Temperature dependence of muon transfer rates from tμ to ^{3}He in solid T_2

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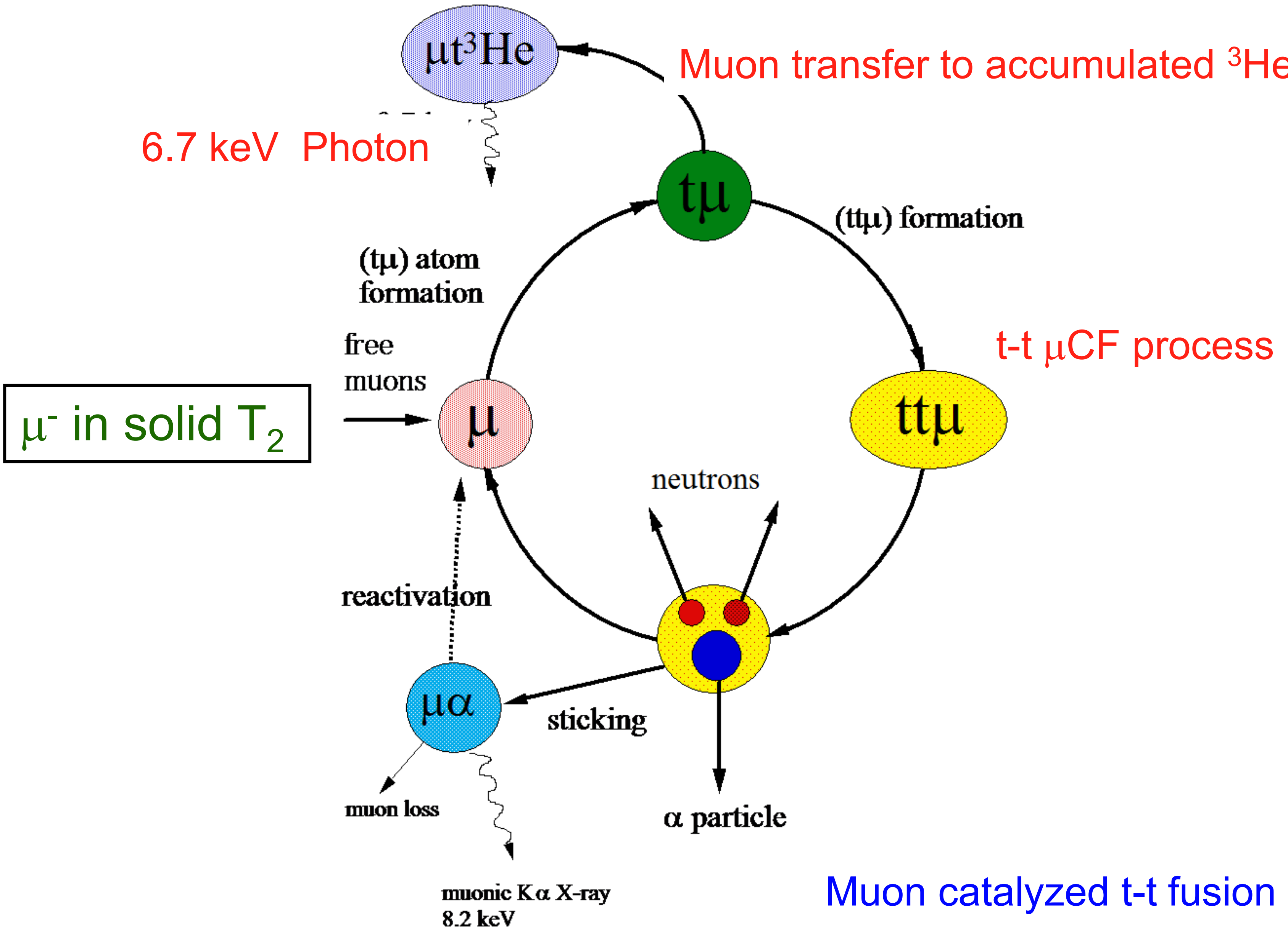
(μCF-07)
Dubna, 18-21 June 2007



Muon catalyzed t-t fusion and muon transfer in solid T_2

(The ^{3}He, decay product of tritium, is accumulated in solidT_2, not in liquid T_2.)

Competing processes of tμ^- in solid T_2

(1) t-t μCF process:

$$t + t + \mu^- \rightarrow t t\mu^- \rightarrow \alpha + n + n + \mu^- + Q\ (11.33\ \text{MeV}) \quad \text{-----}\ (1)$$
$$\rightarrow \alpha\mu^- + n + n + Q. \quad \text{-----}\ (2)$$

$$t\mu^- + T_2 \rightarrow [(tt\mu)_{J\nu} t\ e^-]^+ + e$$

(2) **muon transfer process:**

$$t\mu^- + {}^3He \rightarrow \mu^- t\,{}^3He^* \rightarrow t + {}^3He\mu^- + \gamma\ (6.76\ \text{keV}) \quad \text{-----}\ (3)$$

The muon transfer rate is determined by measuring the time dependent change of neutron disappearance rates (λ_n) and the 6.8 keV photon yields.

Muon Transfer from $t\mu^-$ to ^3He in solid T_2

(The ^3He, decay product of tritium, is accumulated in solidT_2, not in liquid T_2.)

1. Direct μ^- capture to ^3He: ^3He concentration is small

   $\mu^- + {}^3He \rightarrow \mu^- {}^3He$

2. Direct transfer from $t\mu^-$ to ^3He: rate ~ $10^{5\text{-}6}$ /sec

   $t\mu^- + {}^3He \rightarrow t + \mu^- {}^3He$

3. μ^- transfer from $t\mu$ to ^3He through $\mu^- t {}^3He$ molecule: rate ~ 10^9 /sec

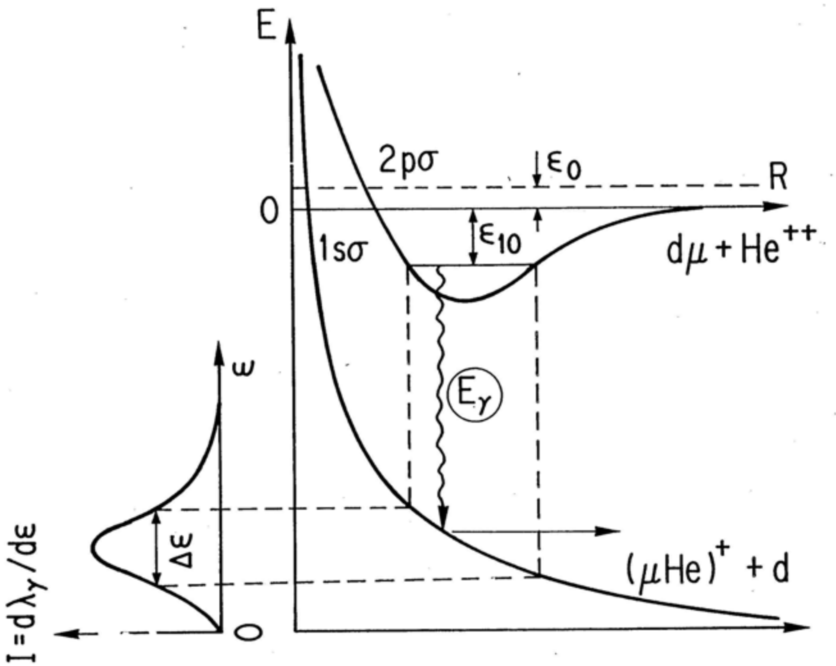
   $t\mu^- + {}^3He \rightarrow (\mu^- t {}^3He)^* \rightarrow t + \mu^- t {}^3He + \gamma$ (6.8KeV) (dominant for $t\mu^- + {}^3He$)

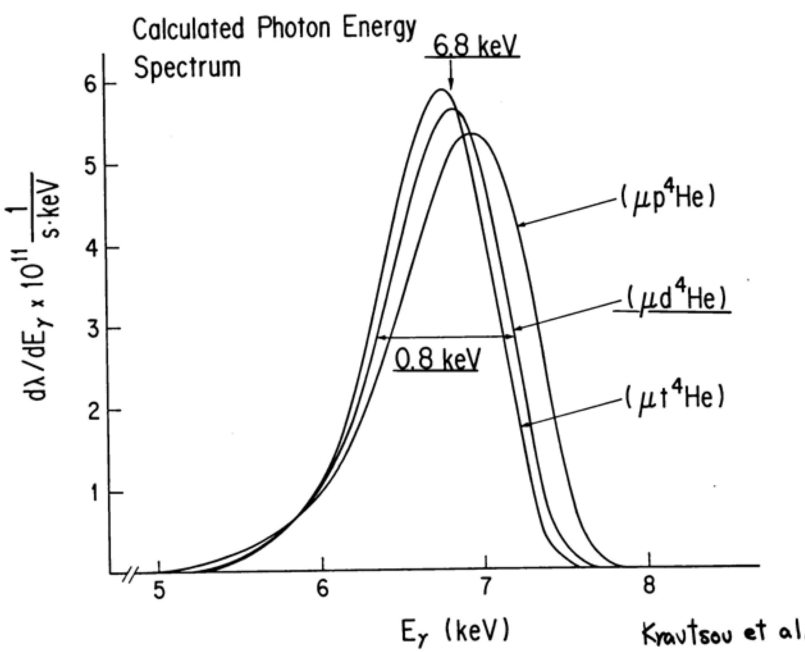
   $\rightarrow t + \mu^- t {}^3He$ + K.E. (M.Kamimura,Y.Kino)

   $\rightarrow t + \mu^- t {}^3He$ + Auger electron

History of “Muon Transfer mechanism from $d\mu$ to ^4He through μd^4He molecular formation”

