Muon Catalyzed d-t Fusion in Non-equilibrated Mixtures of T_2 with Normal, Ortho and Para-rich D_2

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-μCF collaboration)

Effect of ortho-, para-D_2 in dt μCF

Experimental methods

Result

Muon catalyzed fusion in D/T

More than 100 fusions were observed per muon

Scientific breakeven can be achieved at 300 fusions

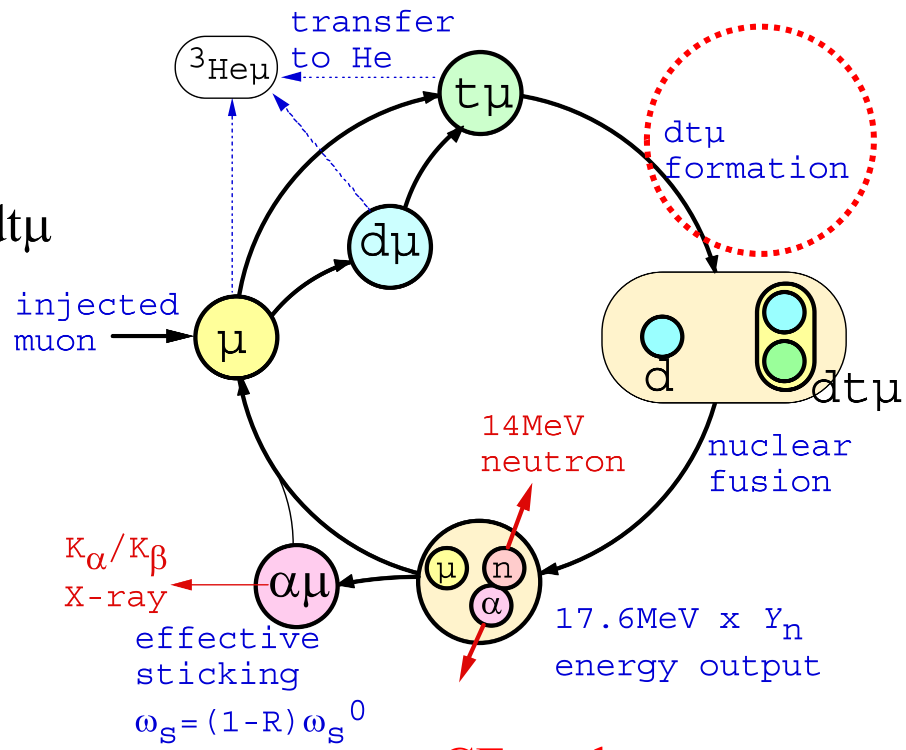
Efforts towards μCF improvement

(1) reaction rate >> muon decay rate (0.45 x 10^6 /s)

- muon thermalization, muonic atom formation
- cascade in muonic atom
- muon transfer
- dtμ formation
- cascade in dtμ, dt fusion in dtμ

(2)muon loss probability<<1

- alpha sticking : ω_s
    - initial sticking
    - muon reactivation
    - by muon stripping
- muon transfer to helium etc



μCF cycle

The most important process in μCF - $dt\mu$ formation

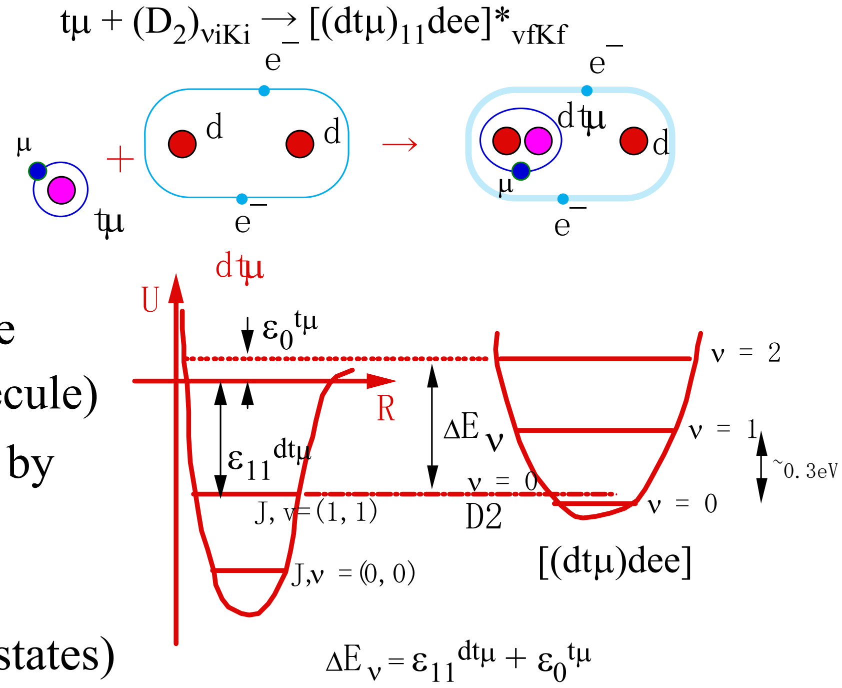
Auger electron emission : 10^6 /s

$t\mu + D_2 \rightarrow (dt\mu) + D + e^-$

resonant molecular formation : 10^9 /s

$t\mu + D_2 \rightarrow ((dt\mu)\ dee)$

$t\mu + DT \rightarrow ((dt\mu)\ tee)$



($dt\mu$ binding energy is absorbed by the excitation of the final composite molecule)

(a small energy difference is matched by $t\mu$ kinetic energy)

large dependence on temperature and on initial molecular state ($t\mu$ spin state, DT, D_2 states)

μCF efficiency could be improved by selection of initial D_2 state

Previous measurements: non equilibrium D/T effect

$dt\mu$-formation was known to be enhanced in non-equilibrated D2/T2 mixture

LAMPF (Jones et al, μCF89, Oxford)

PSI (Ackerbauer et al, Nucl. Phys. A652(1999)311)

