Muon Catalyzed Fusion in Gas/Liquid/Solid D2 under Controlled Ortho-Para Ratio

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Introduction

Meanings of μCF experiment with ortho-para controlled D2

- Search for efficient μCF toward energy break-even
- Understand rich physics of muonic atom and molecule in μCF

Early studies

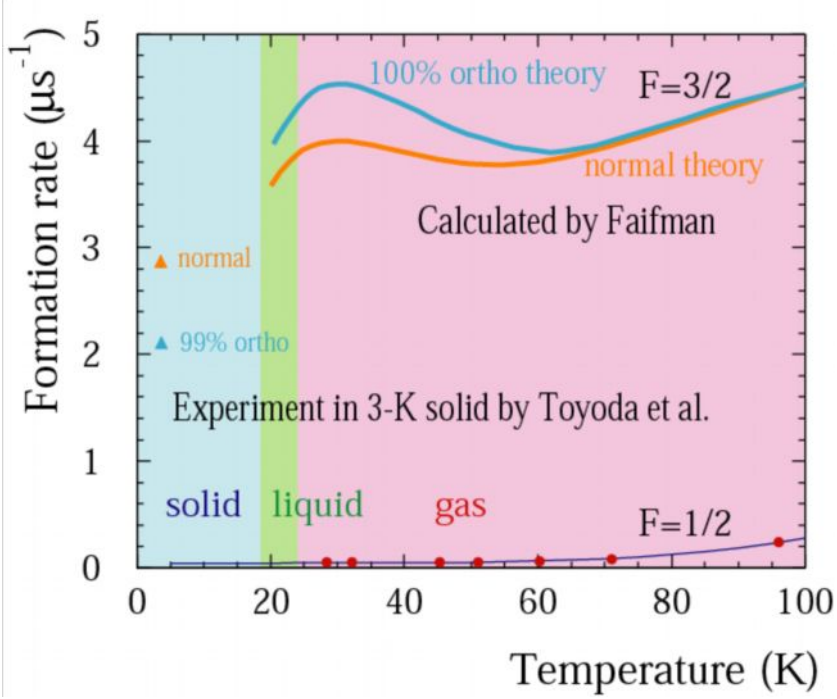
⇒ **only in solid at 3 K**

[A.Toyoda et al. Phys.Rev.Lett.24 243401(2003)]

- Thin solid layer target
- Fusion proton detection
- Thermal conductivity

The results are disagree with theory

⇒ condensed-matter effects in solid?



We studied ortho-para effect in solid, liquid, and gas

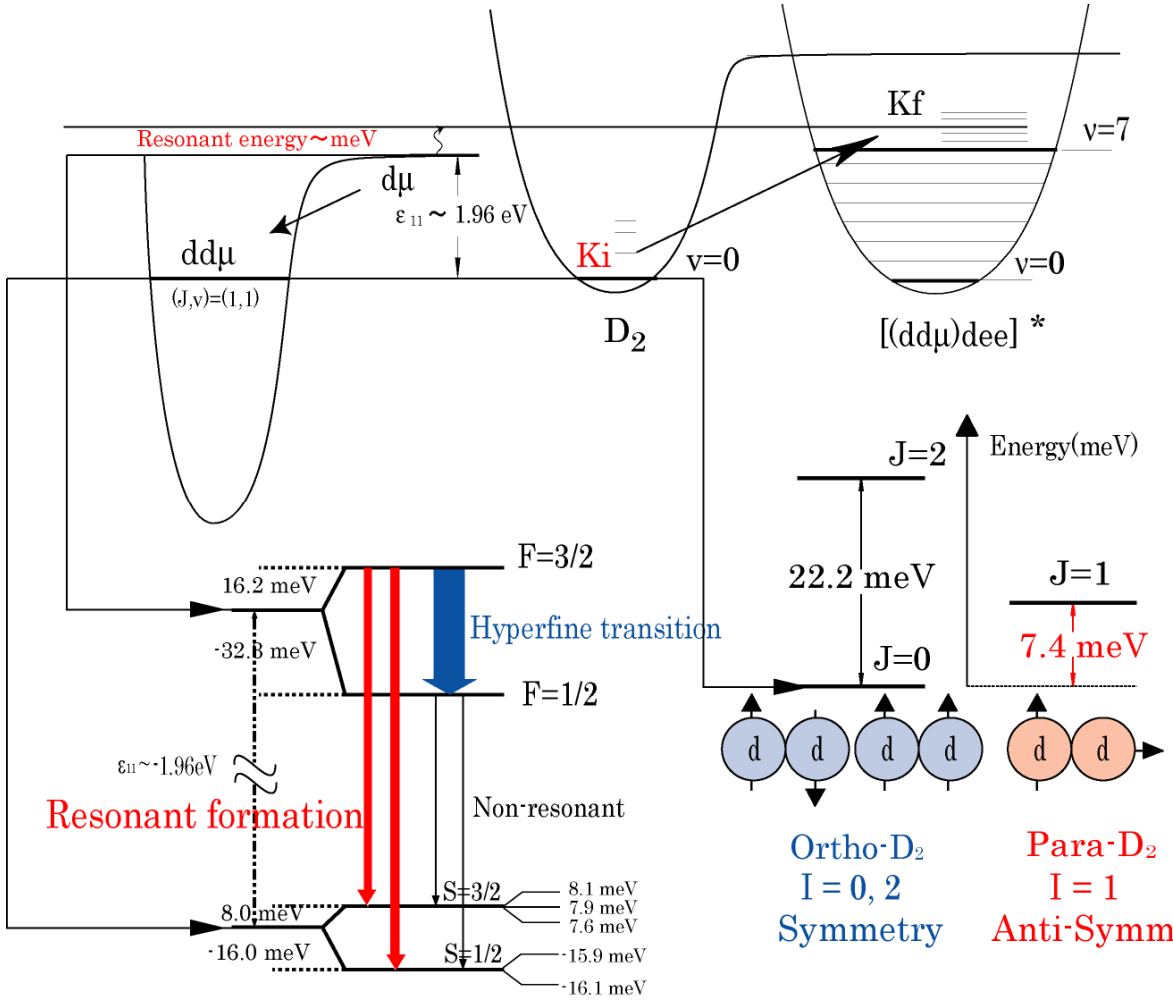
- Large volume target (<30 litter at STP) ⇒ Good S/N ratio
- Fusion neutron detection ⇒ Long mean free path
- Raman spectroscopy method ⇒ Absolute o/p ratio

Ortho-Para Effect

$$d\mu\ F=3/2 + D_2\ K_i=x\ v_i=0 \Leftrightarrow [(dd\mu)_{J=1,v=1}\ dee]_{K_f=x\ v_f=7}$$

Ortho-para effect was firstly pointed out by Leon and Cohen

[M. Leon and J.S. Cohen, Phys. Rev. A31 (1985) 2680]



Ortho-Para State of D2

Parity of total nuclear spin

→Parity of rotational state

Energy gap between J=0 and J=1 is **7.4meV (86K)**

- **Resonant energy ～meV**

ε_{if} (meV)	F	K_i	K_f	S
-6.649	3/2	1	0	1/2
-3.325	3/2	1	1	1/2
0.8157	3/2	0	0	1/2
3.312	3/2	1	2	1/2
4.14	1/2	0	1	1/2
10.78	1/2	0	2	1/2

Condensed Matter Effect

Theory for condensed-matter
[*Adamczak et al. Phys. Rev. A (2001)*]

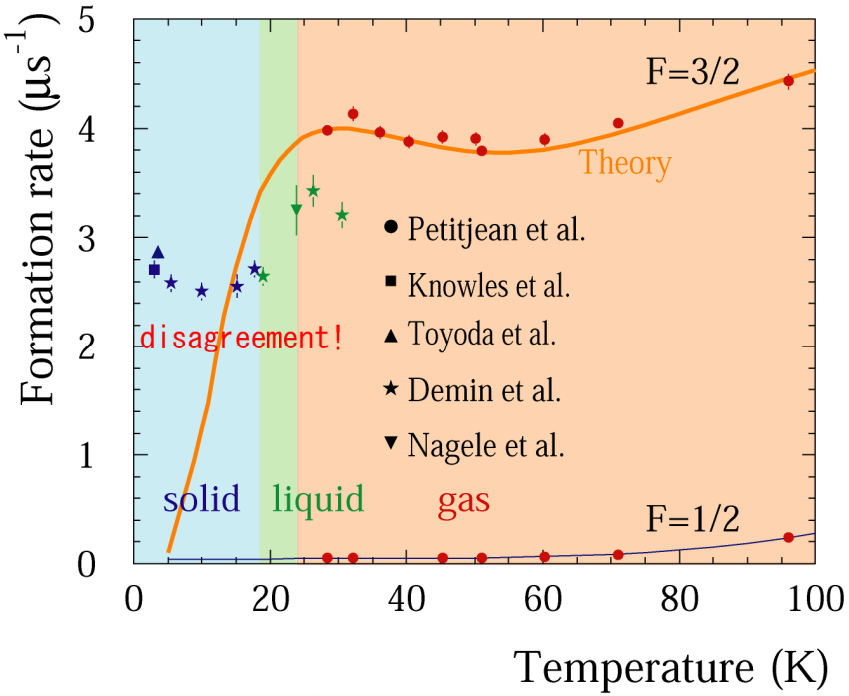
Muonic atom scattering in solid

- Bragg scattering
- Coherent and incoherent phonon
- Internal excitations of D2

⇒ Non thermalization of dμ (2meV)