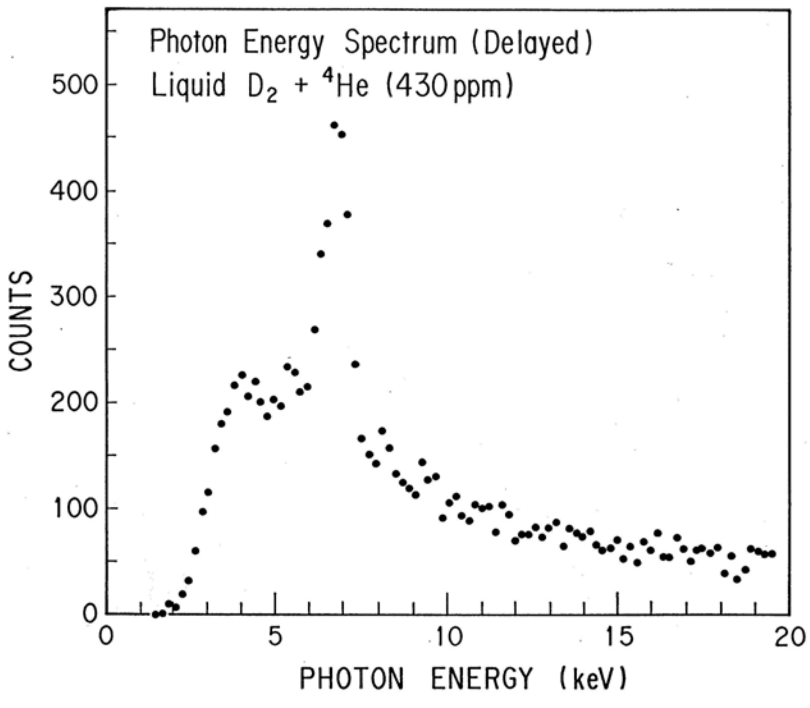
$$d\mu + {}^4He \rightarrow \mu d^4He \rightarrow d + {}^4He\mu + \gamma\ (6.8KeV)$$

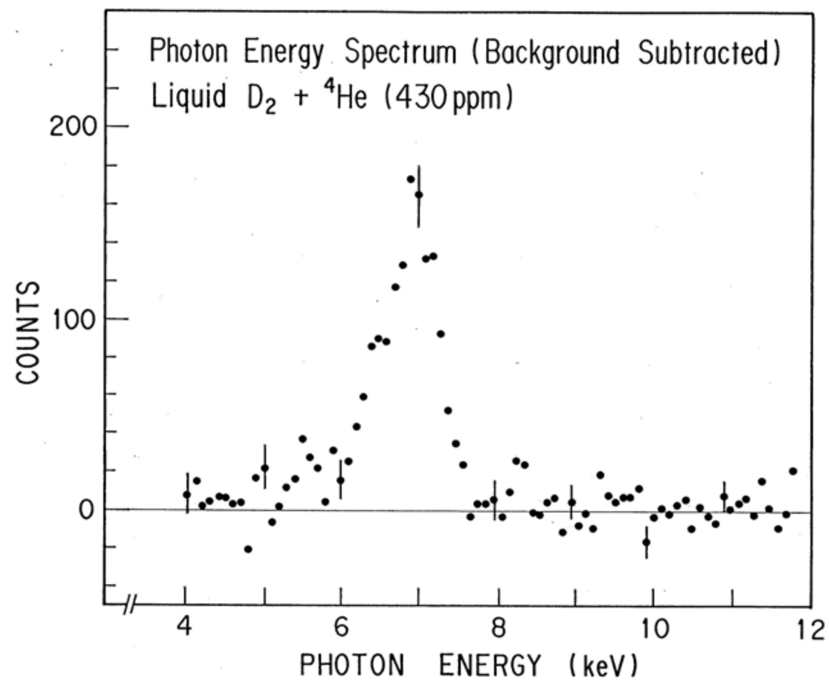




A.V. Kravtzov et al., Phys. Lett.83A (1984)379

The first observation of radiative transition photons (6.8 keV) associated with muon transfer from dμ to ^{4}He through μd^4He molecular formation (KEK-MSL 1987)

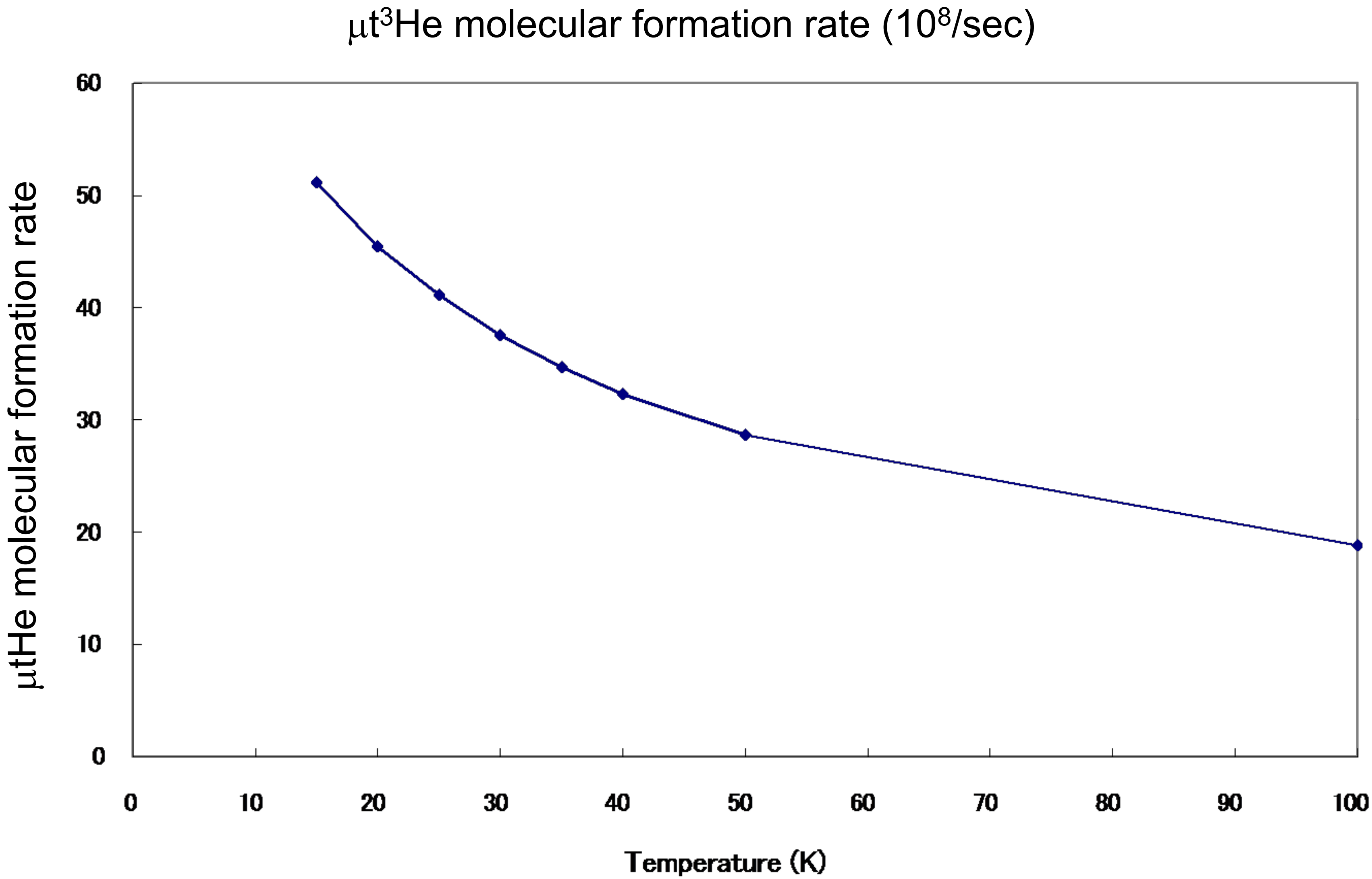




Presented by T.Matsuzaki in μCF-87 at Gatchina

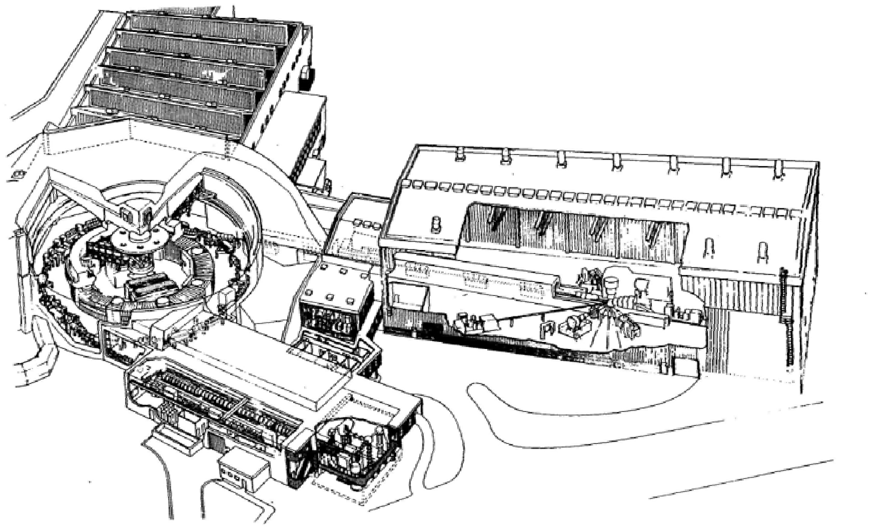
Reference:T.Matsuzaki et. al.,Muon Catalyzed Fusion 2(1988)217