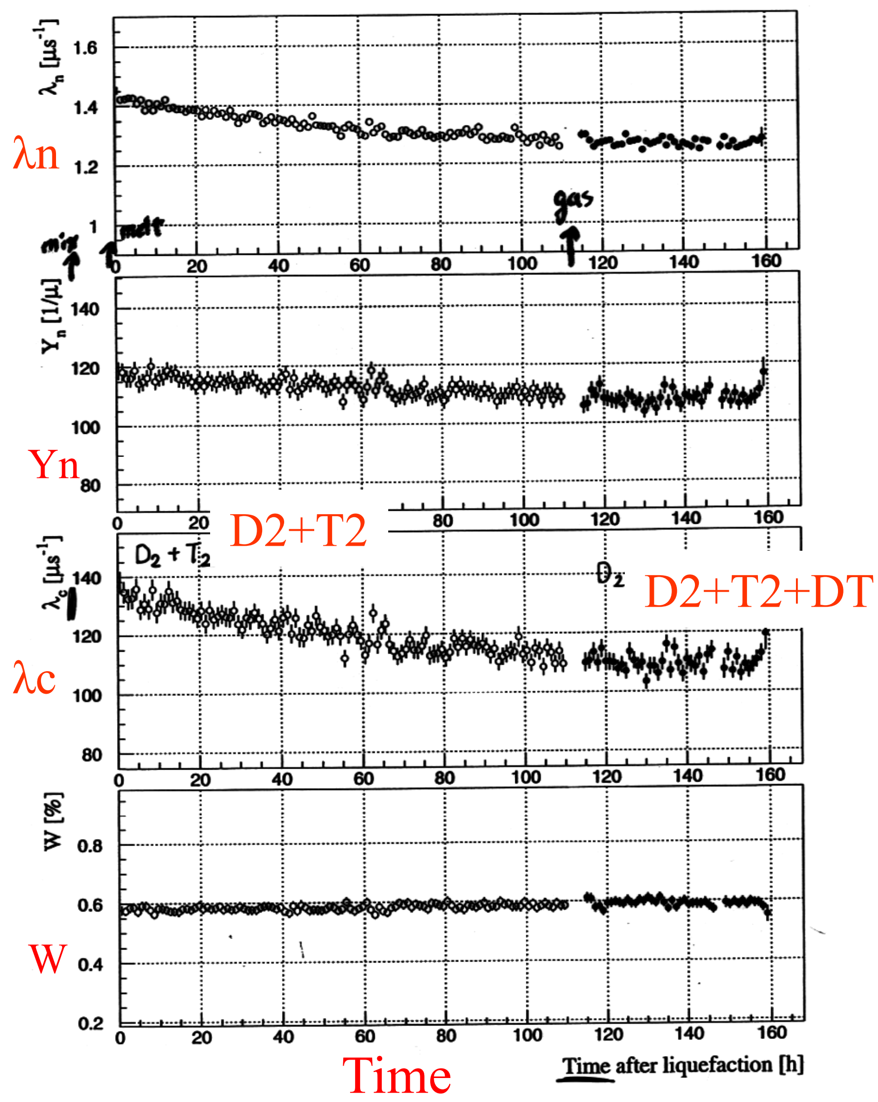
λc(equ.) = 110 μs^{-1}, λc=130(n.equ.) at Ct=0.418

RIKEN-RAL (Aug 2001 RUN) →

1. mix D_2 and T_2 at low temperature (Liq 20K)
2. $D_2 + T_2 \rightleftarrows 2DT$

fusion neutrons decreased as the molecular composition gradually reached equilibrium (time constant ~55 hours at 20K)

confirmation of $\lambda_{dt\mu}^{0,D2} >> \lambda_{dt\mu}^{0,DT}$



Non-equilibrium μCF with ortho-, para-D_2

We have developed production method of ortho- and pard-D_2 for dd μCF experiment (Imao's talk)

Ortho D_2

Ki=even (0, 2, 4,…) coupled to I=0, 2

Para D_2

Ki=odd(1, 3,…) coupled to I=1

Once formed in one state, mutual conversion requires change of coupled nuclear spin state and is usually slow (months)

The small difference in rotational energy (Ki=0 and 1, 7.4 meV) is large enough to affect resonant molecular formation both in dd- and dt-μCF

Theories on ortho/para effect

1. Model with idealistic gas

  tμ + D_2 -> [(dtμ)dee]

contribution of para-D_2 is dominant

at low temperature

 [Leon, Cohen Phys.Rev. A31 (1984) 2680]