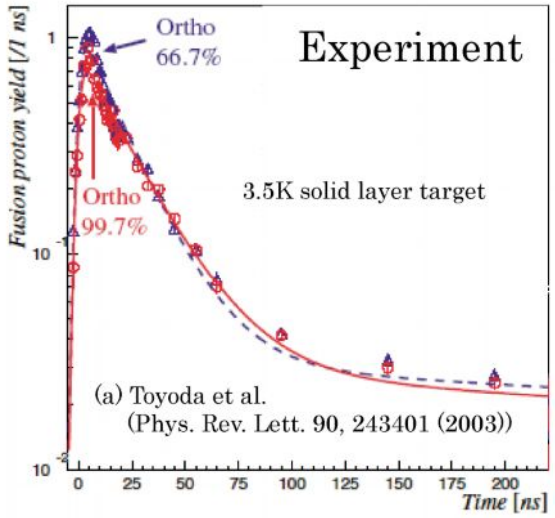
Resonant ddμ formation in solid & liquid

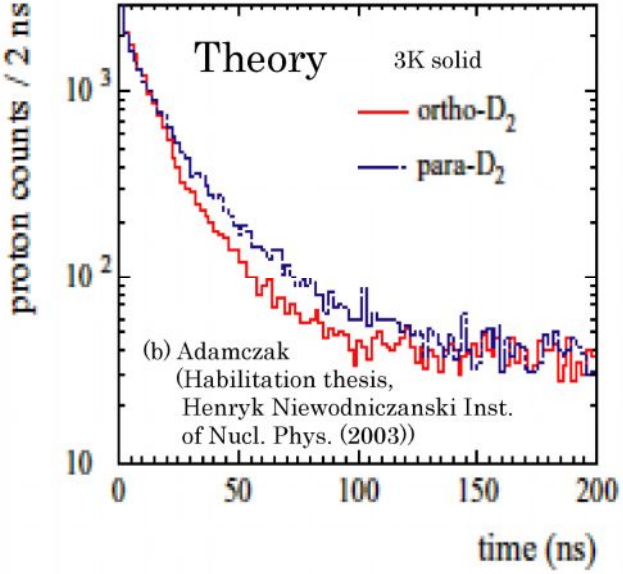
⇒ Resonant energy shift (-1.8meV)
Broadening (0.5meV)



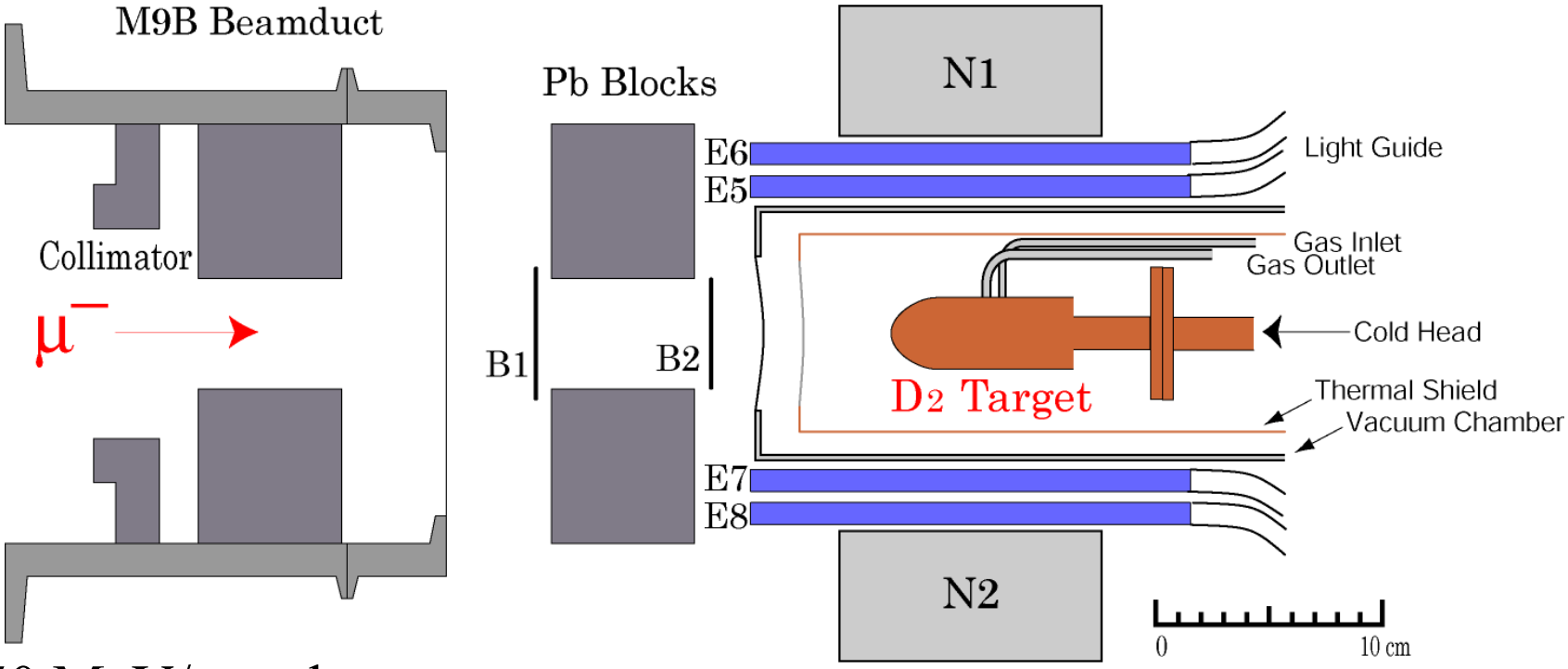
Ortho-para effect in solid was not completely understood

⇒ Further experimental study under various condition are required!!





Experimental Setup



50 MeV/c μ^- beam

@M9B TRIUMF

Detection System:

- NE213 scintillators (N1-N4)
- Beam counters (B1, B2)
- Electron counters (E1-E8)

Target (<30 litter at STP):

