Review of Muon-Catalyzed Deuterium-Tritium Experiments

International Conference on Muon Catalyzed Fusion and Related Topics

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presented by
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outline of talk

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

(I) cycle & molecular formation rates
$\lambda_c$, $\lambda_{dt\mu}$, etc. are "reduced rates" normalized to liquid hydrogen density ($\varphi = 1 \sim 4.25 \times 10^{22}$ 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 $\mu \alpha$ sticking experiments & methods
$\omega_s$ is the final sticking probability after $dt\mu$ fusion
$w$ is the "effective sticking" = observed muon loss per cycle

• comparison of results & open problems - discussion - conclusions
I. the fast \( dt\mu \) 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 \( dt\mu \) analogue process to resonant \( dd\mu \) formation:

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

  \[ \lambda_{dt\mu} \sim 10^8 s^{-1}, \lambda_f \sim 10^{11} s^{-1}, \omega_s \sim 1\% \rightarrow \gamma_f \sim 100 \text{ fusions/}\mu \]

- **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 (\( c_t, \varphi < 0.1 \rightarrow T: 93K - 613K \)):

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

  \( \mu d \rightarrow \mu t \) transfer rate \( \lambda_{dt} = 2.9\pm0.4 \times 10^8 s^{-1} \)

- **1981** LAMPF and PSI laboratories prepare large \( dt\mu \) experiments
LAMPF 1983: first dtμ fusion results


first high yield D-T experiments at
$\varphi = 0.45 - 0.60, \; T = 100-540 \; K$

strong temperature effects observed!

cycle rates: $\lambda_c^{\text{max}} = 1.4 \times 10^8 \; s^{-1}$
effective sticking: $w = 0.77 \pm 0.08 \%$

projected max. fusion yield ($\varphi=1, 540K$):
$Y_f \sim 90 \; \text{fusions/µ}$

meso-molecular formation rates on

D₂ molecule: $\lambda_{dtμ-d} \; (T) \; 4 \to 7 \times 10^8 \; s^{-1}$
DT molecule: $\lambda_{dtμ-t} \; (T) \; 0 \to 3 \times 10^8 \; s^{-1}$
PSI 1983: first $\text{d}t\text{μ}$ fusion results

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


steady state: $\lambda_{c}^{\text{max}} = 0.55 \times 10^8 \text{ s}^{-1}$  $\lambda_{\text{d}t\text{μ}-d} = 1.0-1.3 \times 10^8 \text{ s}^{-1}$

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

time spectra of $\text{dt}$ fusion neutrons with steady state slopes and initial peaks due to thermalisation during first $\mu$s!
PSI 1984: first high yield data in D-T liquid & gas


strong density effects at low temperature observed

in liquid D-T at 20K, density $\phi = 1.2$:  \[ \lambda_{c}^{\text{max}} = 1.2 \times 10^8 \text{s}^{-1} \]

$\gamma_f = 113$ fusions/μ

$\lambda_{\text{dtμ-d}}(\phi) = 1.5 - 4 \times 10^8 \text{s}^{-1}$
LAMPF 1985/86: S.E. Jones reports new surprises
record cycle rates & yields  S.E. Jones et al., PRL 56 (1986) 588.

\[ \lambda_c \quad \text{max} = 1.5 \times 10^8 \text{s}^{-1} \quad (600K) \]

\[ \lambda_{\text{d}t\mu-d} (\phi) = 2 - 7 \times 10^8 \text{s}^{-1} \]

highest observed yield published:

\[ Y_f \sim 150 \pm 20 \text{ f/}\mu \]

in liquid D-T with

\[ \phi = 1.2, \ c_t = 0.3 \]

\[ \lambda_c = 1.1 \times 10^8 \text{s}^{-1} \]

\[ w = 0.35\% \ (\text{?}) \]

start of sticking controversy!
PSI 1987: new survey in solid, liquid & gaseous D-T

$\phi = 0.1-1.45$, $T = 12-30$ K, non-equilibrated $D_2+T_2$

C. Petitjean et al., MCF 2 (1988) 37, Hyp.Int.82 (1993) 273,

$\lambda_c^{\text{max}} = 1.3 \times 10^8 \text{s}^{-1}$ strong density effects confirmed!