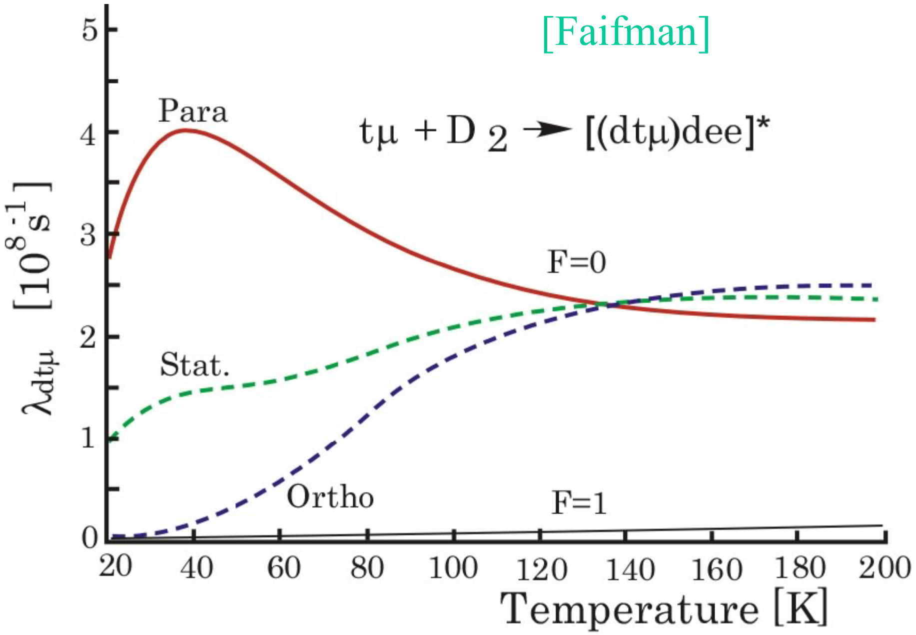
 [Faifman] →

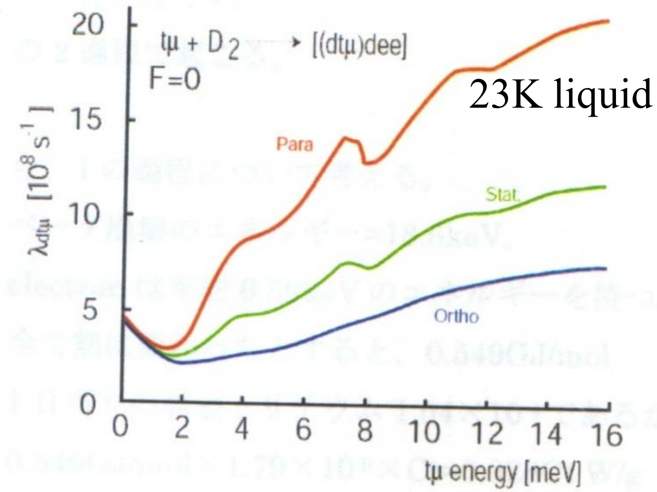
2. with condensed matter effect

  broadening of molecular energy

   under development

 [Adamczak, habilitation thesis 2003] →





A large effect by ortho/para

D_2 selection is expected

Practical problems: Ortho-para state relaxation in D/T

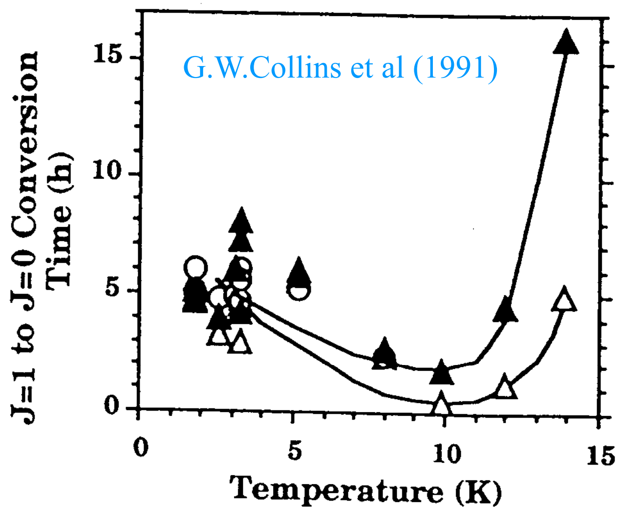
Produce ortho-D_2 or para-D_2 and mix with T_2

Enhancement of μCF right after mixing, but

1. Equilibration by molecular reconfiguration
 (~55 hour in D/T(50%) by our measurement)

$$D_2 + T_2 \rightleftarrows 2DT$$

2. Equilibration of ortho-para state by radiation effect
 ortho-para transition by paramagnetic T atom
 according to a reference
 16 hours in 14K solid D/T(50%)
 (no liquid data, T atom concentration could
 reduce by recombination, while mobility
 could be larger)



Expected μCF with ortho/para D2+T2

Cycling Rate

$$\lambda c = 1/(\tau d+\tau t)$$

$$=1/[\, q_{1s} C_d/(\lambda_{dt} C_t) + (3/4)/(\lambda_{t\mu}{}^{1,0} C_t) + 1/(\lambda^{0}{}_{dt\mu\text{-}D2(o,p)} C_{D2(o,p)} + \lambda_{dt\mu}{}^{0,DT} C_{DT})]$$

