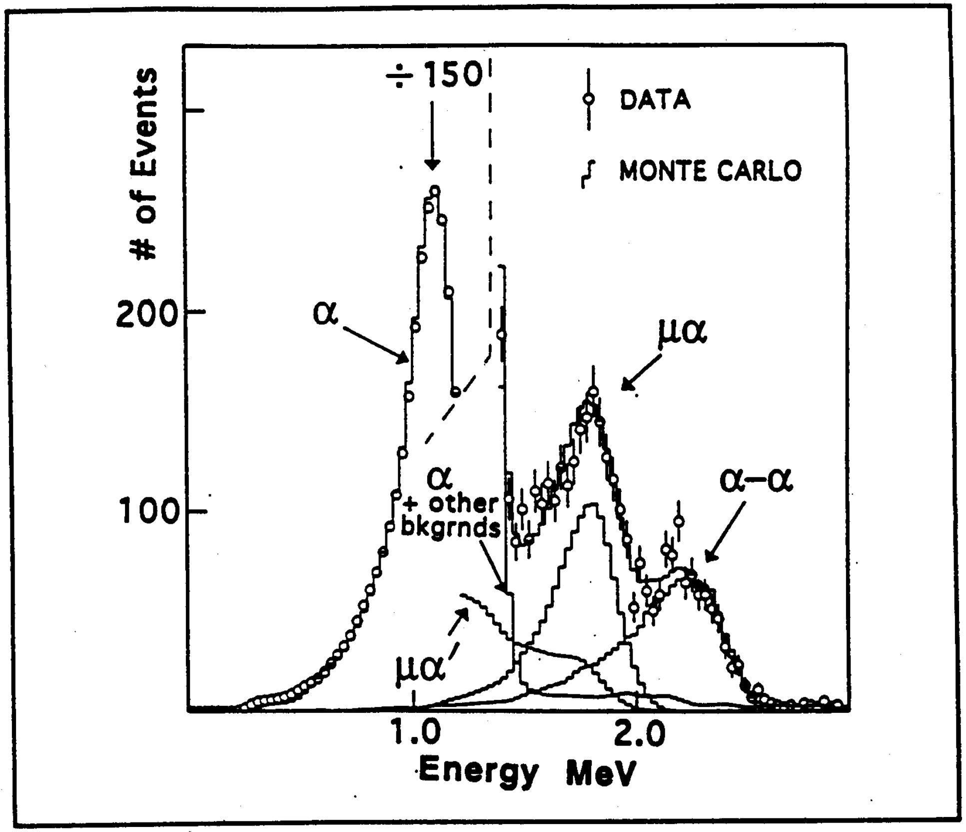
PSI 1992 T.Case, K. Lou et al. H/D/T mixture at 70 bar (c_t=0.036%)

Hyp.Int. 82 (1993) 295
Hyp.Int. 118 (1999) 197

final result: $\omega_s = 0.57 \pm 0.04$ %



Ionization chamber active volume.



Gatchina ionisation chamber using recombination effect !

survived muon method (developed by Gatchina)

K. Lou et al., Hyp.Int. 82 (1993) 313 and thesis

C. Petitjean et al., Hyp.Int. 82 (1993) 273

$\omega_S = 0.565 \pm 0.052\ \%$

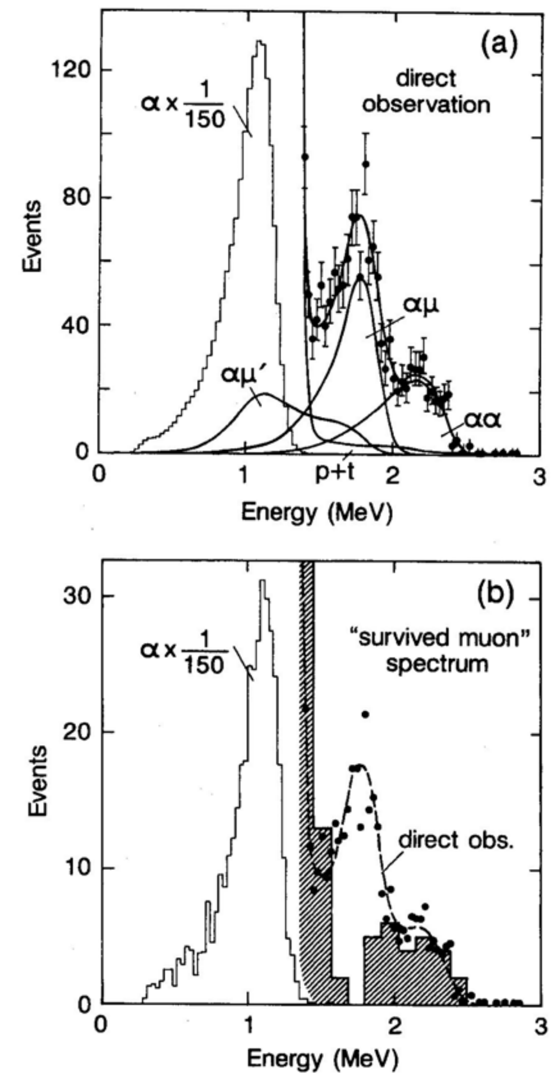
proves beyond any doubt presence of sticking !