$Y_f = 124 \text{ fusions/}\mu$ in solid non-equilibrated mixture

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Normalized cycle rates.}
\label{fig:cycle_rates}
\end{figure}
PSI 1987: the highest observed fusion yield
14-MeV neutron spectra from ultra-fast dµt cycle

solid D₂-T₂ at 12K non-equilibrated 40%-60% mixture

Λc = 1.95 \times 10^8 \text{s}^{-1}

φ = 1.45

w = 0.568 \%

ω_S = 0.48(4) \%

γ_f = 124 \pm 10

(presented 1987 at Gatchina µCF conference)
PSI apparatus in 1987

tritium cryotarget (20 cm³)  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)

$\rightarrow$ increased in non-equilibrated $D_2+T_2$ mixtures
$\rightarrow$ density dependence due to triple collisions
$\rightarrow$ $\lambda_{dt\mu-d}$ 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
$\rightarrow$ $\lambda_{dt\mu-t}$ large at high temperatures (~ 1000 K)

$\epsilon_{11} = -596$ 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

PSI experiments 1989-92 using Gatchina ionisation chamber:

fusion time distribution in H-D-T gas with $\varphi=0.17$, $c_p=0.9-0.97$, $c_t=0.036\%$
shows initial peak from epithermal $\mu t$

theory 1991:

plot of $\lambda_{dt\mu}$ vs. $\mu t$ energy
$\lambda_{dt\mu}^{max} \sim 10^{10} \text{ s}^{-1}$!
TRIUMF 1990\textsuperscript{th}: experiments in T-doped solid H\textsubscript{2}

M.C. Fujiwara et al., PRL 85 (2000) 1642,

diffusion of epithermal $\mu$t atoms due to Ramsauer-Townsend effect!
$\rightarrow$ direct observation of reactions with epithermal $\mu$t atoms on D\textsubscript{2} or HD

setup of solid H\textsubscript{2}(T) target for $\mu$t TOF measurement detecting $\alpha$ & n from dt$\mu$ fusion in D\textsubscript{2}, HD

$\mu$t + D\textsubscript{2}$ \rightarrow$ [dt$\mu$-dee]
showing epithermal resonances
TRIUMF run on $\mu t + HD \rightarrow [dt\mu_{(1,1)}p2e]$


qualitative agreement with Faifman-Ponomarev theory
of epithermal resonances
RIKEN-RAL 1990th dμ fusion in solid & liquid D-T

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

$\varphi$: 1.2 - 1.45, $T$: 16K / 20K

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

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

Cycle rates $\lambda_c$ in solid & liquid D-T
RIKEN-RAL 1995/96: temperature and density effects in solid D-T mixtures


\( \varphi: 1.2 - 1.45, \)

\( T: 5K - 20 K \)

density effects at low temperature
comparison with LAMPF & PSI data
explained by \( \varepsilon_{res} < 0 \)

temperature effects in solid D-T
unexplained! - due to solid state?
Dubna 1997-2005: new dmt experimental survey


ϕ: 0.2-1.2   T: 22K - 800K   81 \( \lambda_c \) - data points

\[ \lambda_c^{max} = 1.25 \times 10^8 \text{s}^{-1} \text{ (liquid DT)} - 1.73 \times 10^8 \text{s}^{-1} \text{ (T=800K)} \]
Dubna 2005 vs. LAMPF 1986

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

\[ \lambda_{dt\mu-d}(\phi) \quad \text{on } D_2 \]

\[ \lambda_{dt\mu-t}(T) \quad \text{on } DT \]

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?


favorable: more epithermal $\mu_t$ near the big mmf resonances due to Ramsauer-Townsend effect

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

Dubna result:
$H^1$ admixture reduces $\lambda_c$ in liquid phase and as well at higher Temp.!