av. time waiting dμ->tμ transfer

av. time in tμ(F=1) state

av. time before dtμ formation

assuming

$Ct = 0.4,\ Cd = 0.6$

$q_{1s} = 0.4$

$\lambda dt = 280\ [\mu s^{-1}]$

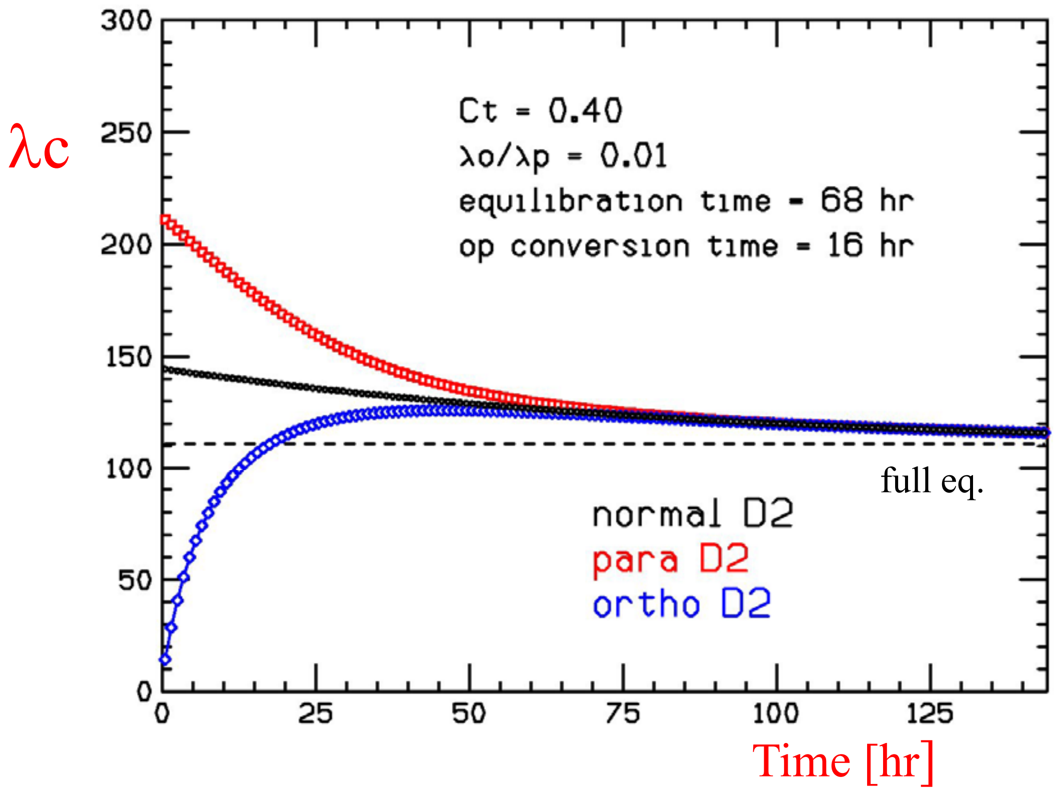
$\lambda_{t\mu}{}^{10} = 1300$

$\lambda_{dt\mu}{}^{0,DT} = 10$

$\lambda_{dt\mu}{}^{0,D2(o)} = x$

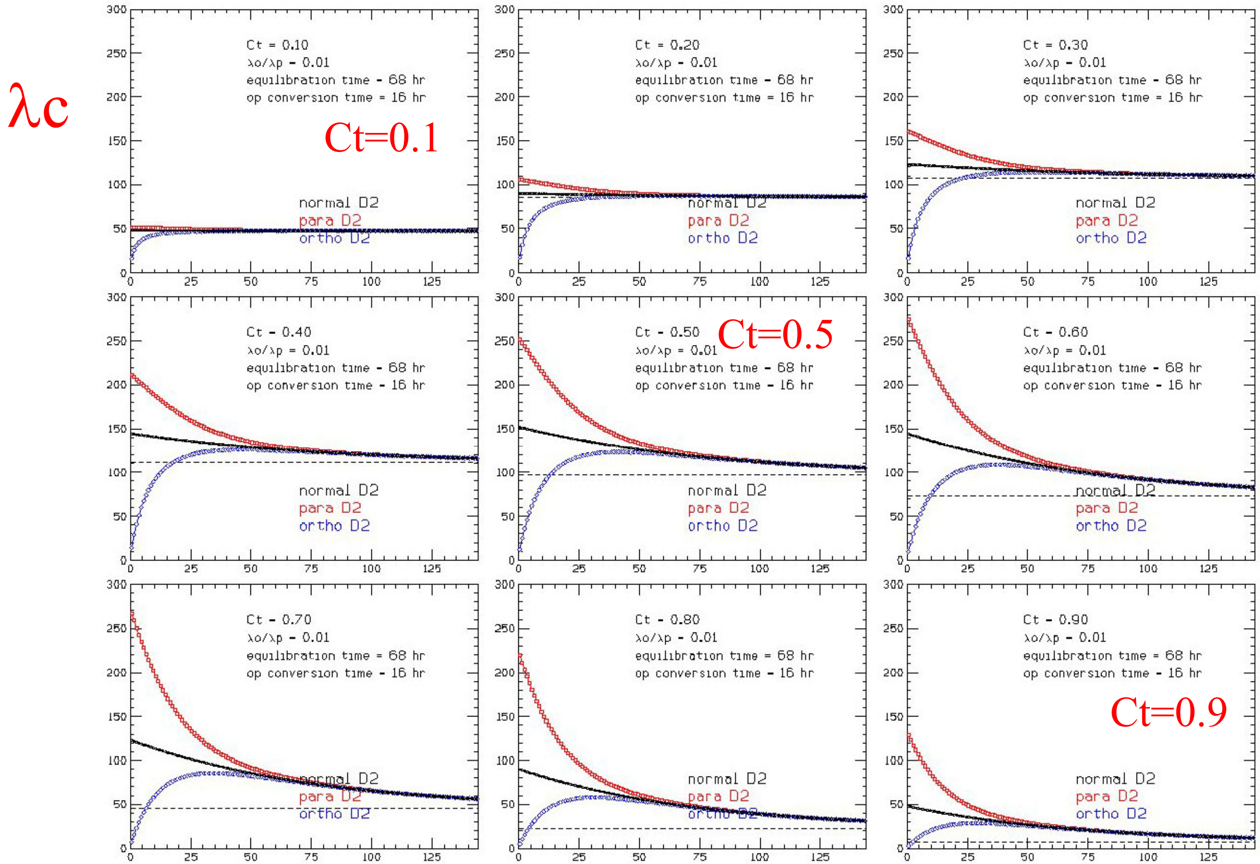
$\lambda_{dt\mu}{}^{0,D2(p)} = y$

$(2/3)x + (1/3)y = 500$



Expected effect – based on gas model result

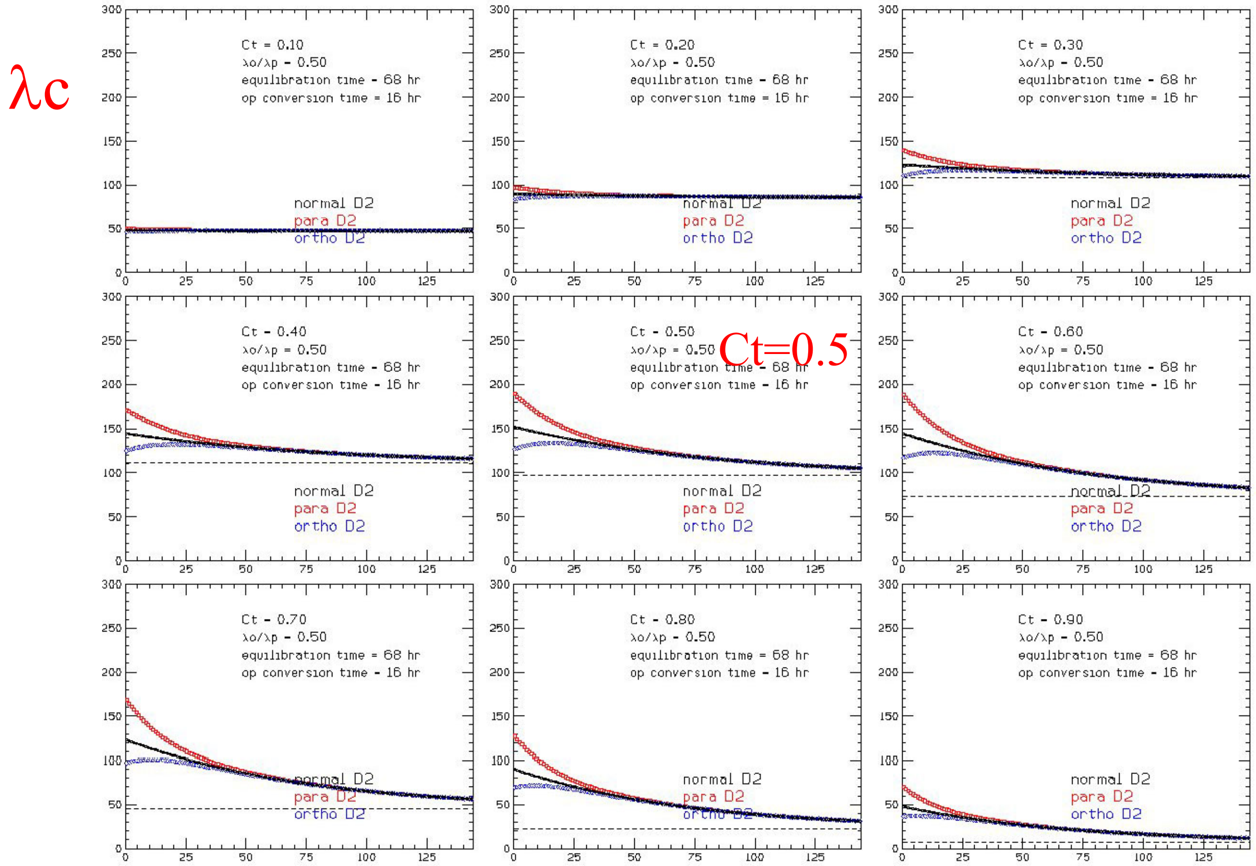
$\lambda_{dt\mu}(\text{ortho})/\lambda_{dt\mu}\ (\text{para}) = 0.01\ (Ct = 0.1 \sim 0.9)$



Expected effect – based on theory with condensed matter effect

$\lambda_{dt\mu}$ (ortho)/$\lambda_{dt\mu}$ (para) ~ 0.5 (Ct = 0.1 ~ 0.9)

Ct ~ 0.5 is best suited for the measurement



A possible way to the largest μCF yield

Increase of cycling rate

high density ϕ (liquid, solid)

faster dtμ formation rate

D_2 para-rich (or ortho-rich)