Theoretical calculation of μt^3He molecular formation rate vs Temperature

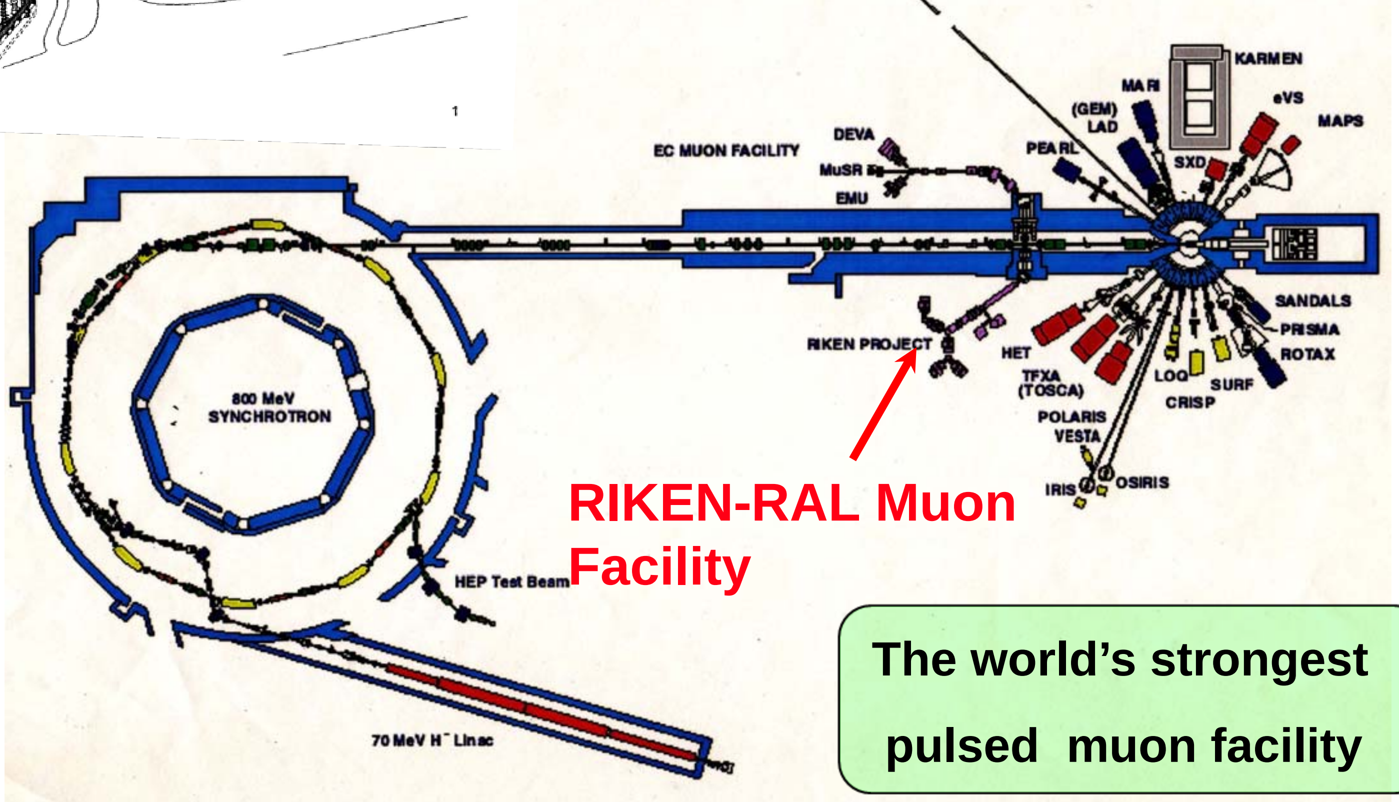


A.V. Kravtzov et al., Z. Phys. D29 (1994) 49

Rutherford Appleton Laboratory



800 MeV proton
200 μA
(300 μA, 2007)
50 Hz

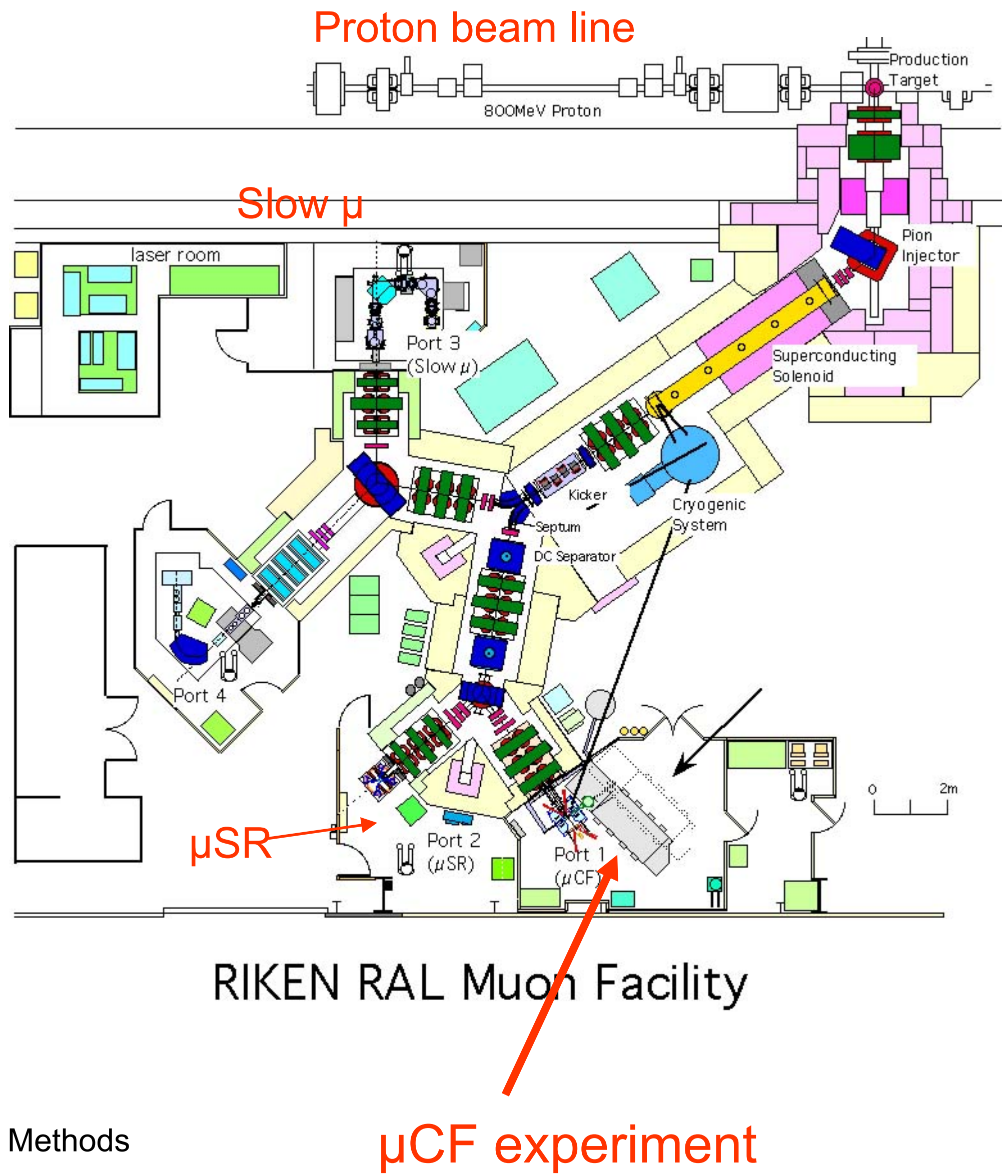


RIKEN-RAL Muon Facility

The world's strongest pulsed muon facility

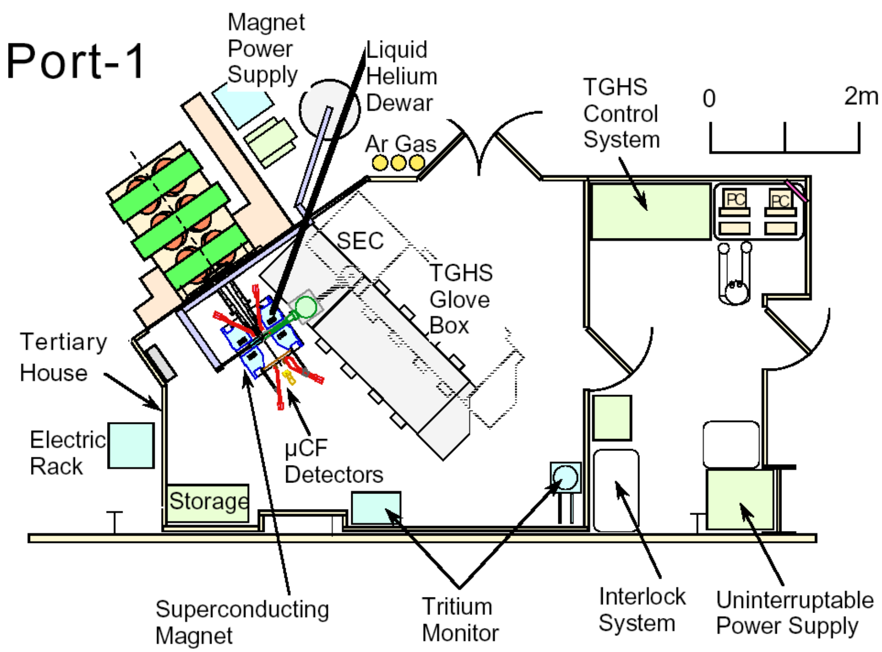
μCF at RIKEN-RAL Muon Facility

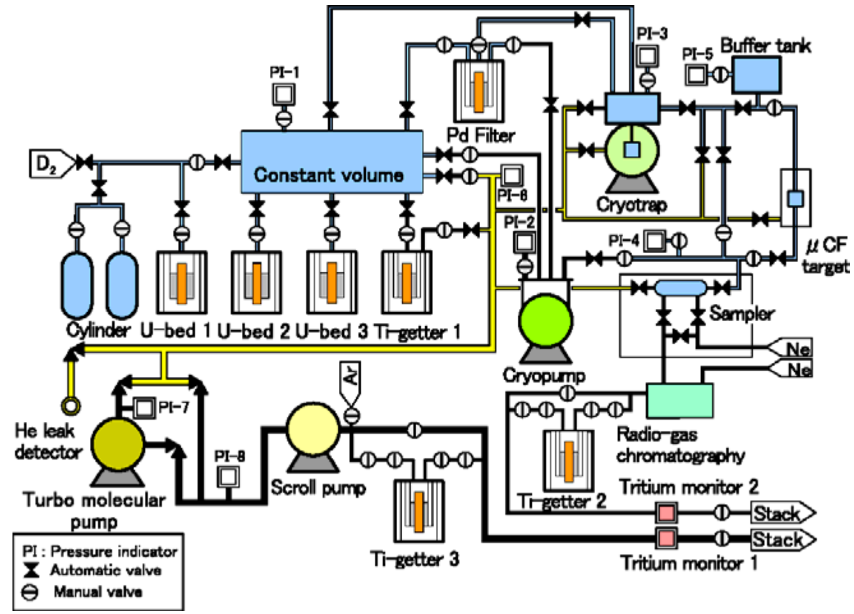
- RIKEN-RAL Muon at ISIS (1995~)
- Intense pulsed muon beam (double pulse)
- (70ns width, 50 Hz)
- 800MeV x 200μA proton
  (up-graded to 300 μA, 2007)
- 25~150MeV/c
- μ^+/μ^- muon
  (decay and surface muon beam)
- 5 x 10^4 μ^-/s (55 MeV/c)