- liquid phase 20K
- gaseous phase 300-800K
conclusions I on $\mu$CF rates

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

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

- low temperature resonance is $\mu t + D_2 \ (\lambda_{dt\mu-d})$; 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)

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

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

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


  The RIKEN/RAL experiment has reported strange temperature effects (16 K $\rightarrow$ 5K) K. Nagamine, Hyp.Int. 138 (2001) 5.
II $\mu \alpha -$ sticking

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

$\omega_s^o$  

$(1-R)$

$\omega_s^o$ initial sticking  

$R$ reactivation ($\mu \mu -$stripping)  

0.30-0.36  

slightly density dependent!

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

0.59-0.65%

$\omega$ „effective sticking“  

$= \omega_s +$ other muon loss terms  

e.g. dd, hd, tt, ht channels, $\mu$ transfers

fusion time curve & yield:

$N_f(t) = \Lambda_c e^{-(\lambda_\mu + \omega \Lambda_c) t}$

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

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

\[ \lambda_\mu \]
muon decay rate

\[ w = \omega_s + \text{other loss channels} = \text{muon loss per cycle} \]

\[ \Lambda_c = \varphi \lambda_c \]
effective cycle rate

\[ \gamma_f = \frac{\Lambda_c}{(\lambda_\mu + w \Lambda_c)} \]
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 $\lambda_n = - (\lambda_\mu + w \Lambda_c)$

$\Rightarrow w$ most sensitive to large $\Lambda_c \ (\gg \lambda_\mu)$

all observed in liquid and solid D-T mixtures!

solid non-eq DT $\Lambda_c = 2 \times 10^8 \text{ s}^{-1}$
liquid DT $\Lambda_c = 1.5 \times 10^8 \text{ s}^{-1}$
world results on $w$ from high-yield $n$-disappearance data