Decrease of muon loss rate

high density (liquid/solid) -> high reactivation after μα sticking W ~ 0.6%

Normally, muon catalyzed fusion efficiency in liquid D/T ~110/muon

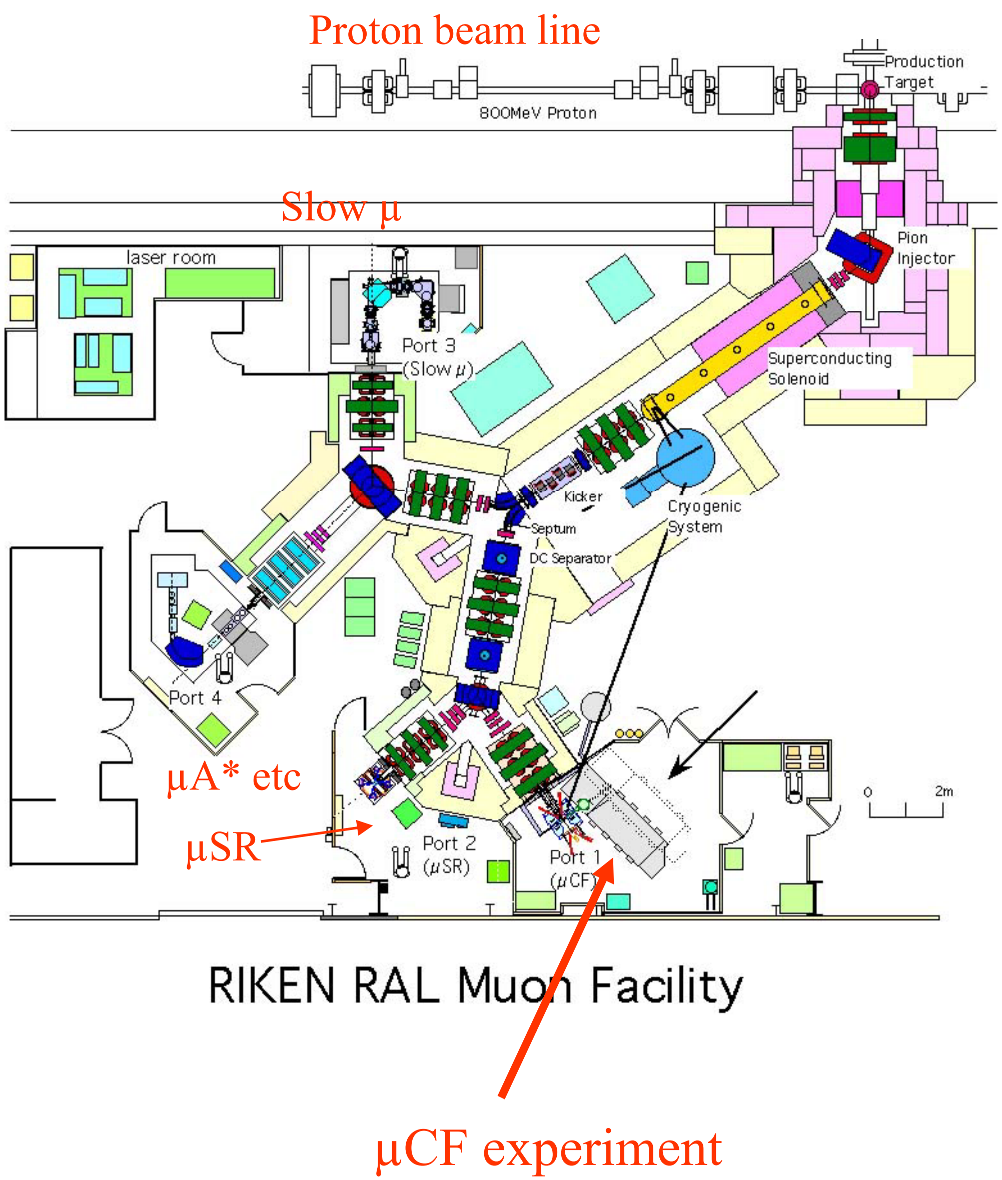
if $\lambda c=300$

$Yn = \lambda c/\lambda n = 1/(\lambda 0/\phi\lambda c + W) = 1/(0.45/1.25*300+0.006)=140$