Reference: T. Matsuzaki et. al.,Nuclear Instruments & Methods A465(2001)365

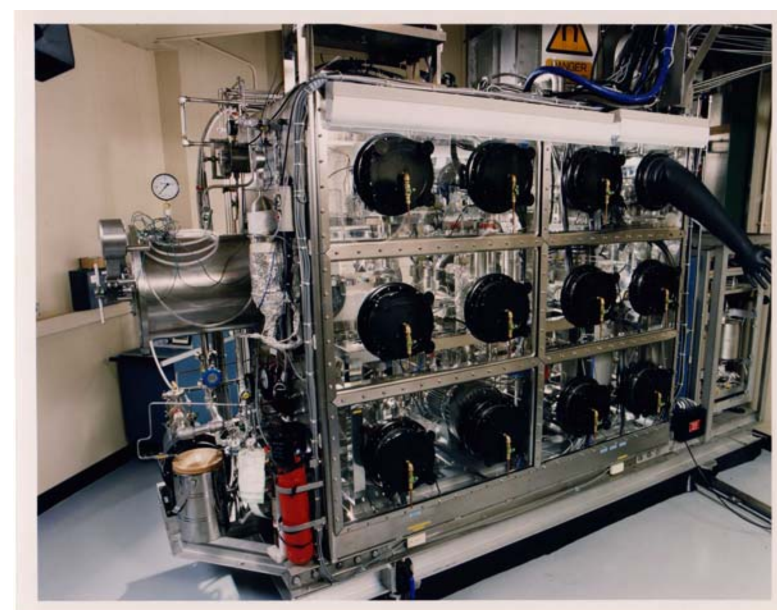
Muon catalyzed fusion experiment facility at the RIKEN-RAL





1. ^{3}He removal on site
2. D_2/T_2 mixing ratio
3. Hydrogen isotope analysis

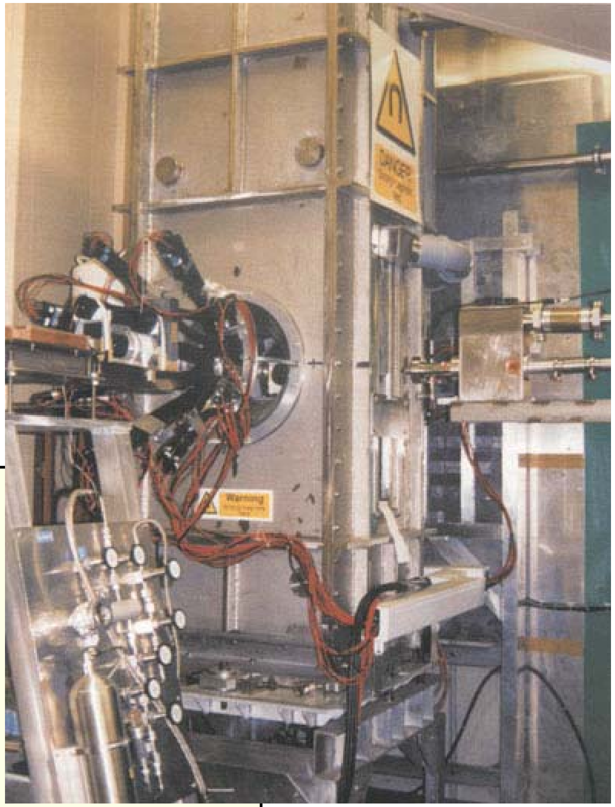
Figure-3

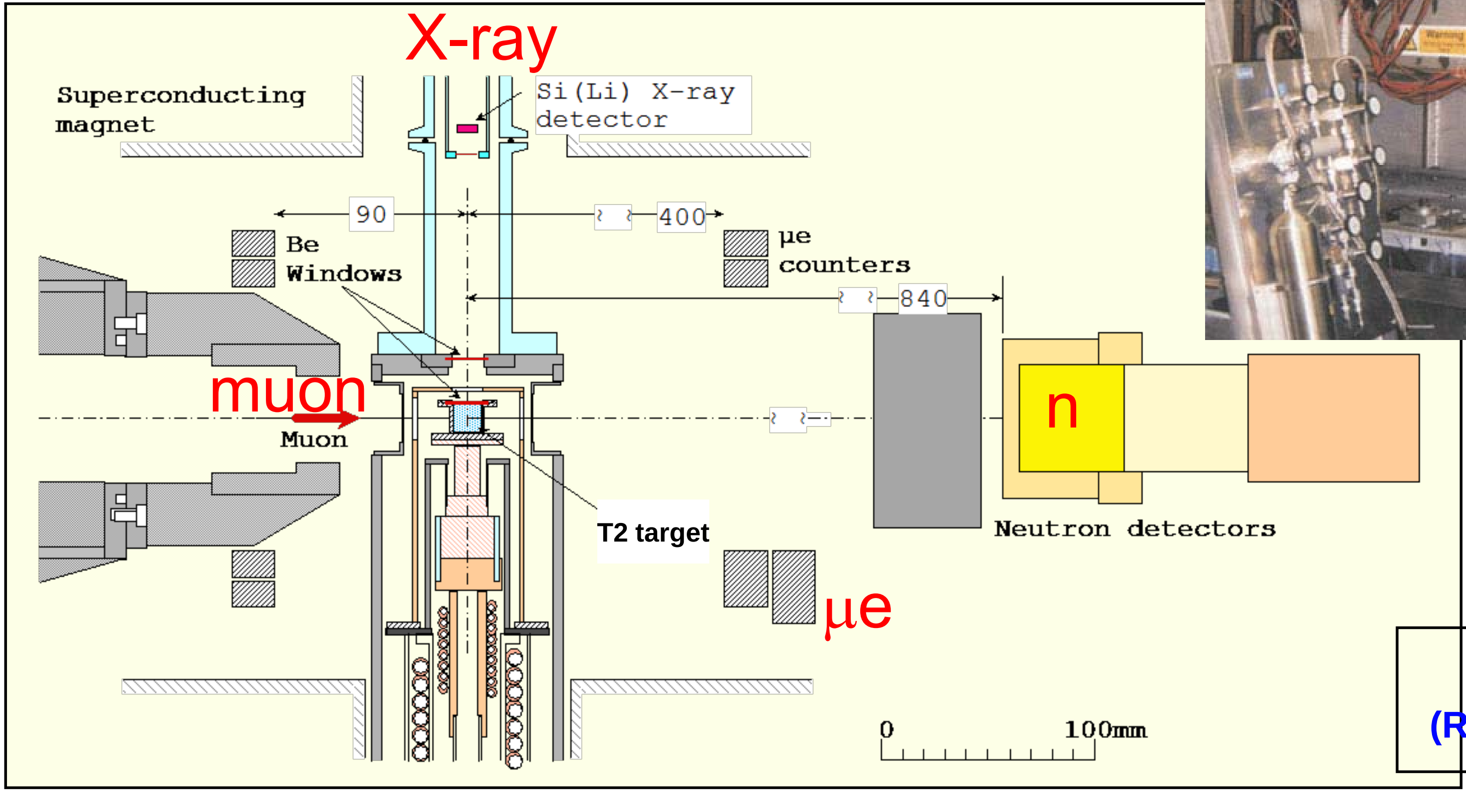


Reference: T. Matsuzaki et. al.,Nuclear Instruments & Methods A480(2002)814

t-t μCF target and detectors

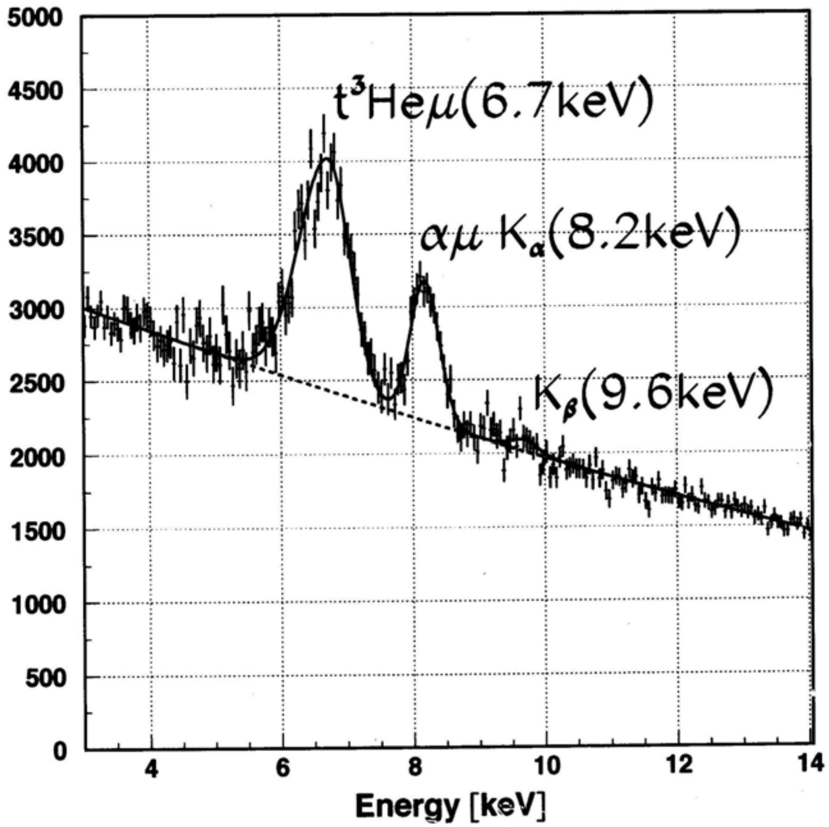
- Cryogenic target : 0.5 cc solid T_2 (1.5 kCi)
- Detectors with the calibration
- fusion neutrons, X-rays, μ-e decay
- 60 (solid) and 30 (liquid) muon stops per pulse

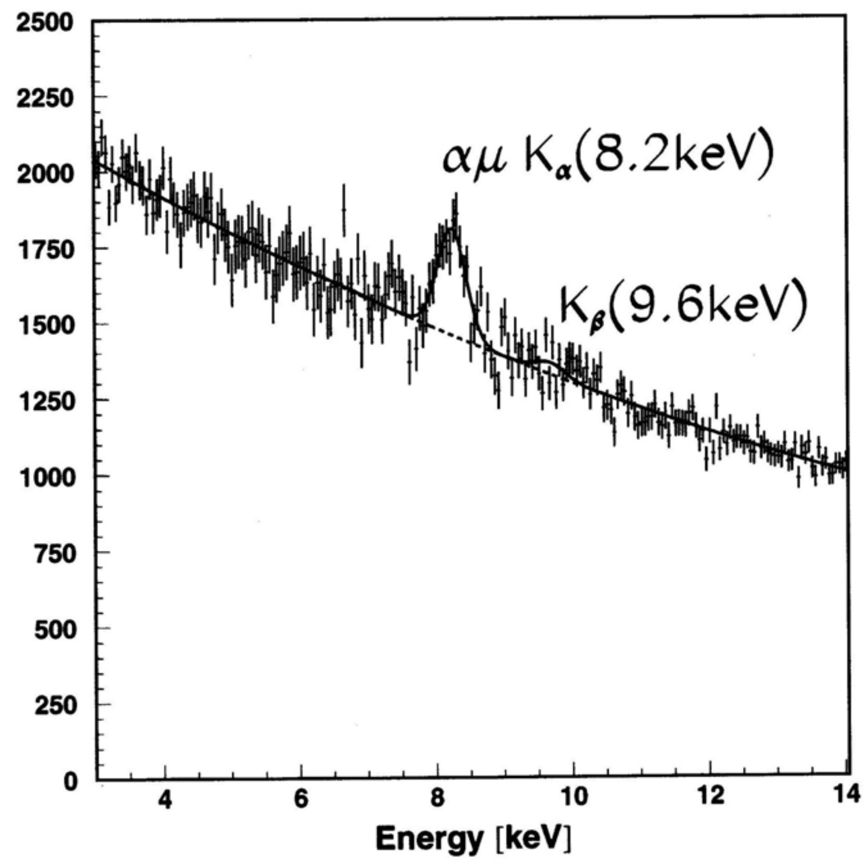




μCF setup
(RIKEN-RAL Port1)