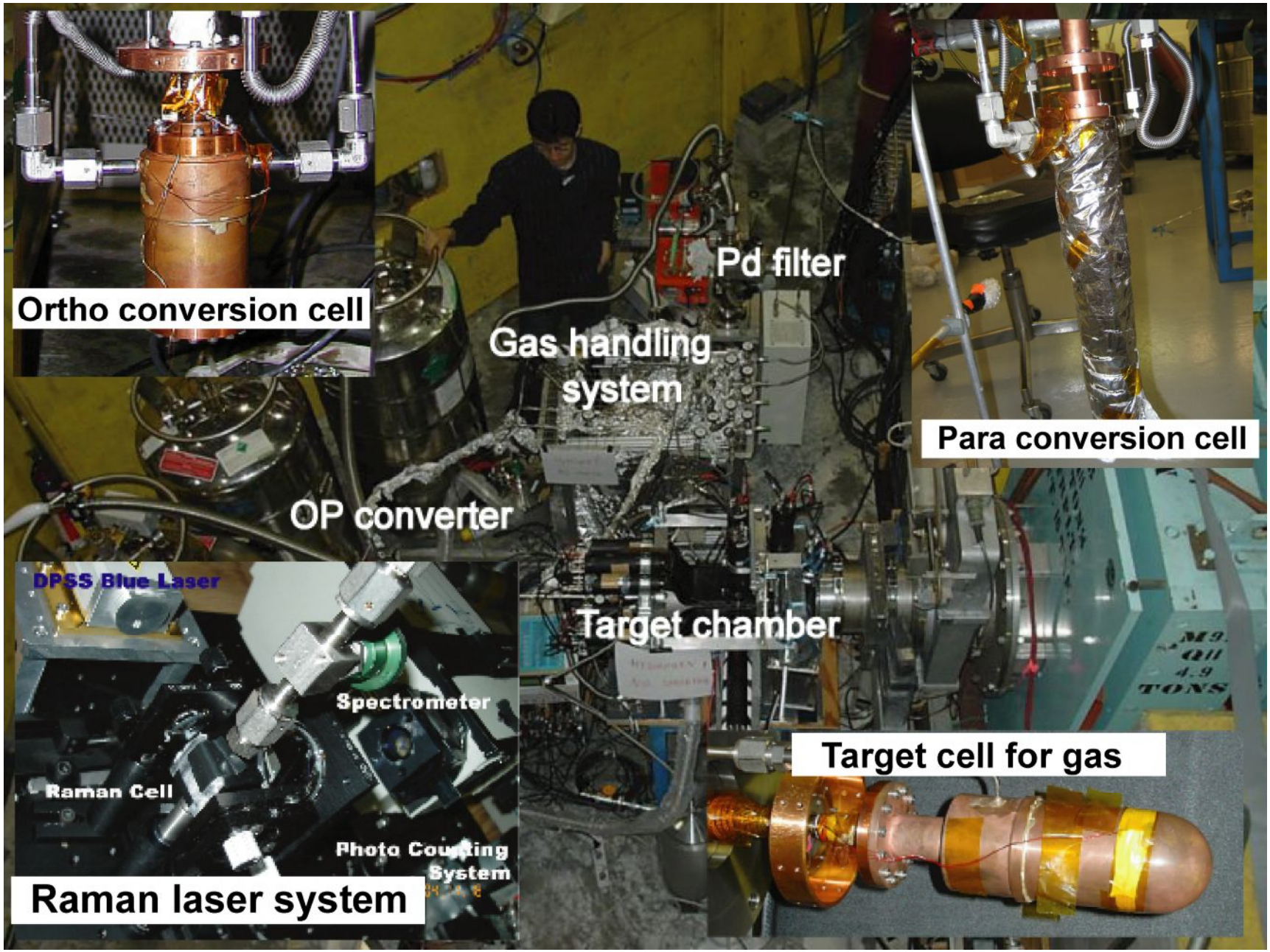
Phase: solid, liquid, gas

T=5K-38.5K

ϕ=0.03-1.4

Ortho 38-99%

Picture of Experiment



Target Preparation

Gas Purification and Normal target:

Pd filter ⇒ Make pure (< 1ppb) & normal(66% ortho) target

Ortho-rich target (66-100% ortho) :

Paramagnetic-catalyst method (Al_2O_3:Cr_2O_3=2:1)

Spin-flip induced by the magnetic gradient of paramagnetic catalyst

Hold 1 day in converter at 10K filled with the catalyst

Para-rich target (21-66% ortho) :

Preferential-adsorption method (Al_2O_3 : p.s.～3mm)

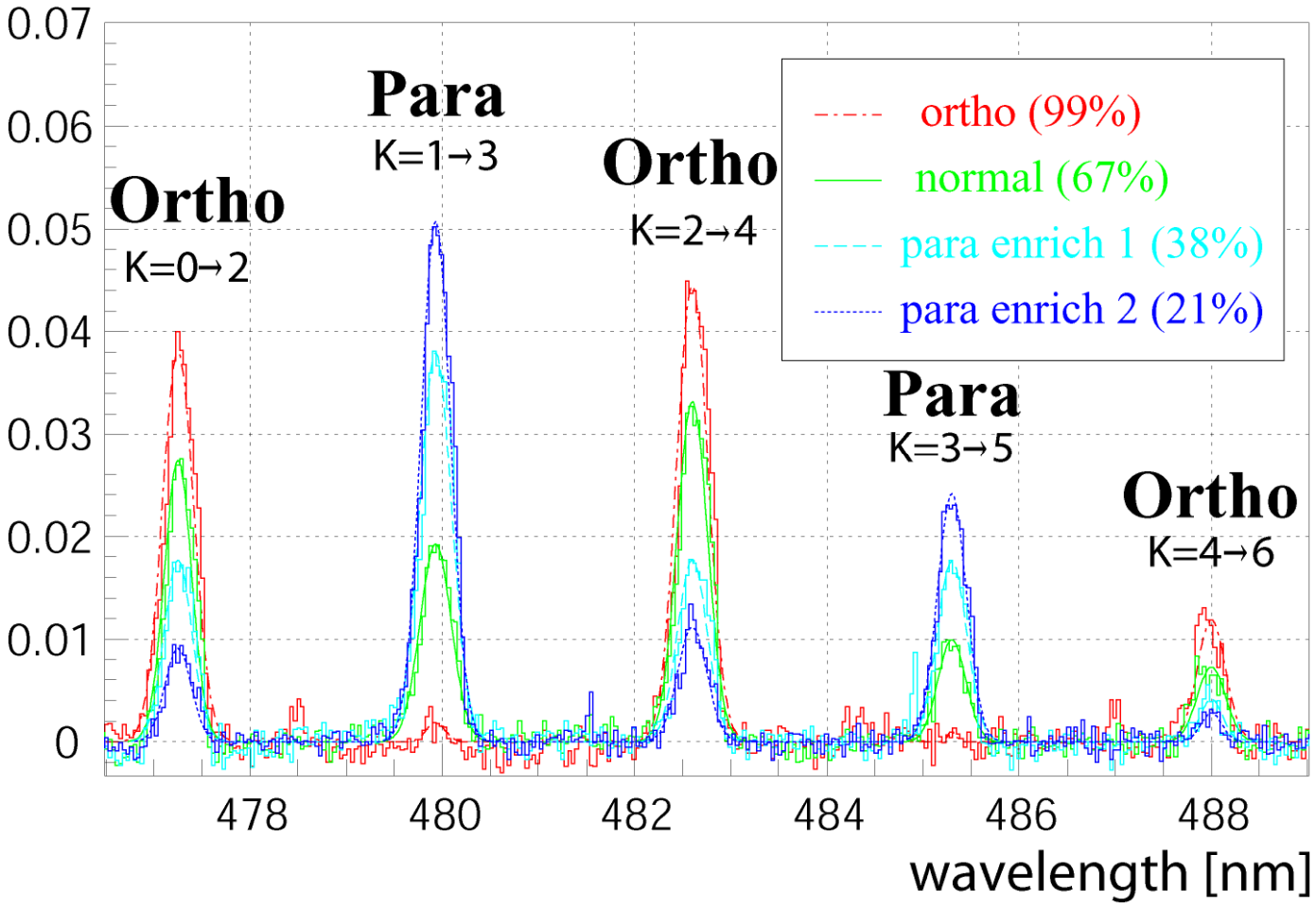
Para-D_2 preferentially adsorbed on Al_2O_3 due to the surface potential

Flow D_2 gas to Al_2O_3 under the equilibrium adsorption condition at 25K

Raman spectroscopy:

The Raman spectroscopy method was employed to measure the ortho-para composition. (20 mW 473nm blue laser: Class 3B)