**LAMPF 1986:** $w_s = 0.32(3)\%$
(liquid D-T)

**RIKEN-RAL:**
- $w_s = 0.515(30)\%$ (liquid D-T)
- $w_s = 0.532(30)\%$ (solid D-T)

**PSI 1987/93:** $w_s = 0.485(17)\%$
(liquid & solid D-T)

**Dubna 2005:** $w_s = 0.574(22)\%$
(liquid D-T)
## Summary Table of $w$ & $\omega_s$ from Neutron Slope Data

*(The World's High-Yield Data in Liquid & Solid D-T)*

<table>
<thead>
<tr>
<th>Lab</th>
<th>references</th>
<th>condition</th>
<th>$c_t$</th>
<th>$\Lambda_c$</th>
<th>$\Lambda_s$</th>
<th>$w$</th>
<th>$Y_f$</th>
<th>$\omega_s$</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMPF 1984</td>
<td>S.E. Jones et al. PRL 56 (1986) 558</td>
<td>liquid $\varphi=1.2$</td>
<td>0.3</td>
<td>120</td>
<td>144</td>
<td>0.35(3)</td>
<td>150</td>
<td>0.32(3)</td>
<td>inconsistent!</td>
</tr>
<tr>
<td></td>
<td>Hyp.Int.82(1993)303</td>
<td>liquid $\varphi=1.14$ non eq.</td>
<td>0.7</td>
<td>102</td>
<td>117</td>
<td>0.70(3)</td>
<td>92</td>
<td>0.43(5)</td>
<td></td>
</tr>
<tr>
<td>PSI 1984</td>
<td>W. Breunlich et al. PRL 58 (1987) 329</td>
<td>liquid 23K $\varphi=1.20$</td>
<td>0.32</td>
<td>122</td>
<td>145</td>
<td>0.57(3)</td>
<td>113</td>
<td>0.45(5)</td>
<td>global fit</td>
</tr>
<tr>
<td></td>
<td>C. Petitjean et al. Hyp.Int.82(1993) 273</td>
<td>solid 12K $\varphi=1.45$ non eq.</td>
<td>0.41</td>
<td>134</td>
<td>195</td>
<td>0.568(12)</td>
<td>124</td>
<td>0.485(17)</td>
<td>8% calib.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>liquid 23K $\varphi=1.21$ non eq.</td>
<td>0.41</td>
<td>134</td>
<td>162</td>
<td>0.554(14)</td>
<td>120</td>
<td>0.466(21)</td>
<td>8% calib.</td>
</tr>
<tr>
<td>RIKEN-RAL 1996</td>
<td>K.Nagamine et al. &amp; K. Ishida et al.</td>
<td>solid 16K $\varphi=1.45$</td>
<td>0.3</td>
<td>~100</td>
<td>~145</td>
<td>0.57(3)</td>
<td>~113</td>
<td>0.515(30)</td>
<td>global fit</td>
</tr>
<tr>
<td></td>
<td>Hyp.Int.138(2001) 25</td>
<td>liquid 20K $\varphi=1.25$</td>
<td>0.3</td>
<td>~110</td>
<td>~137</td>
<td>0.62(3)</td>
<td>~105</td>
<td>0.532(30)</td>
<td>global fit</td>
</tr>
<tr>
<td>JINR Dubna 2003</td>
<td>V.R. Bom et al. JETP 100 (2005) 663</td>
<td>liquid 22K $\varphi=1.20$</td>
<td>0.334</td>
<td>118</td>
<td>141</td>
<td>0.72(6)</td>
<td>97</td>
<td>0.574(22)</td>
<td>global fit</td>
</tr>
</tbody>
</table>
2) X ray method

\[ dt\mu \rightarrow \mu\alpha^* \rightarrow \mu\alpha + X \]
3) direct observations of sticking

**PSI**

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

**1992**

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

**final result:**  

\[ \omega_S = 0.57 \pm 0.04 \% \]

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

\[ \omega_5 = 0.565 \pm 0.052 \% \]

proves beyond any doubt presence of sticking!

(a) direct observation
with sticking & stripping

(b) events with 2\textsuperscript{nd} fusion
sticking peak absent!
direct observation of initial sticking $\omega_s^0$

LAMPF
M.A. Paciotti et al.
S.E. Jones, AIP 181 (1989) 2

D-T mixture at 2.4 bar ($c_- = 40\%$)

$\omega_s^0 = (0.80 \pm 0.15 \pm 0.12)\%$

theory: $(0.92 \pm 0.02)\%$

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 μα sticking

- the slope results scatter ±14% around a “world average” $\omega_s = 0.5\%$
  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 $\approx$ consistent with theory
  $(0.574\pm0.022)\%^{\text{exp}}$ vs. $(0.60\pm0.02)\%^{\text{th}}$

- the X ray method (RIKEN/RAL) experiment observes 10–20% lower
  X ray yields and there are some inconsistencies with $K_B$, $K_Y$ yields

- the $\omega_s$ direct observation (PSI) experiment agrees nicely with theory
  $(0.57\pm0.04)\%^{\text{exp}}$ vs. $(0.62\pm0.02)\%^{\text{th}}$

- the $\omega_s^0$ direct observation (LAMPF) experiment also agrees with
  theory, though within large errors $(0.80\pm0.15\pm0.12)\%^{\text{exp}}$ vs. $0.92\%^{\text{th}}$

- question: can sticking be overcome?
  the exp. answer is: no evidence! It looks very difficult to go
  beyond $d\mu t$ fusion yields of $\approx 130$ per muon.
what can we experimentally do in the future?

- understand better the $\mu$t kinetics, especially at the epithermal resonances $\rightarrow$ 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 Japanese group for the J-PARK facility)

we wish for these upcoming experiments good luck!