Photon energy spectrum for t-t μCF experiment





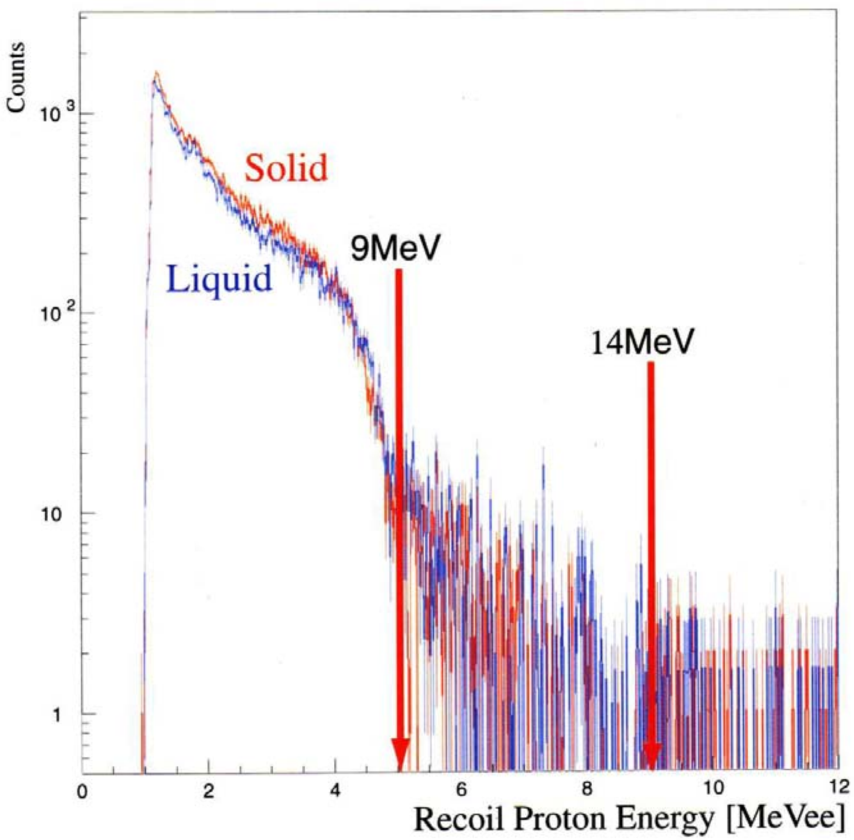
Solid T_2

Liquid T_2

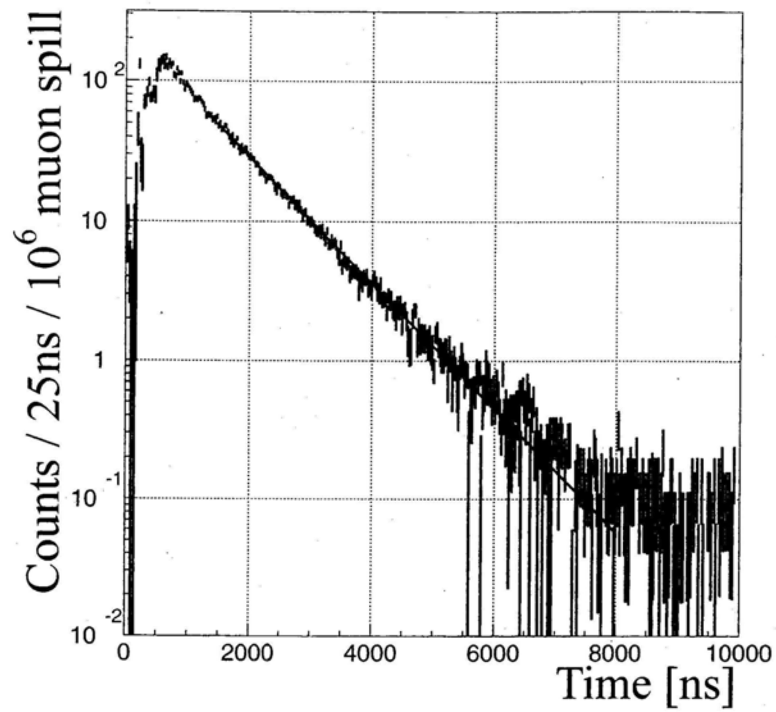
$t\mu^- + {}^3He \rightarrow [\mu^3He\,t]^+ \rightarrow t + {}^3He\mu^- + \gamma$ (6.76 keV)

Reference: T. Matsuzaki et al.,Phys. Lett. B527(2002)43

Neutron energy and time spectrum for t-t μCF experiment



Neutron energy spectrum

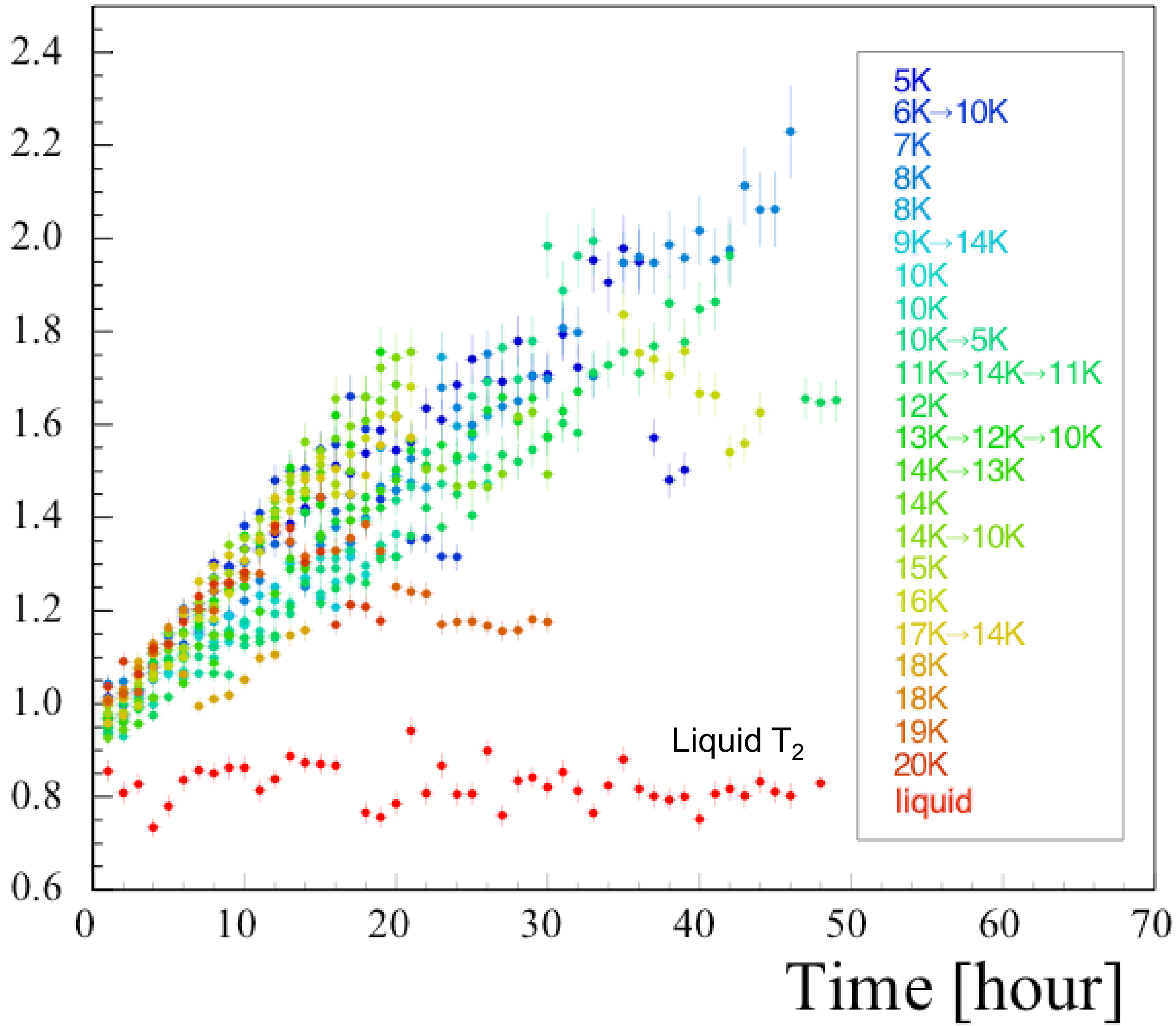


Neutron Time spectrum

$t + t + \mu^- \rightarrow tt\mu^- \rightarrow {}^4He + n + n + \mu^- + 11.33$ MeV

Reference: T. Matsuzaki et al.,Phys. Lett. B557(2003)176

Time dependence of t-t μCF neutron disappearance rate (λ_n) in solid T_2



(^{3}He concentration is zero at t = 0)

Muon transfer process:

Neutron disappearance rate $\lambda_n(\tau)$ vs. Time

$$\lambda_n (\tau) = \lambda_0 + \phi W \lambda_c + \phi C_{3He} (\tau) \lambda_{t3He\mu}$$

$$\lambda_n (0) = \lambda_0 + \phi W \lambda_c$$ (constant term)

$$C_{3He} (\tau) = C_t \lambda_t \tau$$

$C_t = 0.994$, $\lambda_t = 1.54 \times 10^{-4}$ /day

t-t μCF process:

Neutron data:

$$\lambda_c = Y_n \lambda_n (0) / \phi$$

$$Y_n = \phi \lambda_c / \lambda_n (0)$$

$$W = (1 - \lambda_0 / \lambda_n (0)) / Y_n$$

λ_c: muon cycling rate

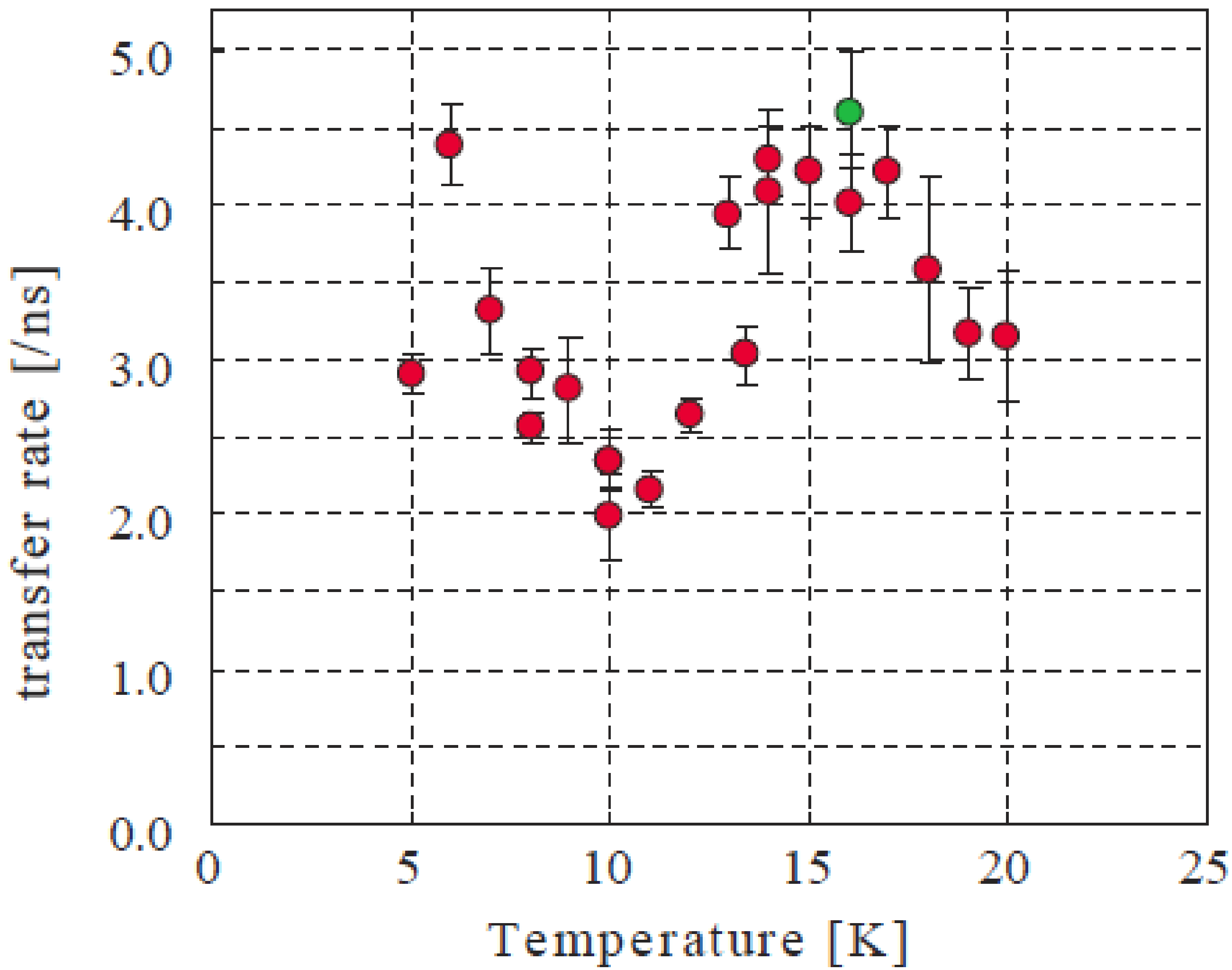
W: muon loss

λ_0: muon decay rate

Y_n : neutron yield

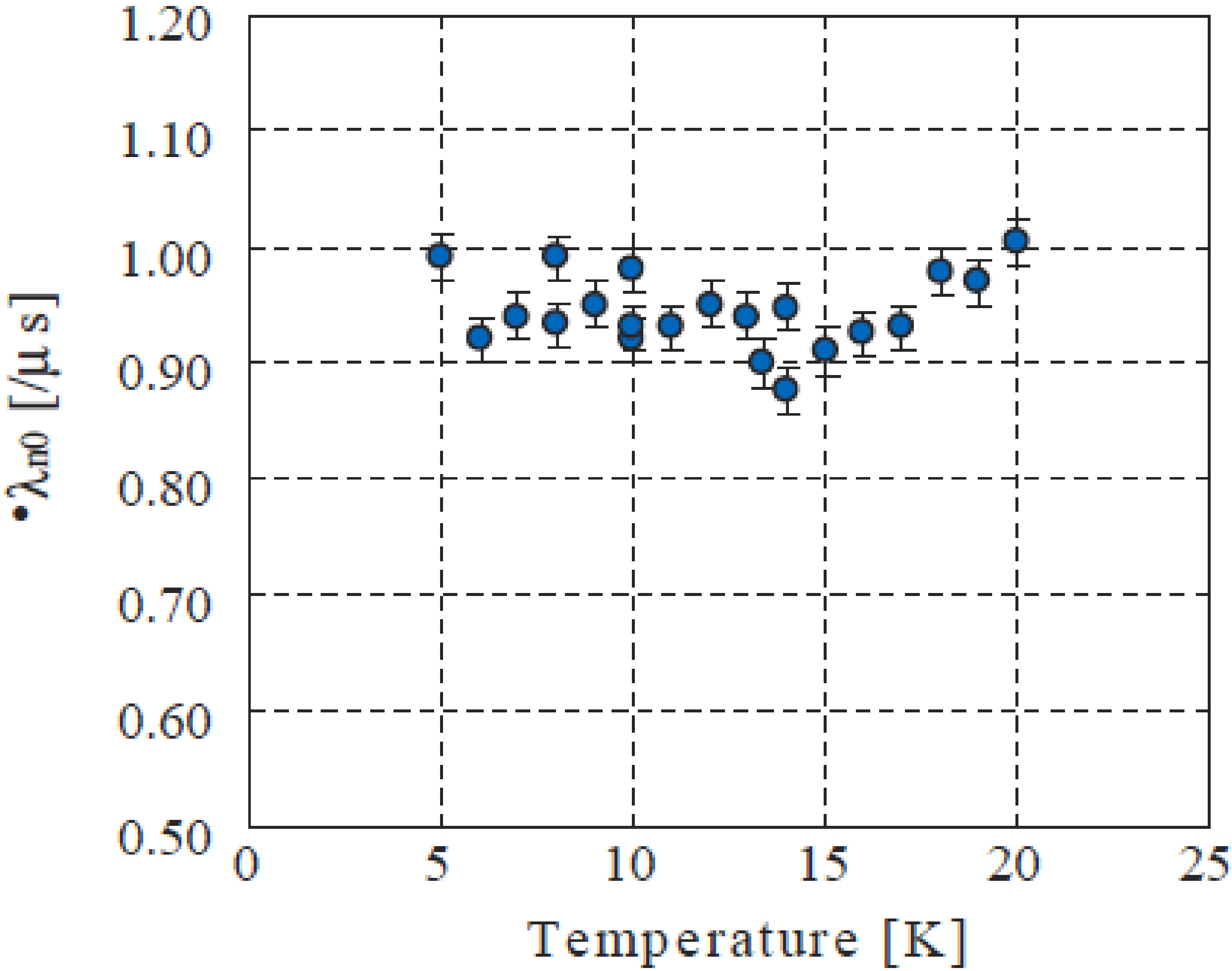
ϕ: target density

Muon transfer rates from tμ to ^{3}He in solid T_2 vs. Temperature



Reference: T. Matsuzaki et.al., Phys. Lett. B 527 (2002) 43

λ_{n0} (constant term) vs. Temperature



Observed phenomena:

Higher temperature region (>13K)

Good reproducibility of $\lambda_n(t)$ to the final state at temperature change (17-14K,14-13K,11-14-11K).

Lower temperature region (<10K)

Good reproducibility of $\lambda_n(t)$ to the final state at temperature change (6-10K).

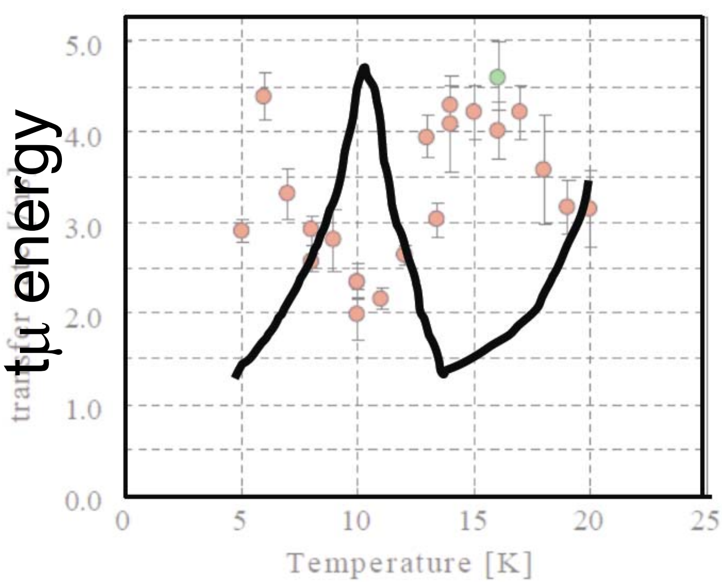
Intermediate temperature region (10-13K)

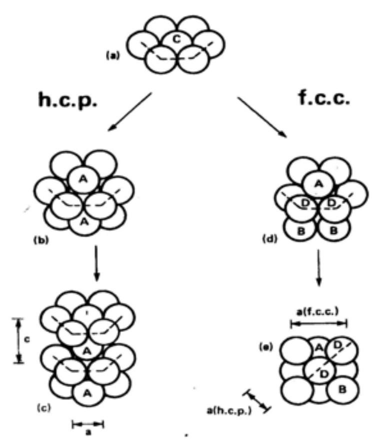
To reproduce $\lambda_n(t)$ to the final state at temperature change, it took longer time. (13-12-10K)

Possible scenario：

1. tμ$^-$ thermalization
2. Two ^{3}He sites in solid T_2 at high and low temperature regions
3. Lattice structure of solid T_2

Assumed tμ$^-$ energy vs. Temperature





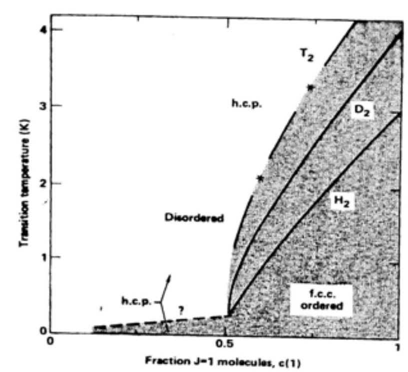


Fig. 6.1. The phase diagram of low-temperature solid hydrogen. A J = 1 fraction greater than 0.55 is needed to form the ordered f.c.c. phase. The T_2 line is our estimate. (Courtesy N. S. Sullivan and Les Editions de Physique.)