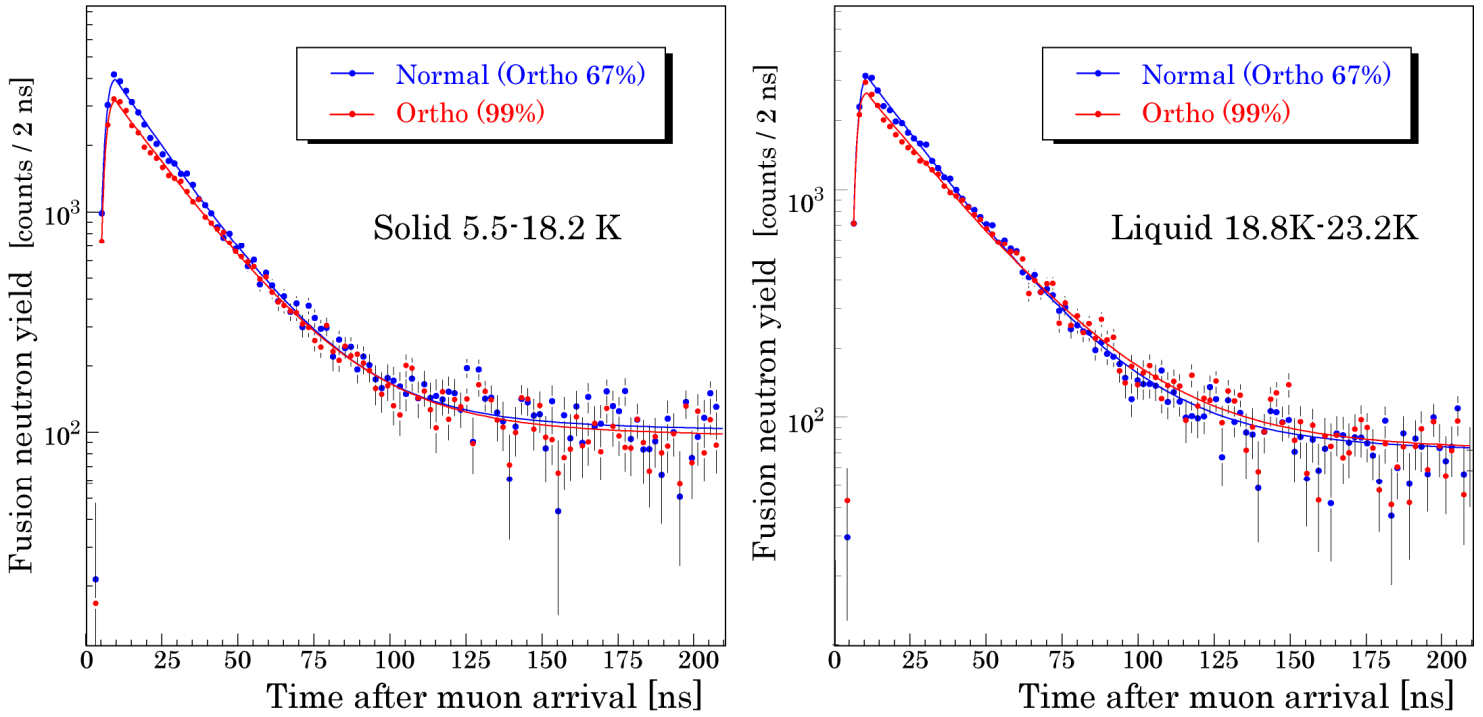
Raman Spectra



Targets with 21%-99% o-D_2 were produced !!!

Currently in all field of science, we are the only group that can control the ortho concentration in such a wide range.

Fusion Neutron Spectra in Solid and Liquid



The ortho-para dependence of the neutron time spectra was observed

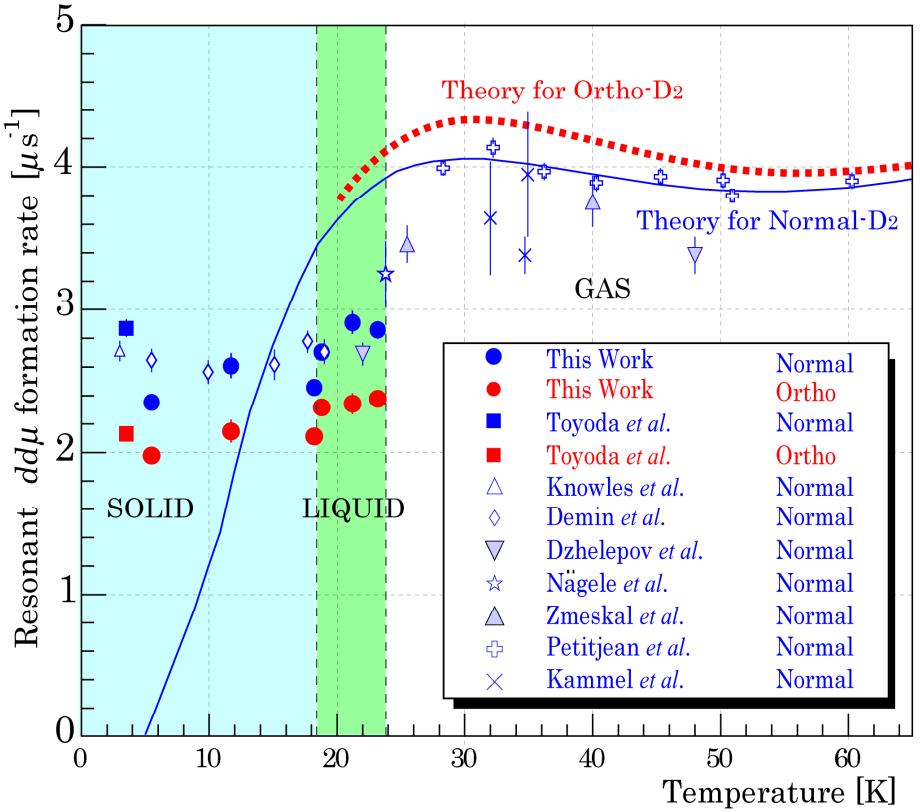
$\lambda_{\frac{3}{2}}$ and $\lambda_{\frac{3}{2}\frac{1}{2}}$ were obtained from fittings with the static model

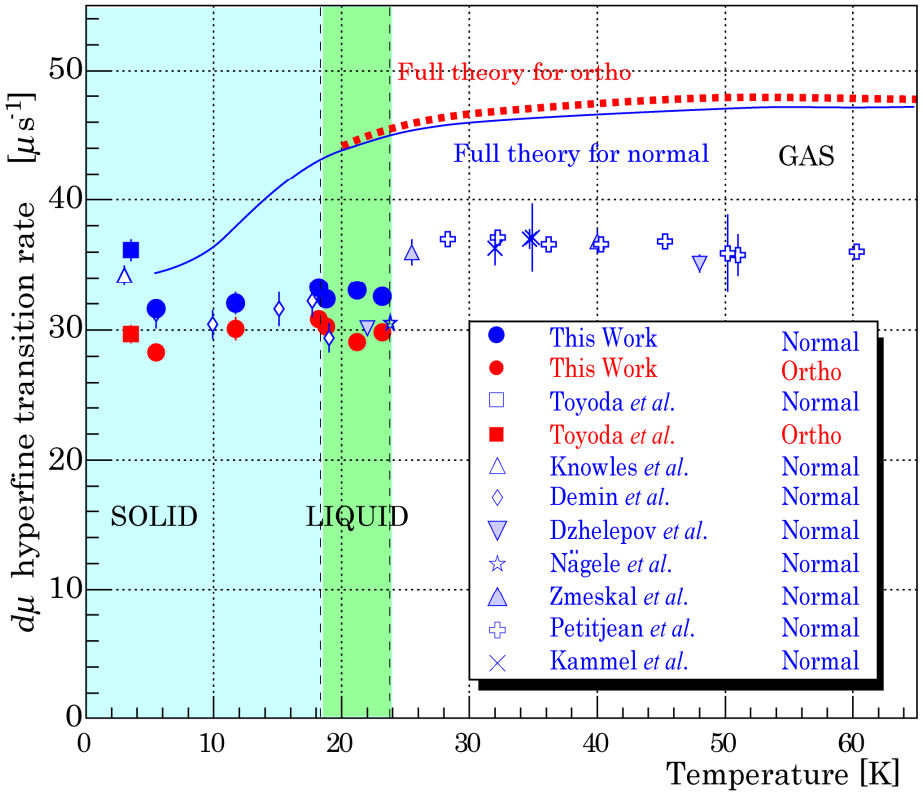
$$F_{res}(t,t_0) + F_{nr}(t,t_0)$$

$$F_{res}(t,t_0) = \frac{1}{3}\phi\beta_{\frac{3}{2}}\tilde{\lambda}_{\frac{3}{2}}\exp(\frac{(\lambda_n^{res})^2\sigma^2}{2})\exp\{\lambda_n^{res}(t-t_0)\}\mathrm{erfc}(-\frac{t-t_0-\lambda_n^{res}\sigma^2}{\sqrt{2}\sigma})$$

$$F_{nr}(t,t_0) = \frac{1}{6}\phi\beta_{\frac{1}{2}}\tilde{\lambda}_{\frac{1}{2}}\exp(\frac{(\lambda_n^{nr})^2\sigma_A^2}{2})\exp\{\lambda_n^{nr}(t-t_0)\}\mathrm{erfc}(-\frac{t-t_0-\lambda_n^{nr}\sigma_A^2}{\sqrt{2}\sigma_A})$$