RIKEN-RAL Muon Facility

RIKEN has constructed
a muon facility at RAL, UK

μCF dedicated port
tritium gas handling system



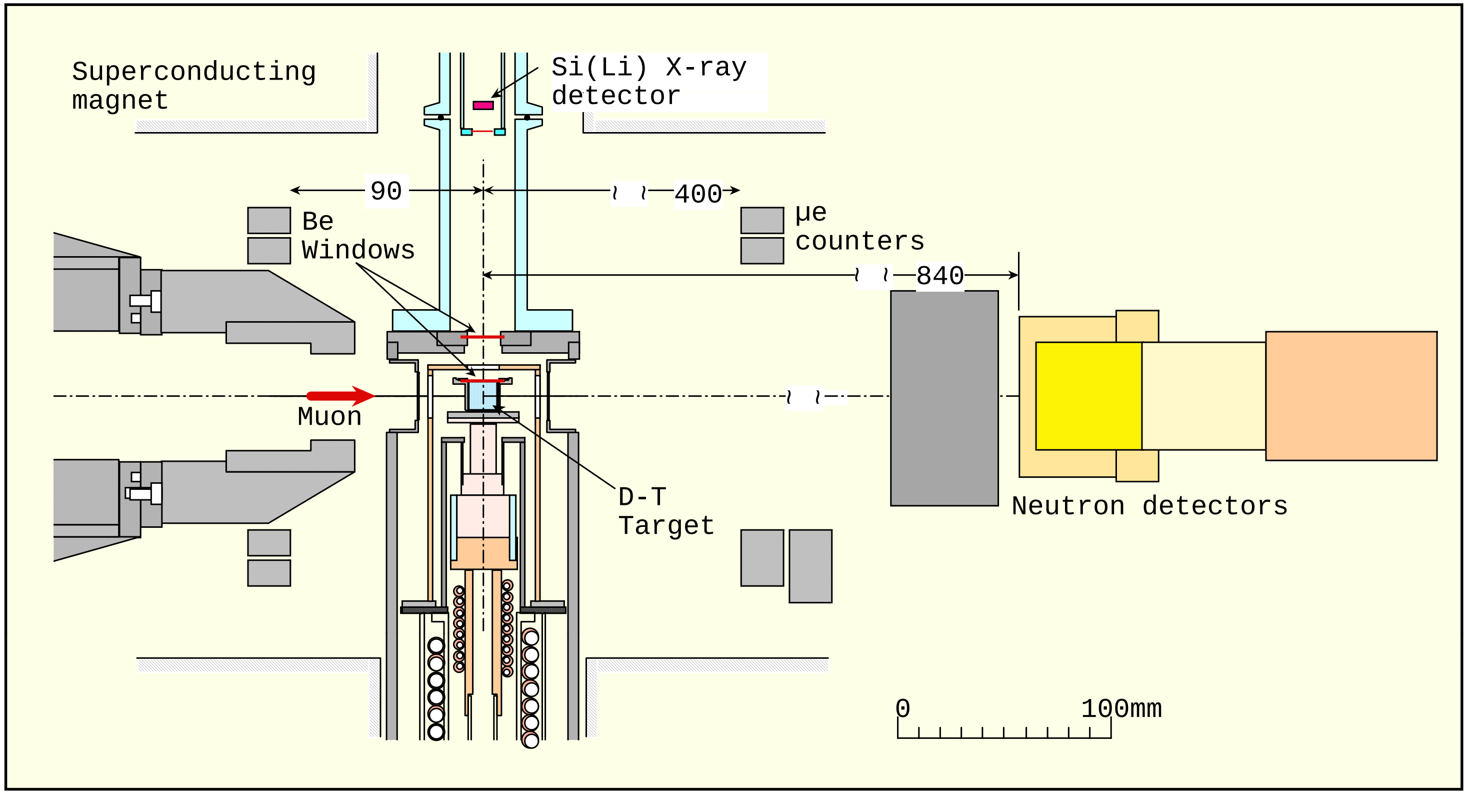
μCF experimental setup

1cc low temperature D/T

strong pulsed muon beam at RIKEN/RAL ~100 /pulse

superconducting magnet for muon focusing

detectors for neutron, x-rays and μe decay

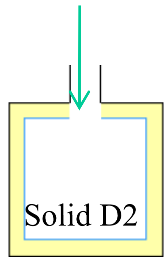


Preparation of noneq. D_2+T_2 target

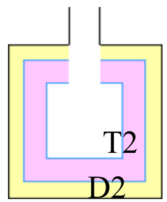
1) Production of normal, ortho, and para-rich D_2
   purification through Pd filter (normal D_2)
   + catalysis conversion at 12K (ortho (99%) D_2)
   or +selective adsorption on Al_2O_3 (para-rich (72%) D_2)

2) Sample Raman analysis of ortho/para ratio

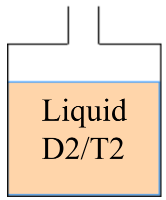
3) Solidify D_2 into target cell (10K) through TGHS



4) Charge T_2 in TGHS and purify (~3 hours)
   and solidify into target (~30 min)

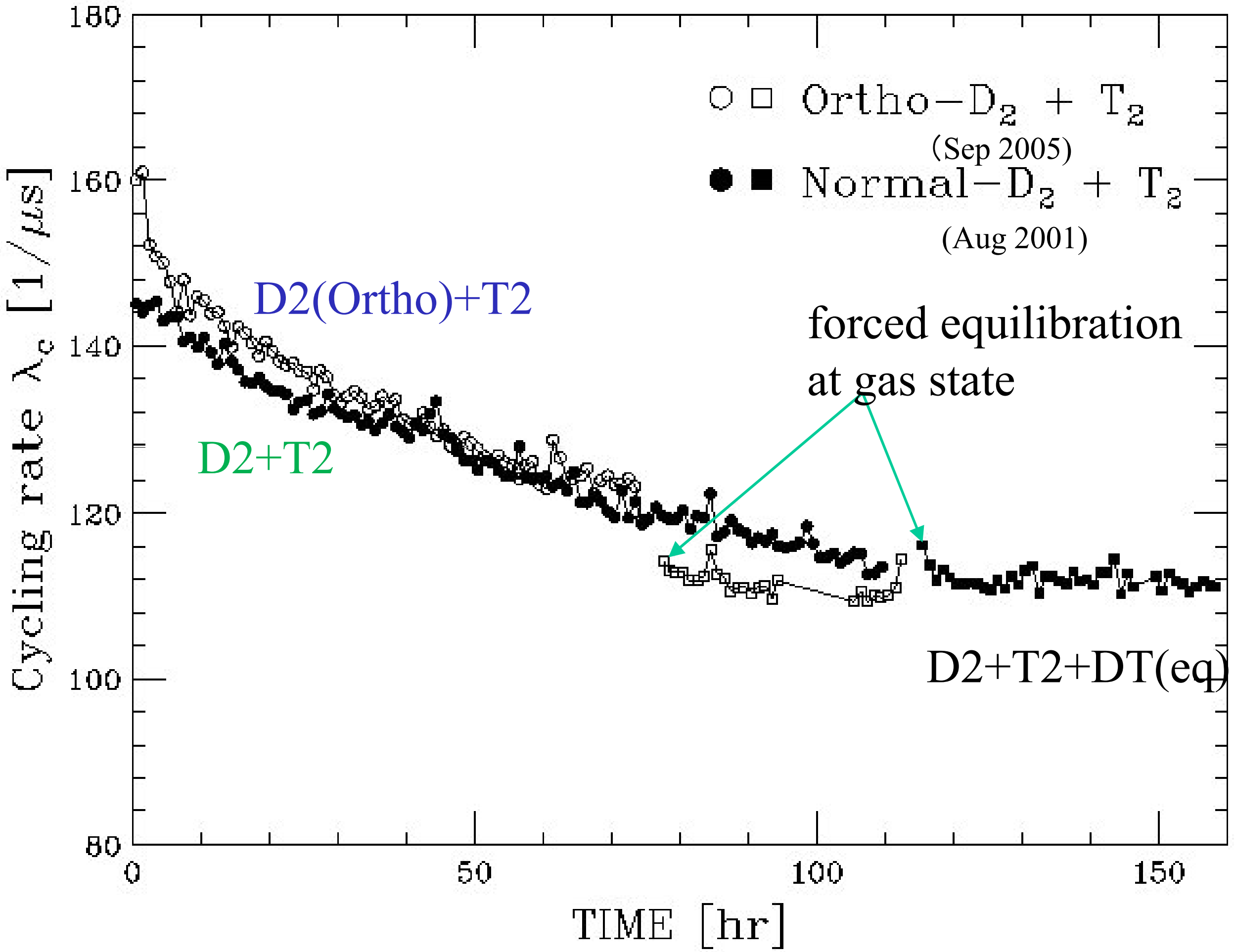


5) mix D_2 and T_2 by melting (time zero),
   μCF measurement at 20K liquid



6) after several days,
turn to 300K gas to force equilibration,
restart μCF measurement with equilibrated gas