Two ^{3}He sites model:

1. Two ^{3}He sites in solid T_2:

   He((L) in low temperature and He(H) in high temperature

2. Muon transfer rate is reduced in He(L) by A_{eff}

3. No ^{3}He diffusion from He(L) to He(H)

4. Diffusion from He(H) to He(L) depends on temperature.

   Diffusion at higher temperature region (> 13K) is zero at He(H).

   Diffusion from He(H) to He(L) is very fast

   at lower temperature region (< 11K)

5. Diffusion probability from He(H) to He(L) after 1 hour : f(T)

   $f(T) = 1 / (1 + \exp (T - T_s) / dT)$

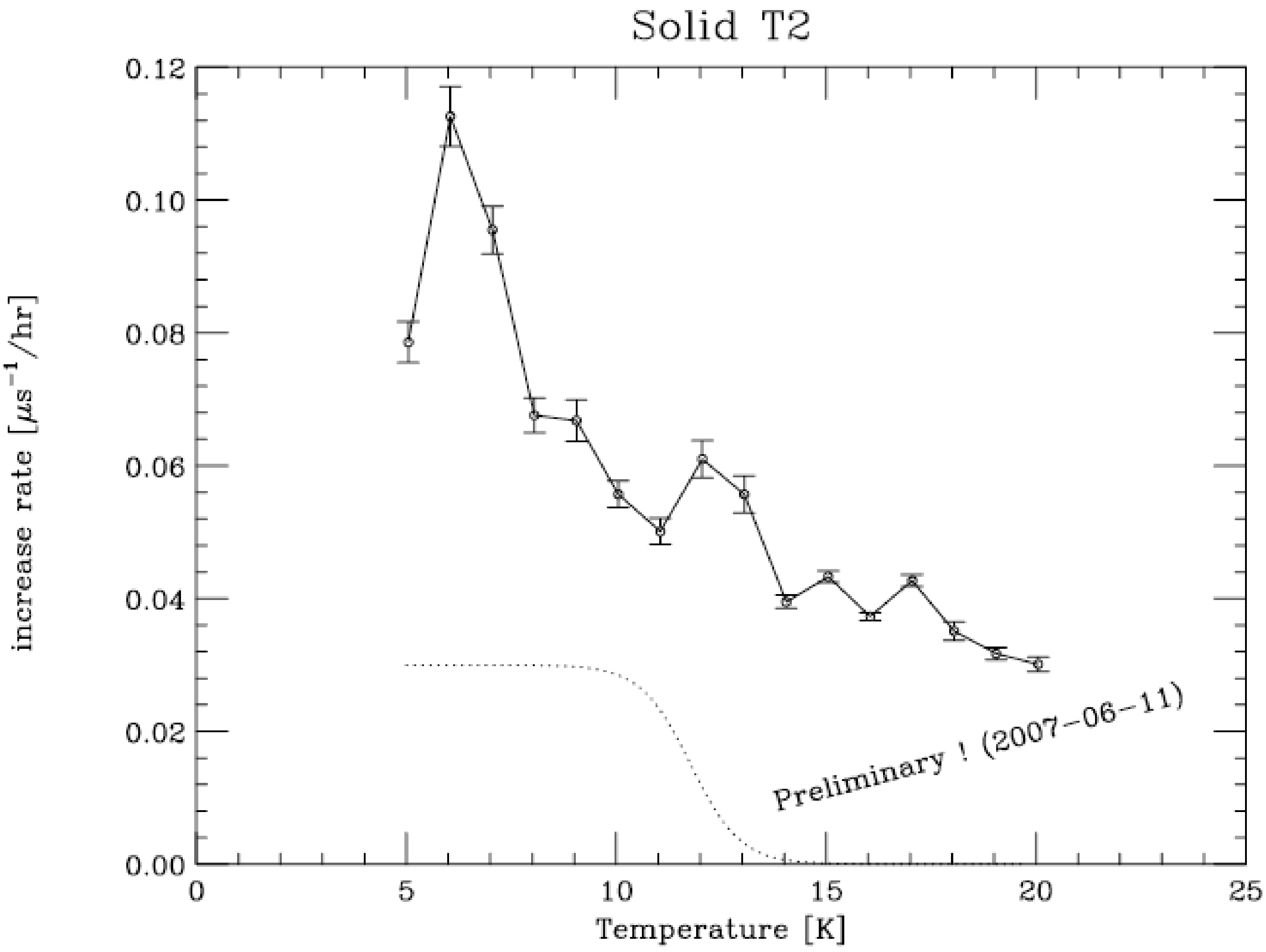
6. Fitting to data with free parameters (A_{eff}, T_s and dT)