Obtained Rates in Condensed Matter





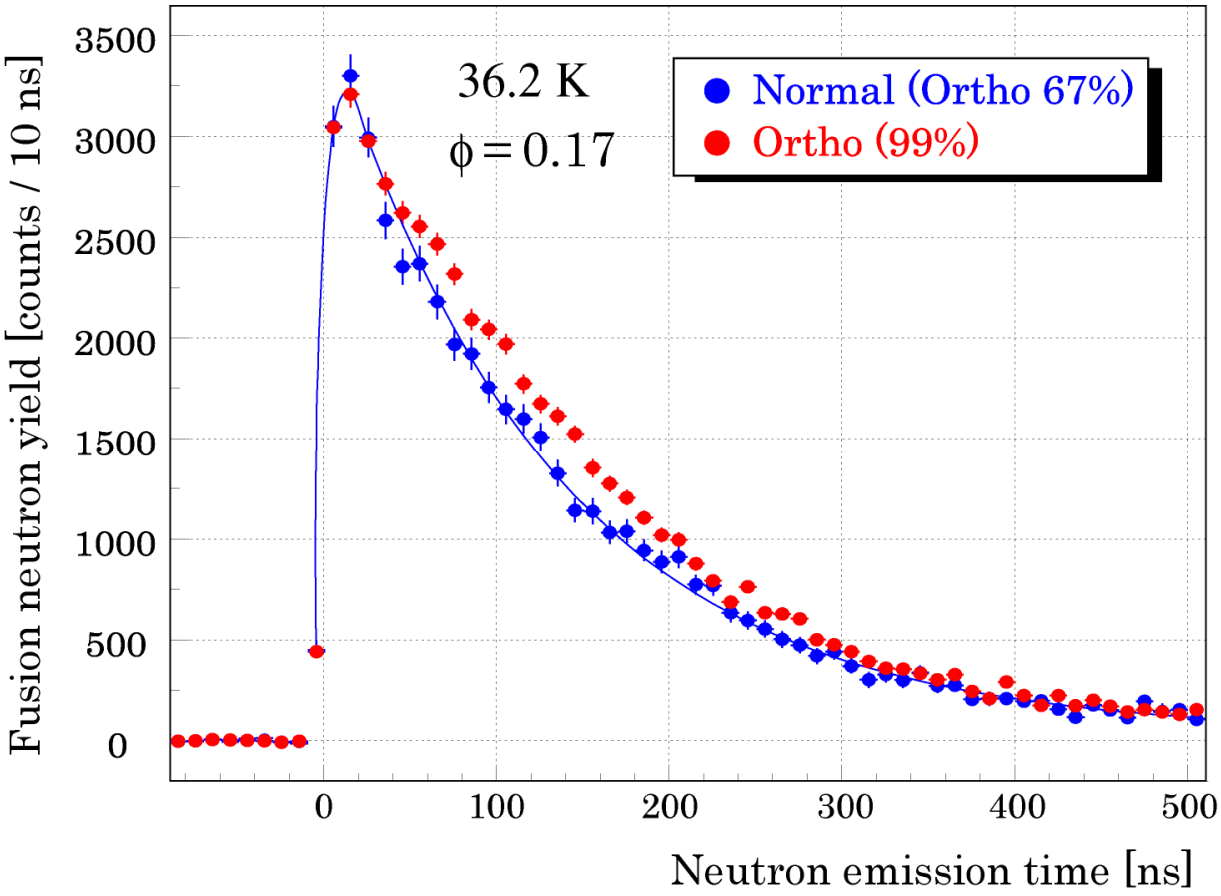
The resonant rates in o-D_2 is 15% lower than that in n-D_2

8% decrease of the HF transition rates in ortho-rich targets

Even in liquid phase, the effect is disagree with the theory

High-density effect

Neutron Time Spectra in Gas



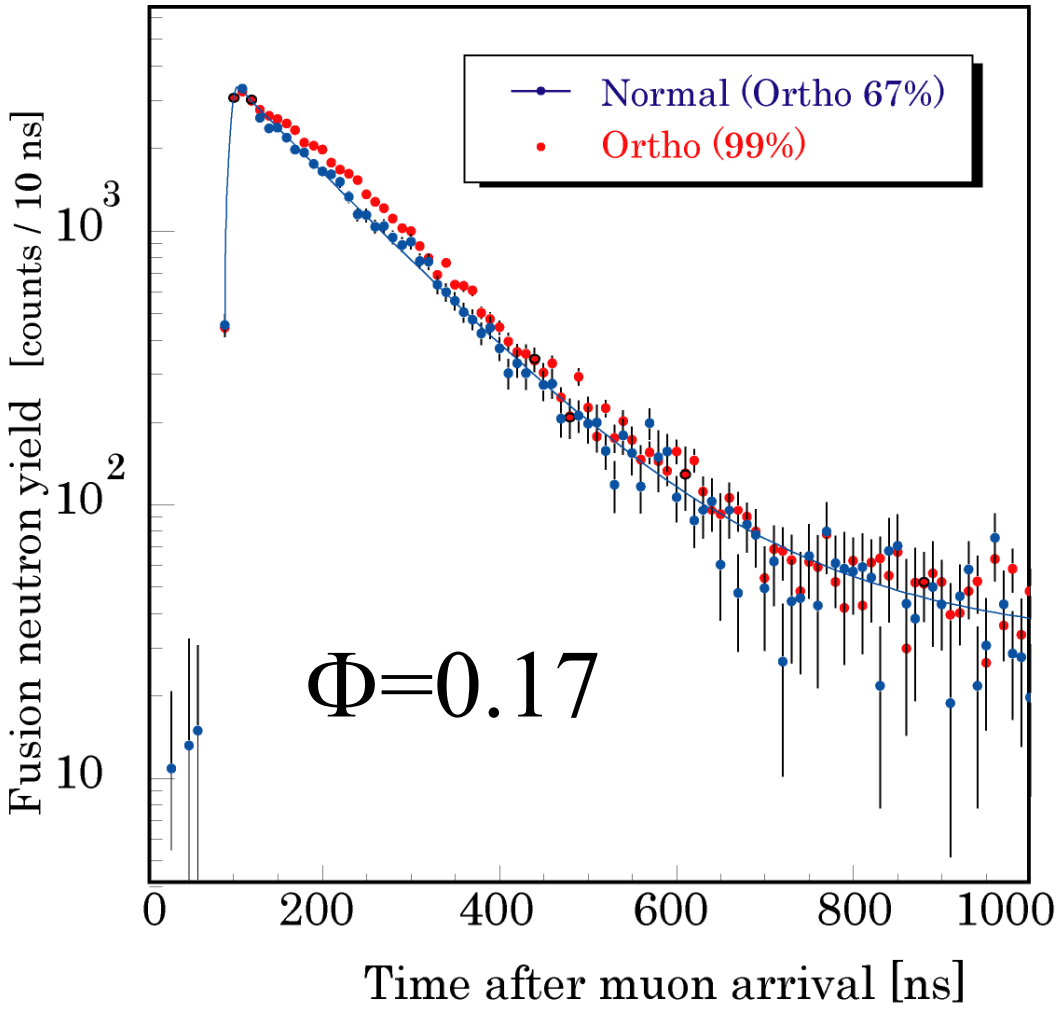
Normal⇒reproduced by the static model

$$\lambda_{\frac{3}{2}}^{Normal} = 4.5(2)(3) \qquad \lambda_{\frac{3}{2}\frac{1}{2}}^{Normal} = 40(1)(2)$$

Neutron yield in o-D2 is 12% enhanced

consistent with theory for dilute gas

Delayed Structure



Fusion neutron spectrum in o-D_2 deviates from simple exponential function around **150 ns (>>1/ϕ ns=6 ns)**

The delayed structure cannot be described by static formation rate assuming rapid dμ thermalization

Slow dμ thermalization

The probable explanation for the structure is the **transient ddμ formation** during slow dμ thermalization ⇒**epithermal effect**