(a) direct observation

with sticking & stripping

(b) events with 2nd fusion

sticking peak absent !



direct observation of initial sticking ω_s^0

LAMPF
1988

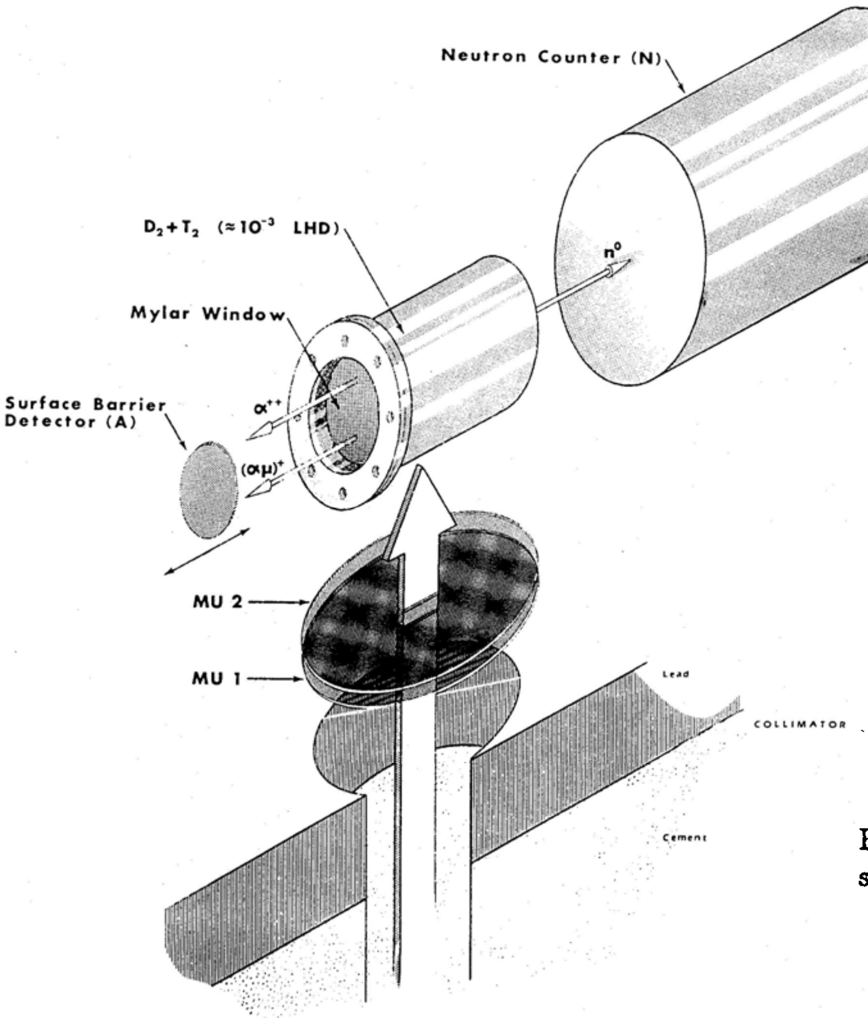
M.A. Paciotti et al.

AIP Conf.Proc 181 (1989) 38
S.E. Jones, AIP 181 (1989) 2

D-T mixture at 2.4 bar (c_t=40%)

ω_s^0 = (0.80±0.15±0.12)%

theory: (0.92±0.02)%



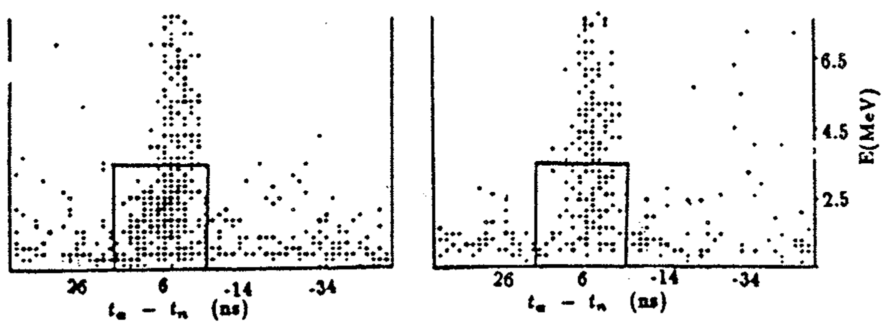


Fig. 6. The $(\alpha\mu)^+$ spectrum for all data taken at 1800 Torr. Background is shown on the right for 3/4 number of incident muons.

conclusions II on $\mu\alpha$ sticking

- the slope results scatter ±14% around a "world average" ω_s = 0.5% that is ~2-3 times the estimated systematic errors (without S.E. Jones inconsistent 1984 data – 6 std. deviations off) perhaps it reflects the difficulty of absolute neutron calibrations! this average is 20% below theory
- however the recent Dubna slope data are ≈ consistent with theory $(0.574\pm0.022)\%^{exp}$ vs. $(0.60\pm0.02)\%^{th}$
- the X ray method (RIKEN/RAL) experiment observes 10-20% lower X ray yields and there are some inconsistencies with K_β, K_γ yields
- the ω_s direct observation (PSI) experiment agrees nicely with theory $(0.57\pm0.04)\%^{exp}$ vs. $(0.62\pm0.02)\%^{th}$
- the ω_s^{o} direct observation (LAMPF) experiment also agrees with theory, though within large errors $(0.80\pm0.15\pm0.12)\%^{exp}$ vs. $0.92\%^{th}$
- question: can sticking be overcome?

  the exp. answer is: no evidence! It looks very difficult to go beyond $d\mu t$ fusion yields of ≈ 130 per muon.

what can we experimentally do in the future?

- understand better the dμt kinetics, especially at the epithermal resonances → more measurements at high temperatures (T = 1000-2000 K) are needed.

  (goal proposed by the Dubna group)

- understand better the lowest temperature physics (solid state effects, ortho/para effects in D_2 molecules)

  (proposal of the Japaneese group for the J-PARK facility)

we wish for these upcoming experiments good luck!