7. Result: $A_{eff} = 0.59 +/- 0.06$

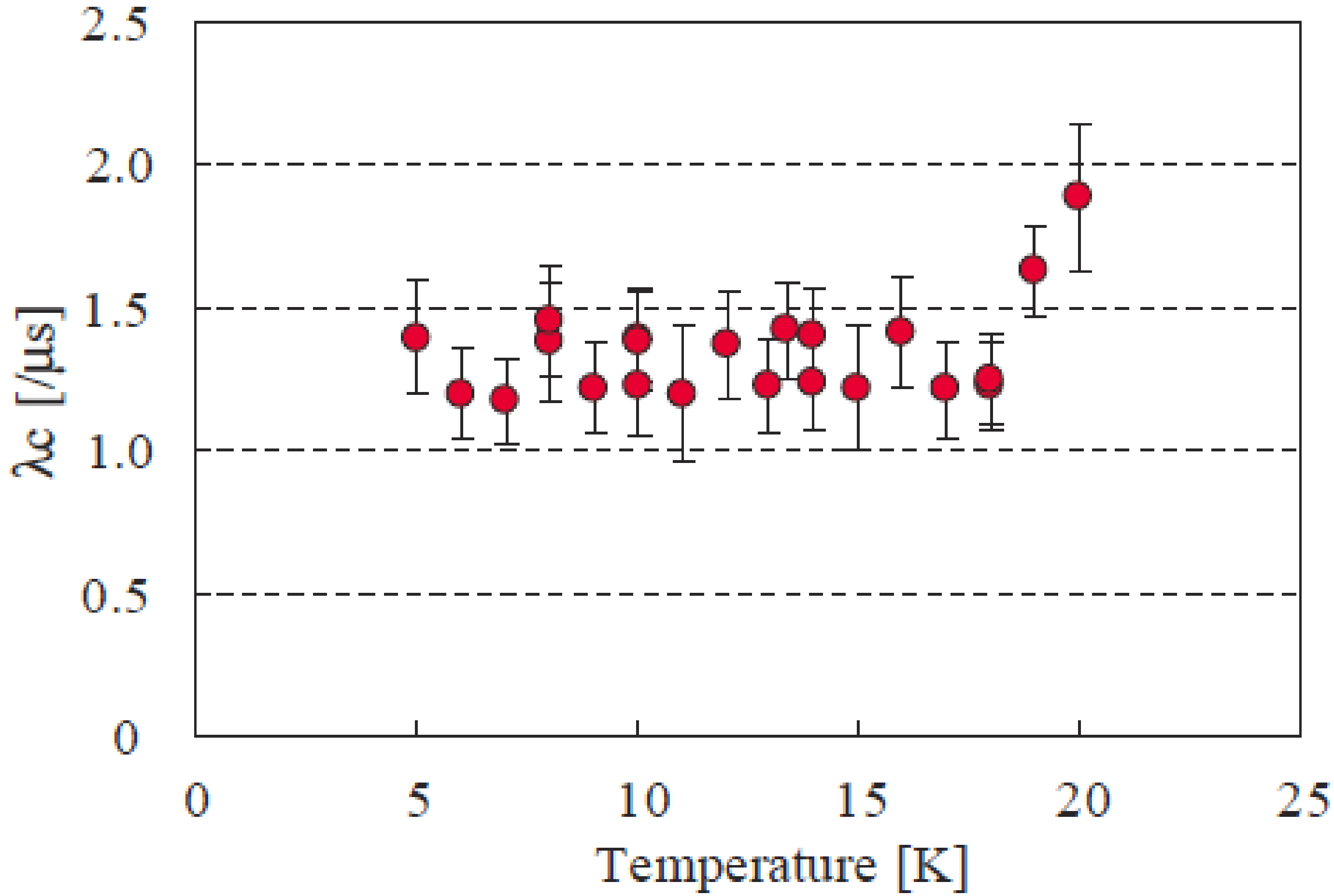
   $T_s = 11.8$ K

   $dT = 0.59$ K

λ_n increase rate (μs^{-1}/hr) vs. Temperature by two sites model



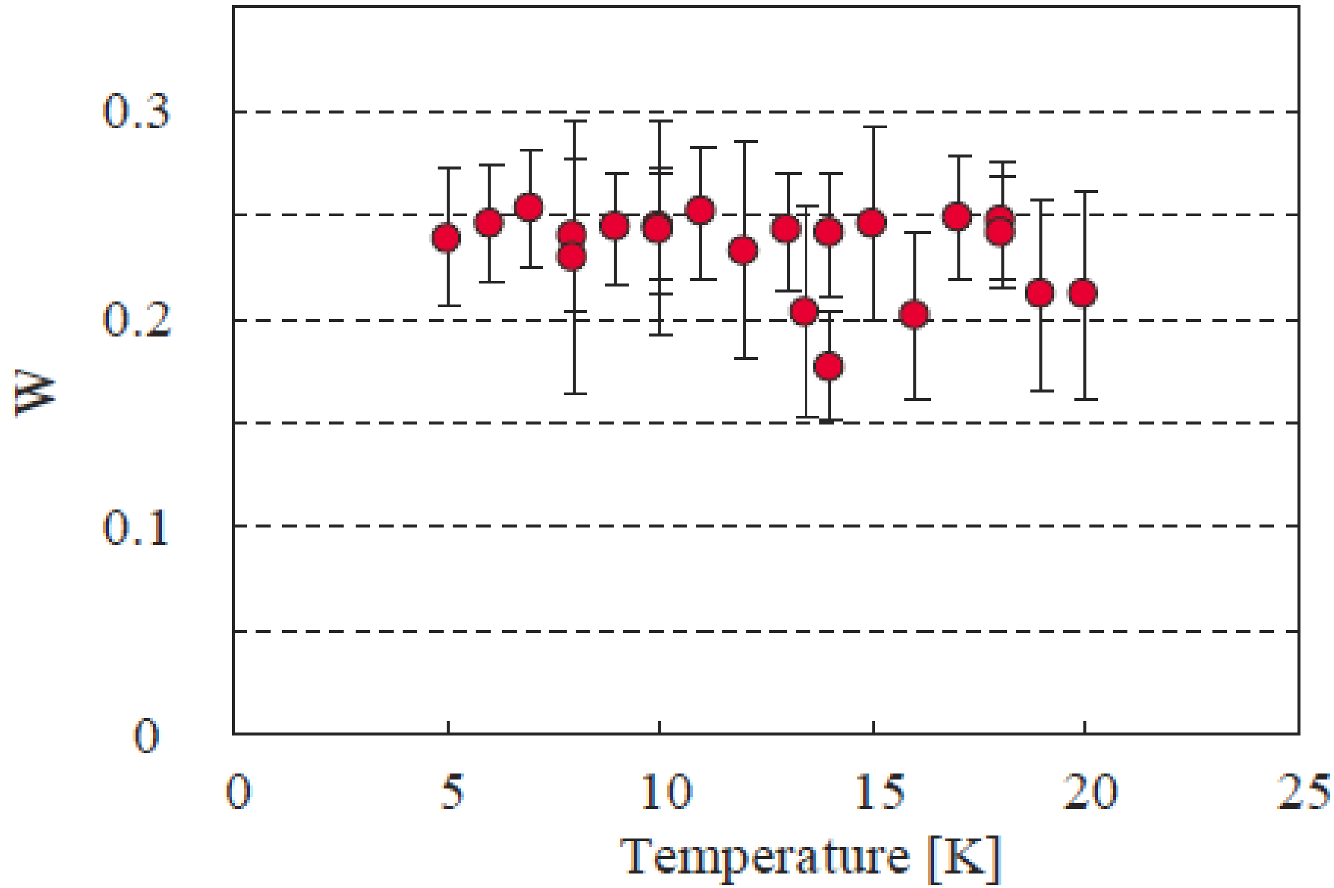
t-t μCF fusion cycling rate vs. Temperature



Reference: $\lambda_{t\mu t}$ = 1.8 +/-0.6 /μs Bruenlich et. al., Muon Catalyzed Fusion1(1987)121

λ_f = 15 +/-2 /μs

Total muon loss (W) vs. Temperature



Reference: ω_f = 0.14 +/-0.03 Bruenlich et. al., Muon Catalyzed Fusion1(1987)121

Summary:

Muon transfer rate

Moun transfer rates in solid T_2 were obtained by observing the time dependent changes of t-t μCF neutron disappearance rates.

The temperature dependence was obtained in the region from 5K to 20K, and showed an interesting structure.

Possible scenario：1. $t\mu^-$ thermalization

2. Two ^3He sites in solid T_2 at high and low temperature regions

3. Lattice structure of solid T_2

An interesting structure was analyzed by the two ^3He sites model, and a smooth temperature dependence, which was theoretically predicted, was well reproduced.

The origin of the interesting temperature dependence is still unclear, and be studied further.

Muon Catalyzed t-t fusion

The temperature dependences of t-t μCF cycling rates and total muon loss were obtained.

No prominent temperature dependences were observed.

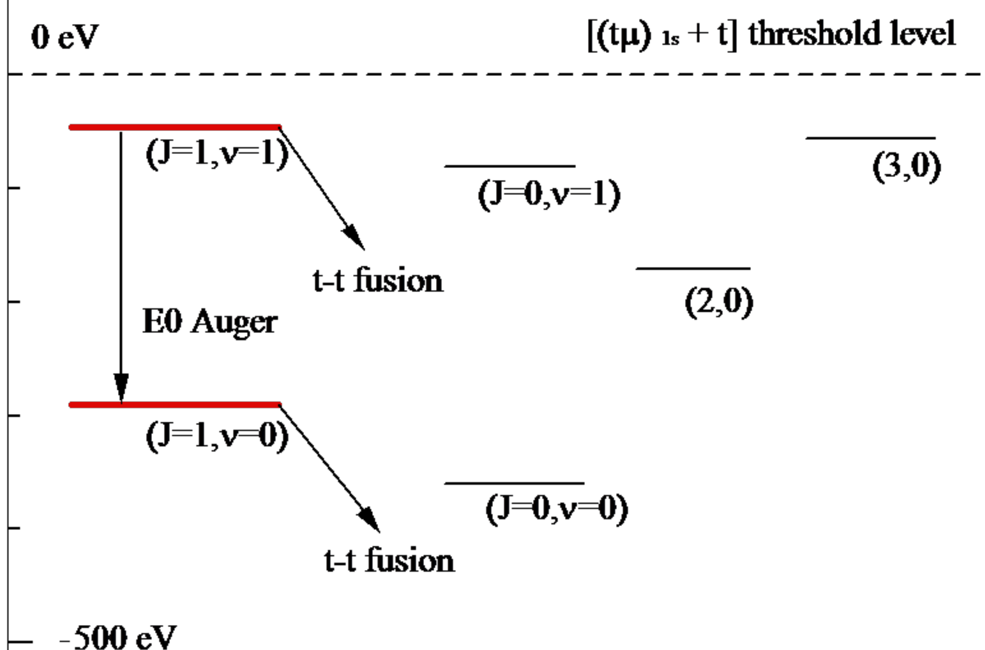
Non resonant $tt\mu$ formation in the t-t μCF cycle

The obtained cycling rate was in agreement with the PSI data.

Thank you for your attention.

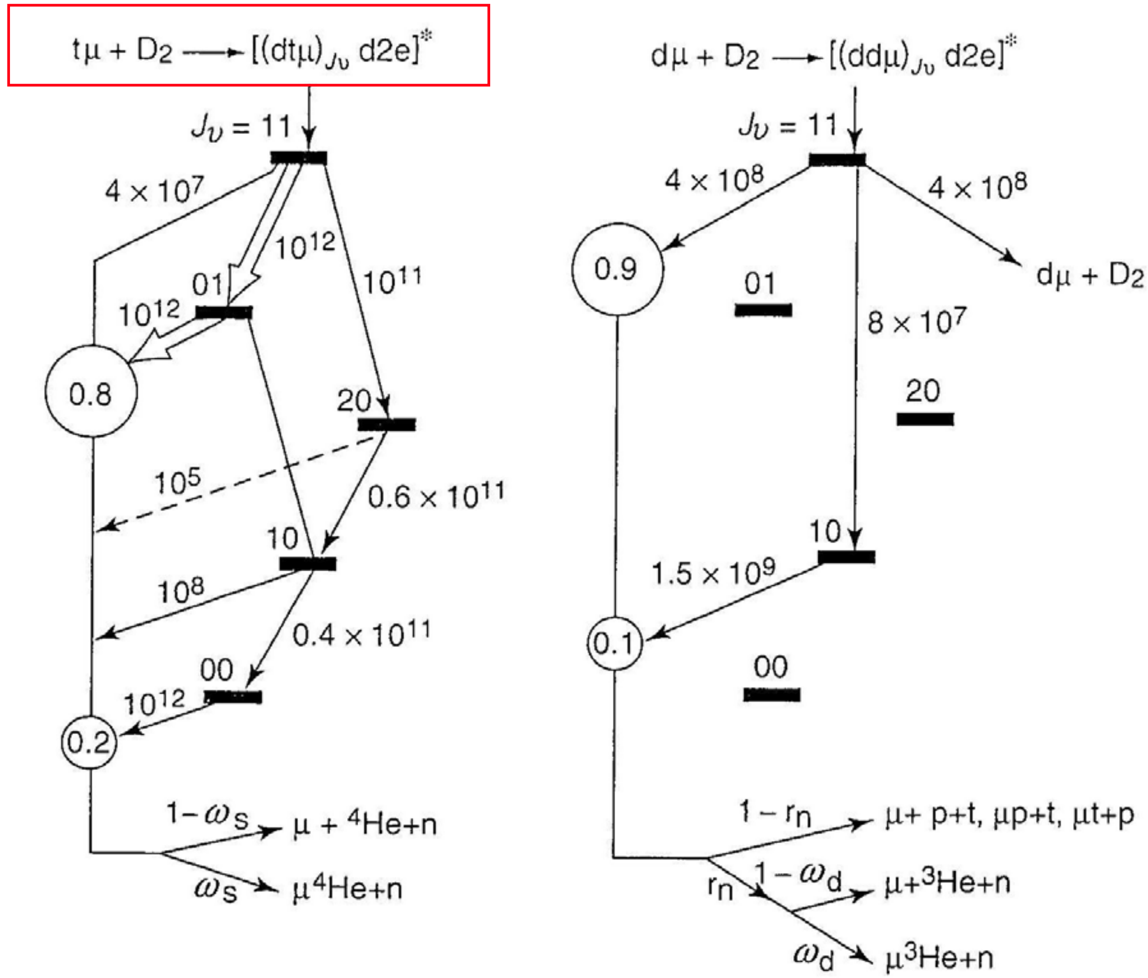
$$(t\mu) + T_2 \longrightarrow [(tt\mu)_{J\nu}\, t\, e]^+ + e$$

J: rotational quantum number
ν: vibrational quantum nimber



λ(E0 Auger) = 2 x10^8 /sec
$\lambda(\Delta=1) < 10^5$ /sec
λ((1,1), fusion) = 1.2 x10^7 /sec
λ((1,0), fusion) = 1.3 x10^7 sec

Energy: Y. Kino et. al
Fusion Science Tech. 41 (2002) 363
Transition rate: L.N. Bogdanova
Muon Catalyzed Fusin 3 (1988) 359



Scheme of cascade processes in $dt\mu$ and $dd\mu$ molecules after resonant molecular formation in the (1, 1) state, calculated by Bogdanova *et al.* (1982).