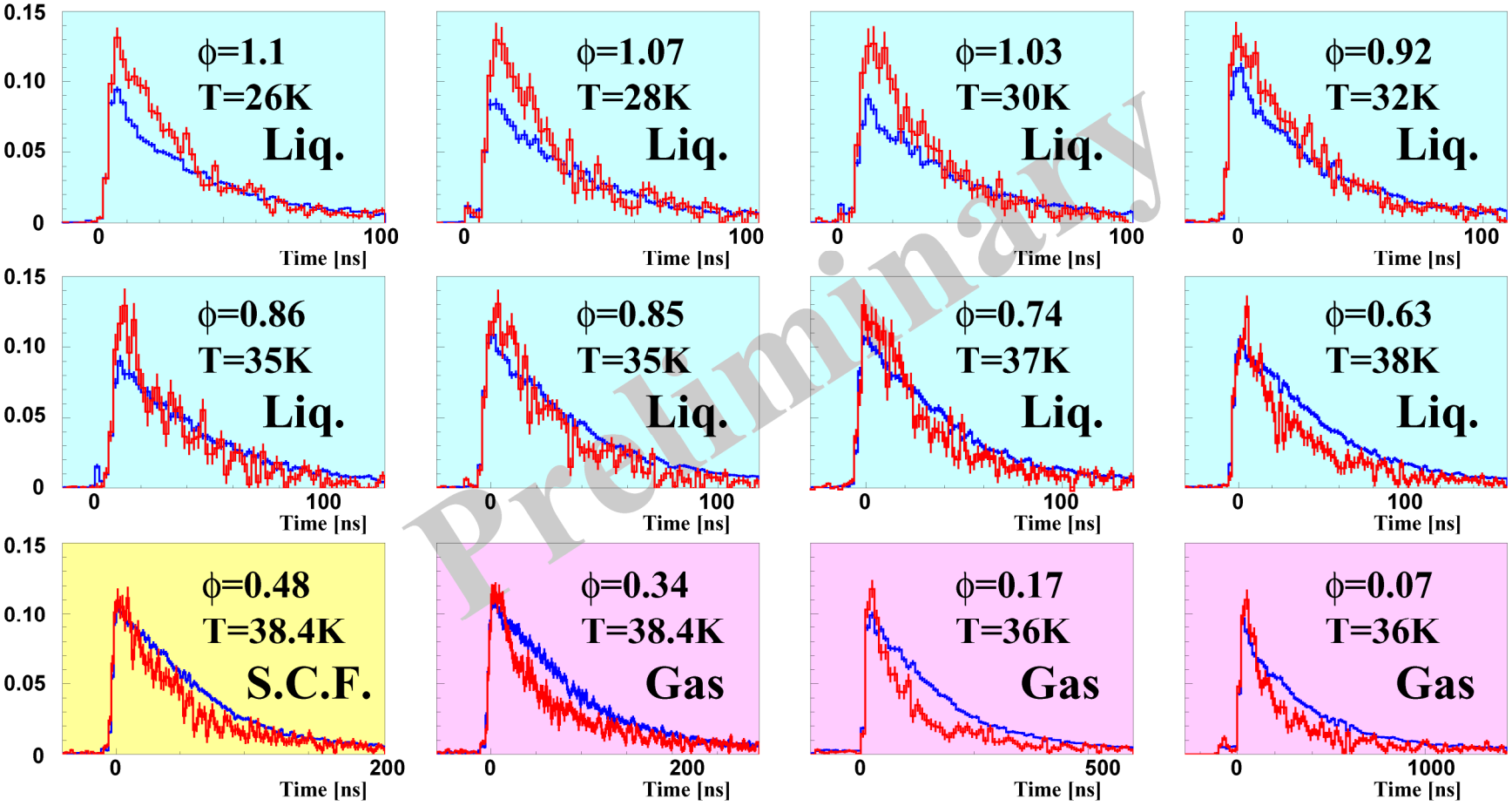
Density Effect (Preliminary Data)

How are the liquid data and the gas data connected?

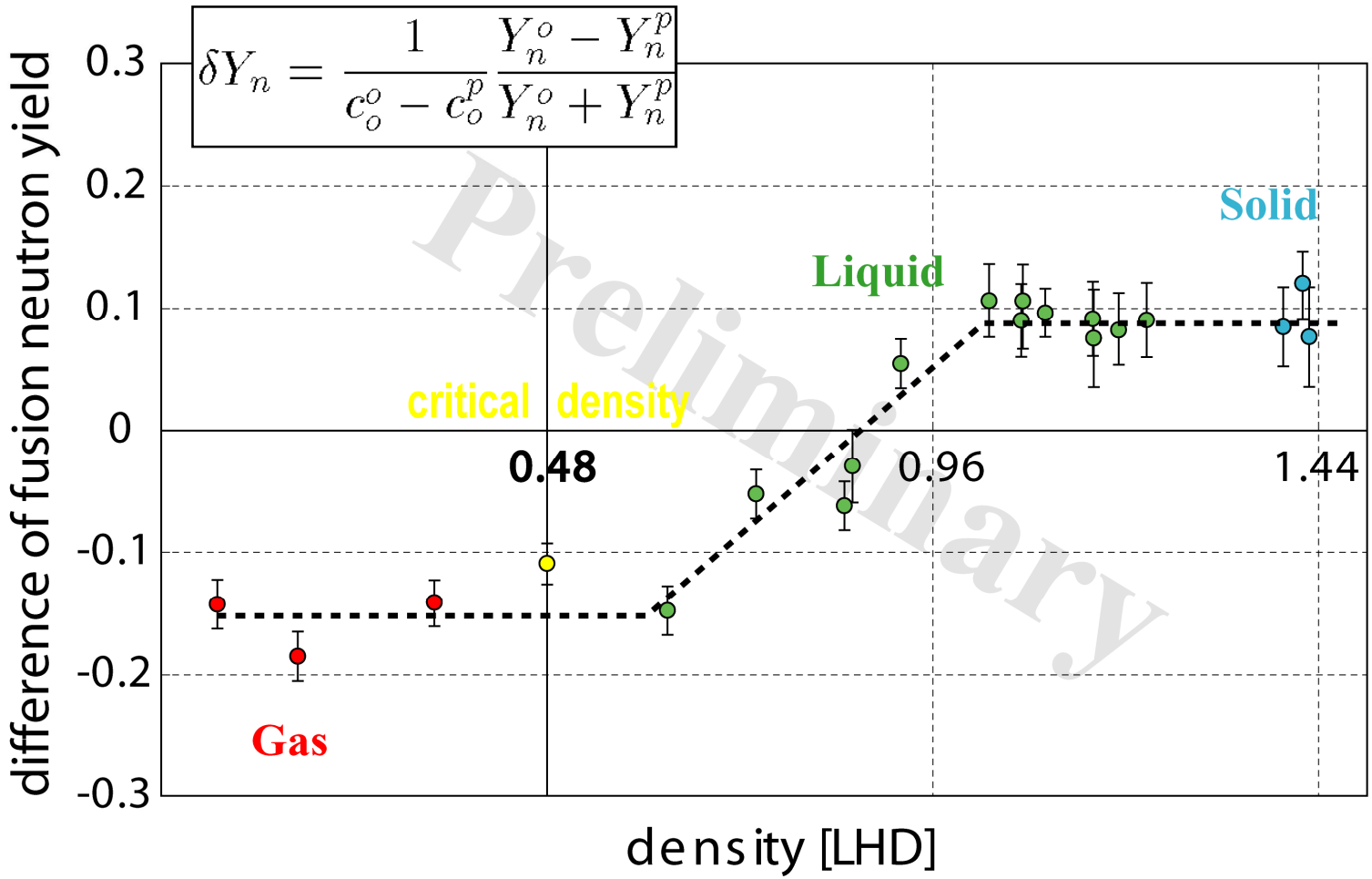
The complete data set of the density dependence with ortho-para D_2 (ϕ=0.03-1.3) were obtained in May 2007!

— para 100%

— ortho 100%



Density Effect (Preliminary Data)



Surprisingly, it is not simple linear density dependence!

Target density (= intermolecular interaction of D2) is an essential parameter in d-d μCF.

Resonant Condition in High Density

Possible explanations of **density dependence**

1. Level shift on excited state of [(ddμ)dee] in a high density

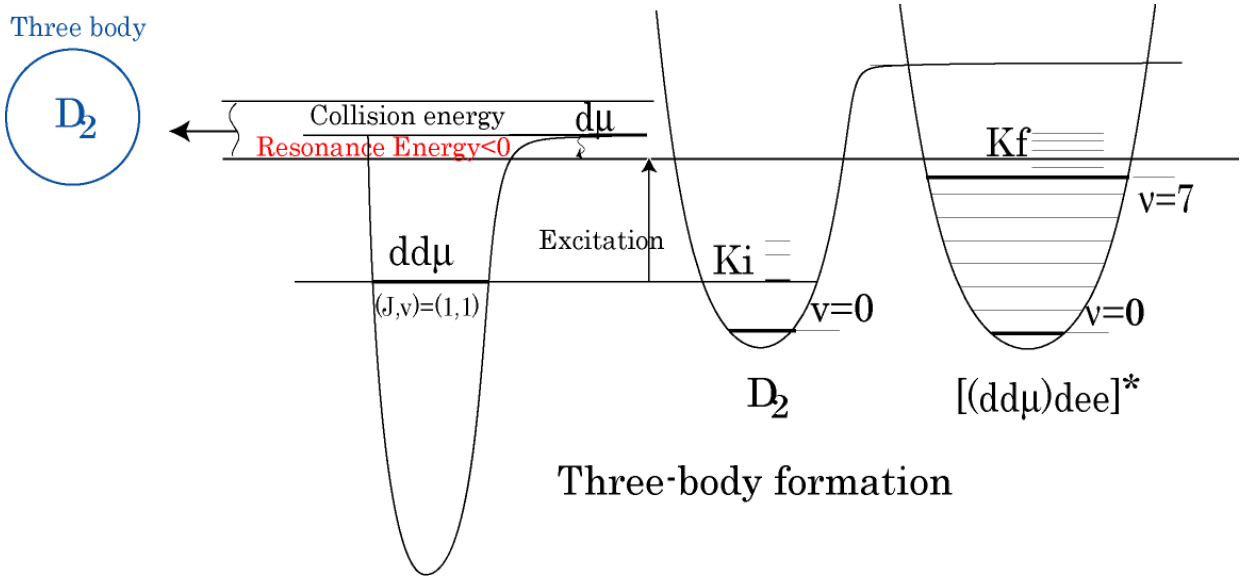
High precision (0.05 meV) in isolated system

Study of the excited D2 in a high density

2. The "three body effect" in d-d μCF

dt-μCF -14meV(for ortho) –11meV(for para)

ddμ 0.8meV(for ortho) -3.3meV(for para)



Further theoretical investigation of a high-density effect will be important

Summary

We performed the ortho-para experiment in various condition.
The ortho-para ratio of D_2 was perfectly controlled (21-99%) .