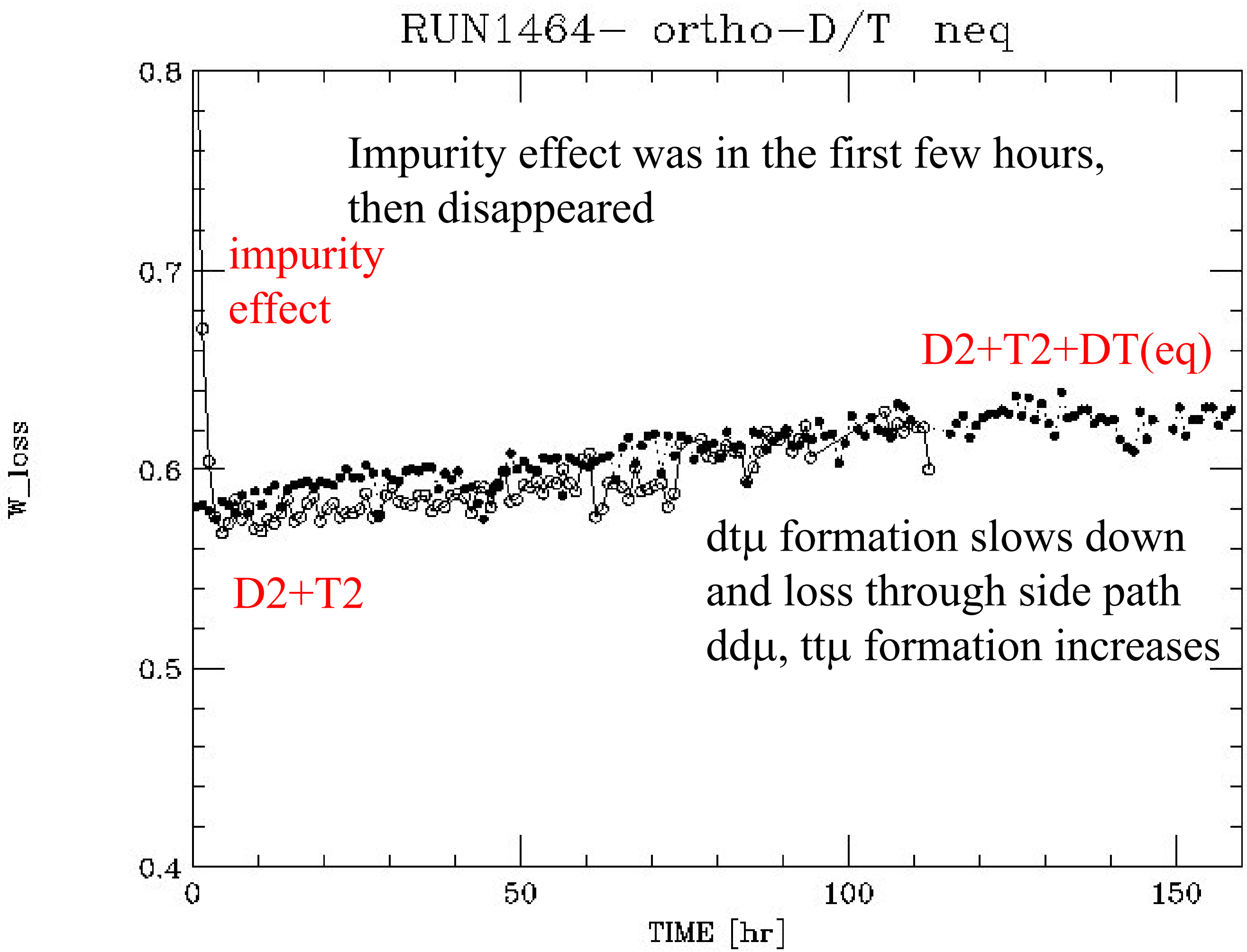
Result of Aug 2001 and Sep 2005 RUNs: Cycling rate : λc



Difference between normal D_2 and orthoD_2 was observed but was not so convincing at this stage:

It was small (~5%) and opposite to most of the prediction

Result: Muon loss probability W



New Dec ‘06 RUN (para rich D_2+T_2)

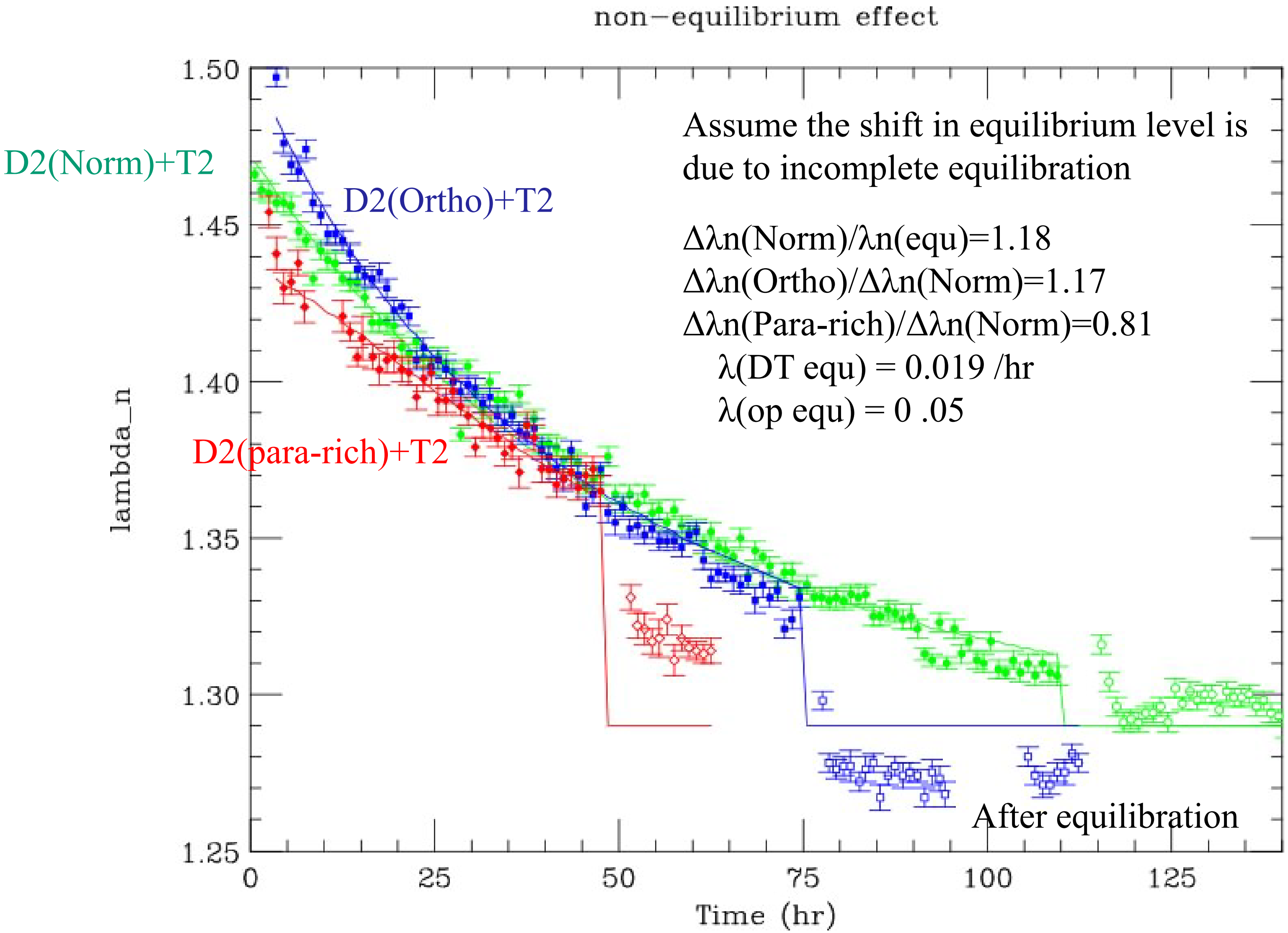
New non-equilibrium RUN with para-rich (72%) D_2 was done in Dec 2006.