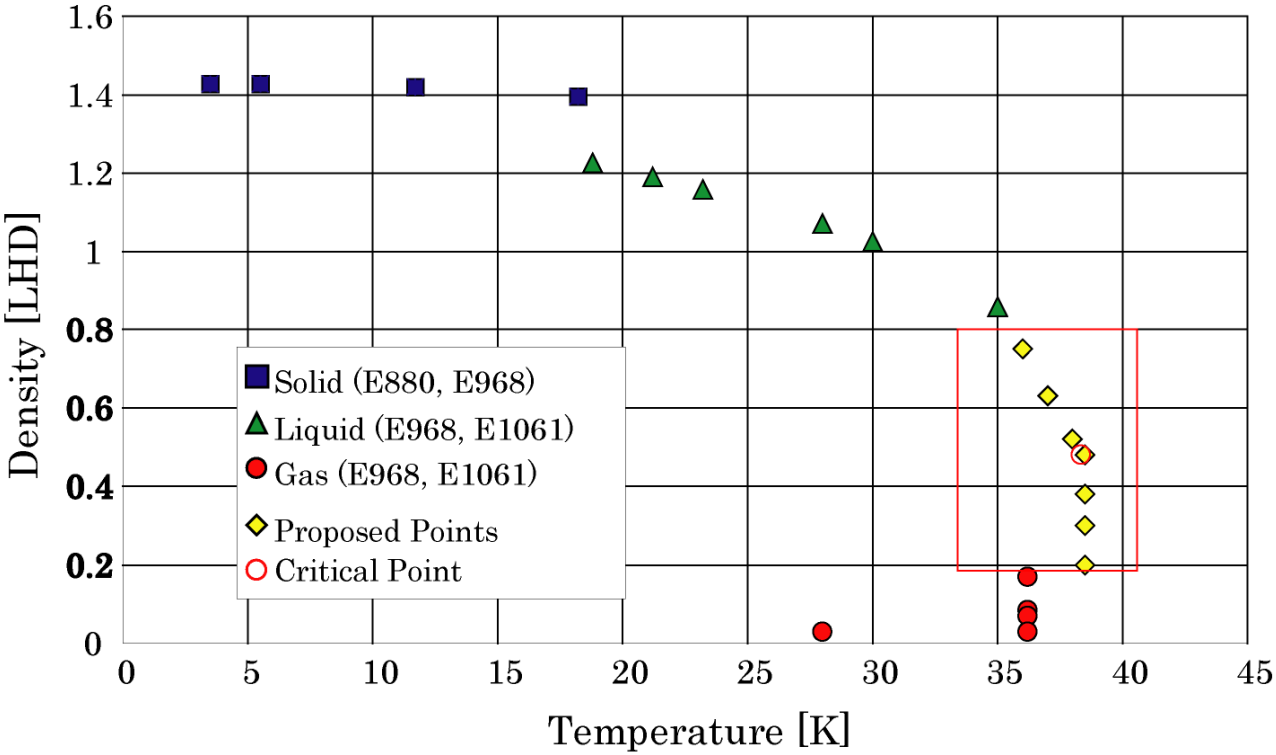
- Ortho-para effects in solid were consistent with the previous experiments.
- Ortho-para effects in liquid were similar to those in solid.
- Yield of fusion neutrons was enhanced in ortho D_2 gas.
- Neutron time-spectra in ortho D_2 gas had a delayed structure.
- Ortho-para effects were dependent on the target density.

Epithermal effect and **High-density effect** are important even in d-d μCF

- Competition between dμ thermalization and ddμ formation
- Resonant ddμ formation with intermolecular interaction of D2

Proposed Condition

Experimental condition in E968 and E1061



Observed ortho-para effect in high-density region(ϕ>0.88) was drastically different from that in low-density region(ϕ<0.17).

We propose the measurement at middle density !!

Why the measurement in the proposed conditions are important?

-Details of E968 and E1061 will be explained in the following slides-

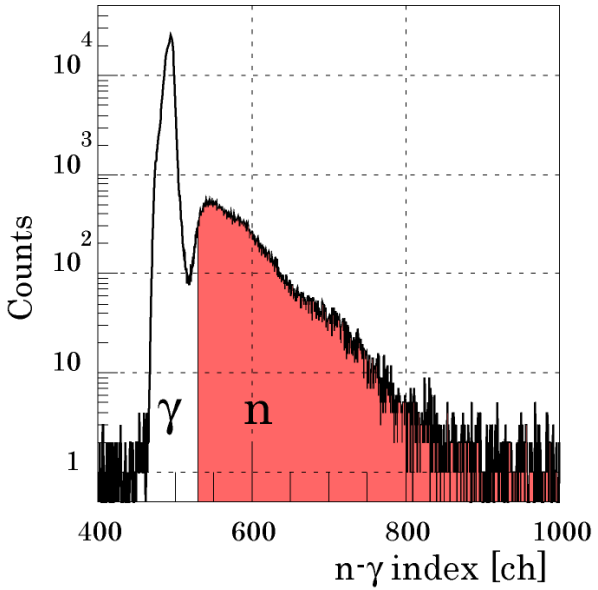
Neutron Detection

To observe 2.45-MeV d-d fusion neutrons

Gamma-rays:

Pulse shape discrimination method

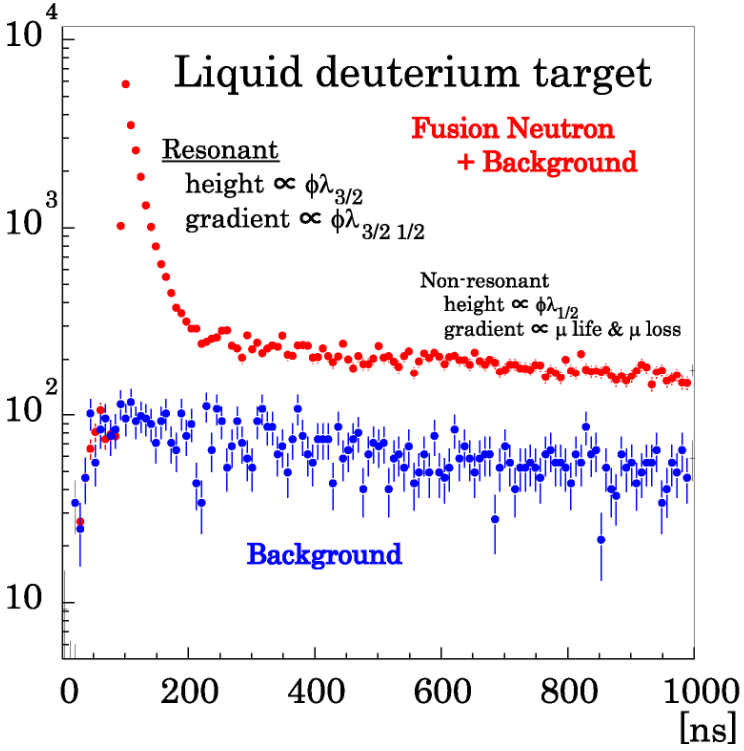
n-γ discrimination by using NE213 scintillator
+ PSA & DLA modules