The RUN has much smaller muon intensity (30%) than usual due to proton beam-line problem,

and shorter beam time (late completion of gas preparation)

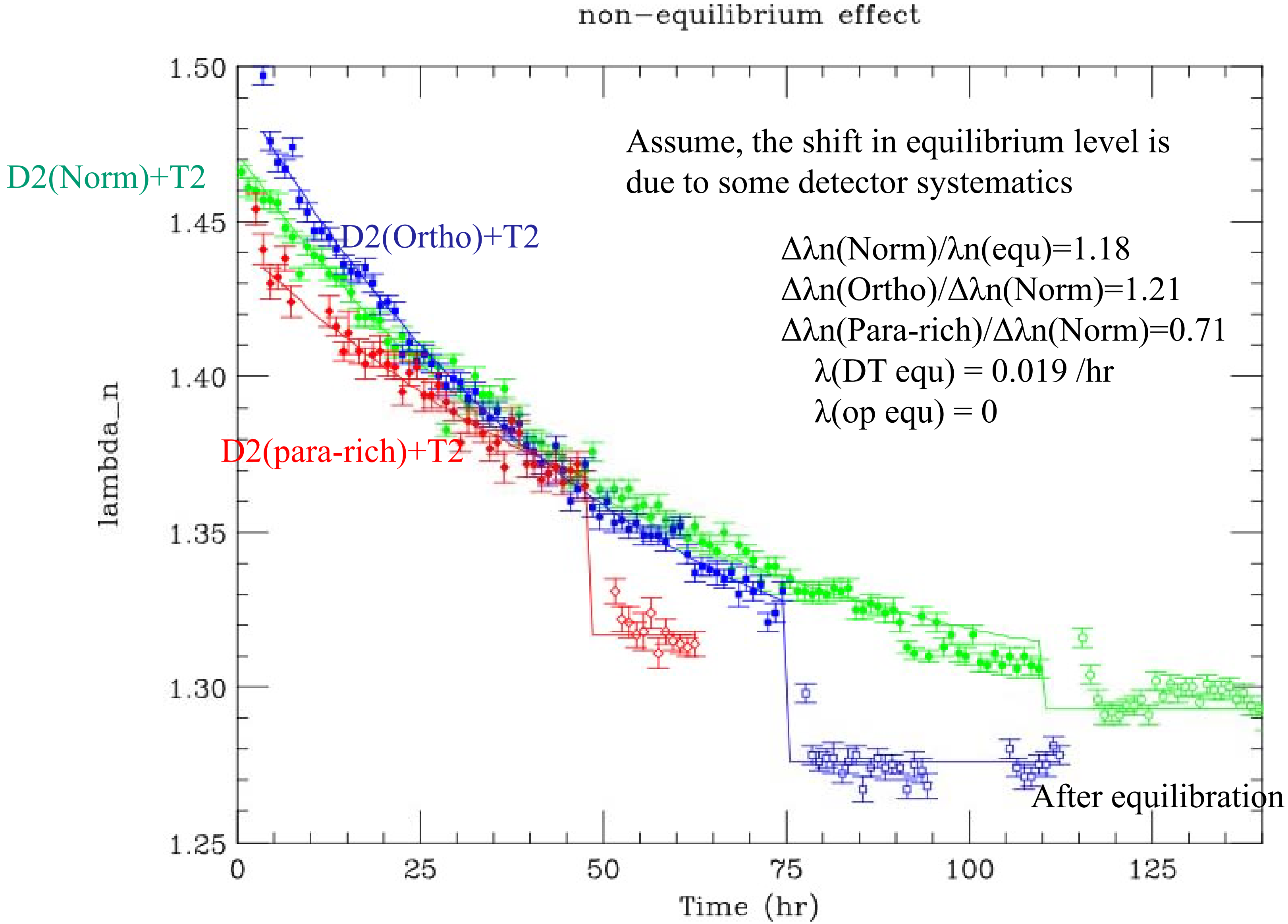
Due to lower statistics and possible systematic (S/N?) problem we show analysis on λn ($\lambda n = \lambda 0 + W\phi\lambda c$) only

Analysis -1



non-equilibrium effect
D2(Norm)+T2
D2(Ortho)+T2
D2(para-rich)+T2
Assume the shift in equilibrium level is due to incomplete equilibration
Δλn(Norm)/λn(equ)=1.18
Δλn(Ortho)/Δλn(Norm)=1.17
Δλn(Para-rich)/Δλn(Norm)=0.81
λ(DT equ) = 0.019 /hr
λ(op equ) = 0 .05
After equilibration
lambda_n
Time (hr)
1.50
1.45
1.40
1.35
1.30
1.25
0
25
50
75
100
125

Analysis -2


non-equilibrium effect
D2(Norm)+T2
D2(Ortho)+T2
D2(para-rich)+T2
Assume, the shift in equilibrium level is
due to some detector systematics
Δλn(Norm)/λn(equ)=1.18
Δλn(Ortho)/Δλn(Norm)=1.21
Δλn(Para-rich)/Δλn(Norm)=0.71
λ(DT equ) = 0.019 /hr
λ(op equ) = 0
After equilibration
lambda_n
1.50
1.45
1.40
1.35
1.30
1.25
0
25
50
75
100
125
Time (hr)

Conclusion from ortho/para-D_2/T_2 RUNs

In both analysis with different assumptions ,

the effects of the order of 20% were observed in enhancement (or decrease) of λn change for each case using ortho or para-rich D_2.

This can be converted to ~5% increase (or dcrease) in λc, and extrapolation to full range ortho-para effect indicates 15% effect

(and $\lambda_{dt\mu}$(ortho)/$\lambda_{dt\mu}$ (para) ~1.4)

Also,

1) Equilibration time for D_2/T_2 in our 20K liquid target is about 50 hours

2) ortho-para conversion in liquid D/T is long enough so each state stays long enough for our measurement

Summary and future plans

Summary

1. The ortho-para effect in dt-μCF was observed for the first time using liquid D_2/T_2 (T=20K) mixtures
2. μCF with ortho-D_2 showed larger dtμ formation rate (contrary to theory)
3. Transient behavior of the target towards equilibration was observed

Plans:

Short term

Repeated measurement with para-rich D_2/T_2 target at full muon intensity, and at larger para- concentration(>90%)

Long term

Target with in situ Raman analysis with optical window