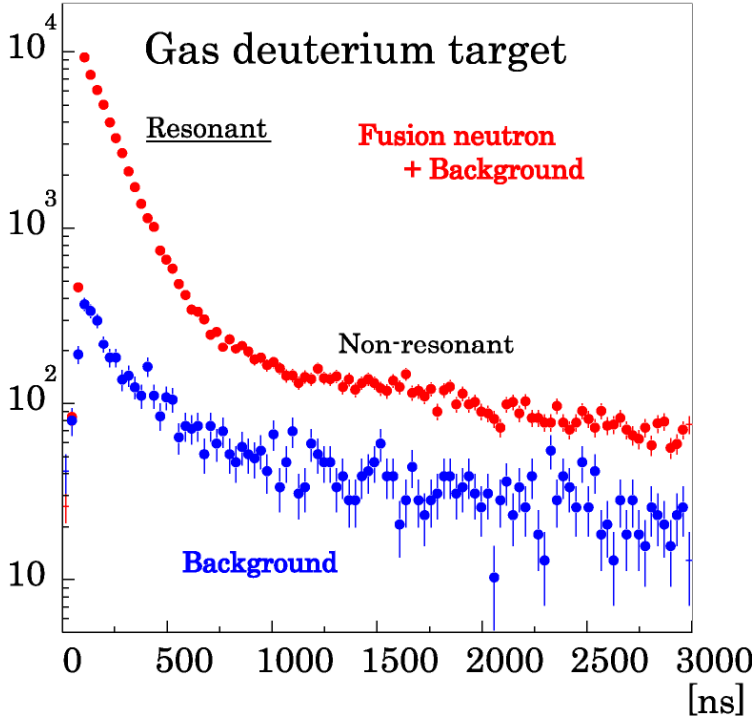


Muon nuclear capture neutrons:

Delayed electron condition

Demand on a electron event after the neutron event





Neutron Detection

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n-γ discrimination by using NE213 + PSA & DLA modules

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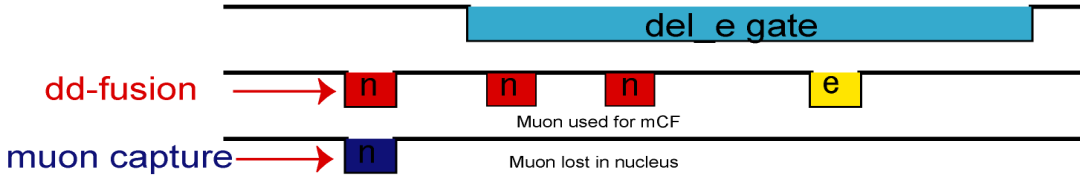
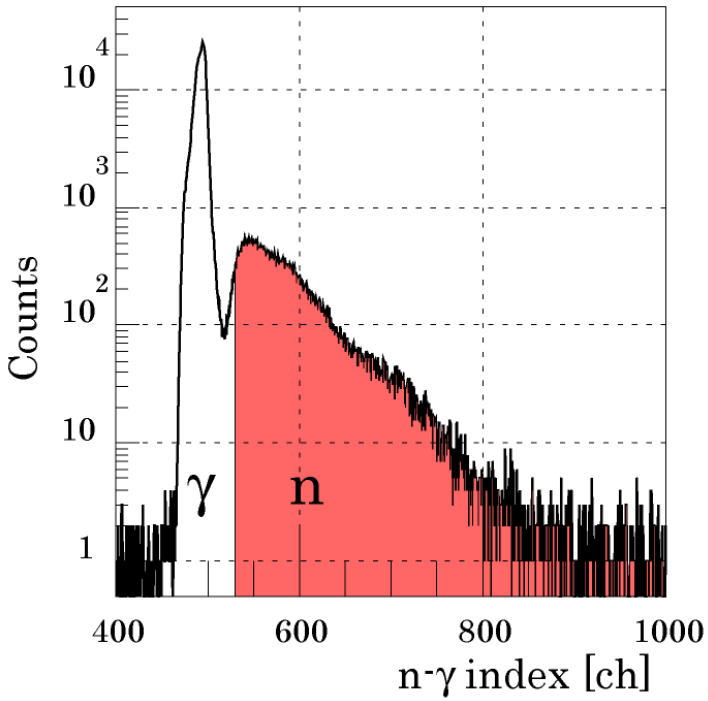
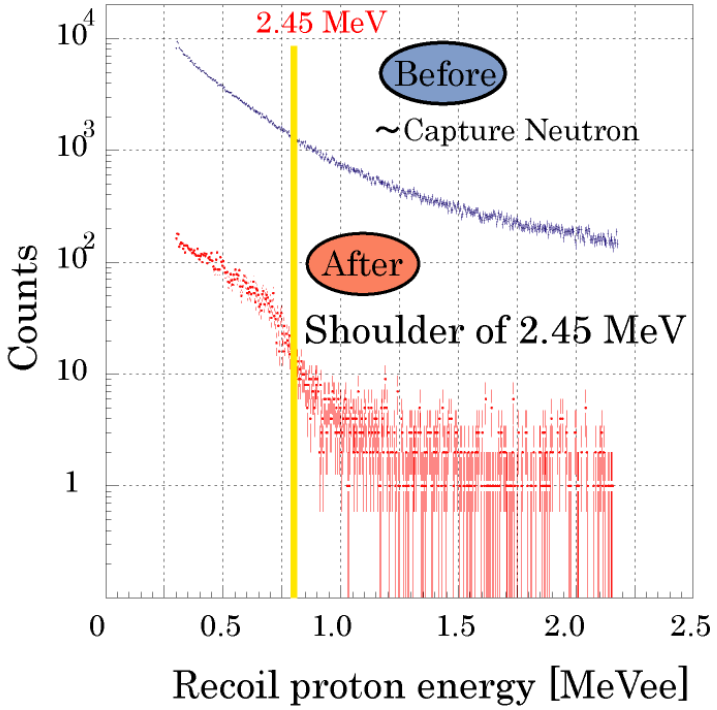






Target Preparation

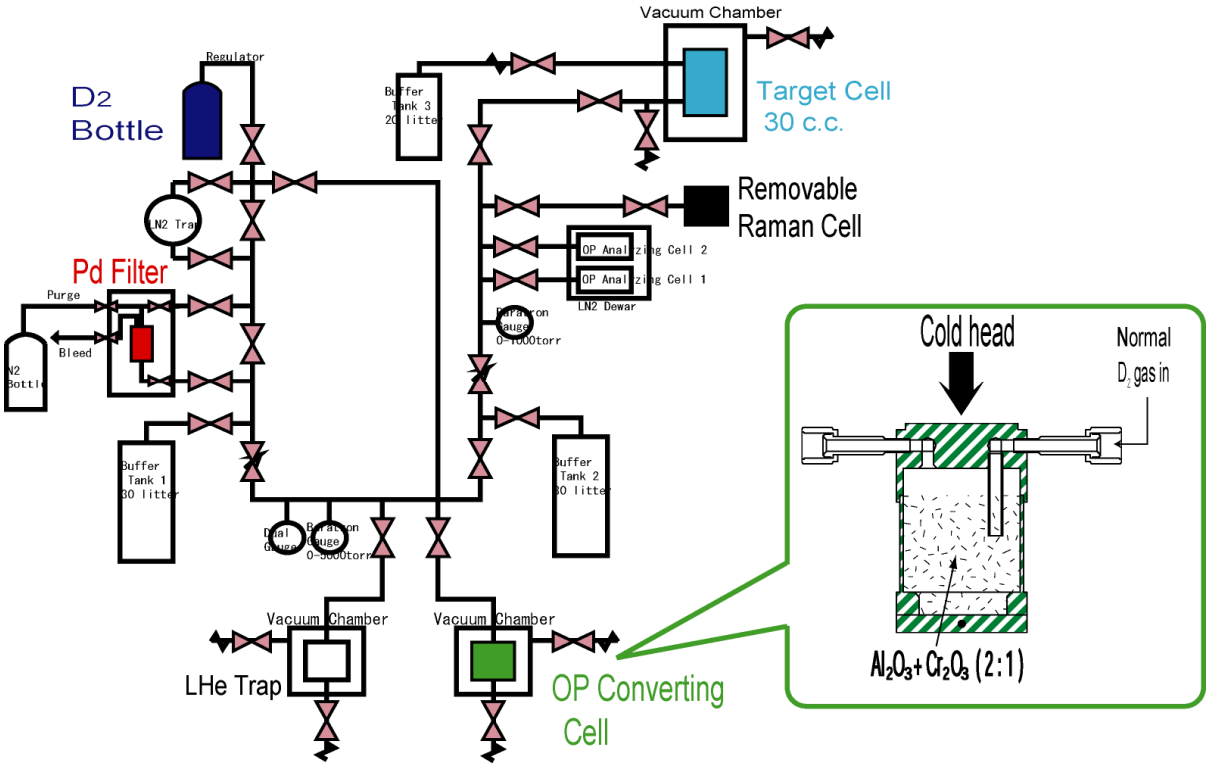
Gas Purification:

Pd filter ⇒ Make pure (< 1ppb) & normal(66% ortho) target

Make ortho-rich target:

Catalyst method

Hold 1 day in converter at 10K filled with paramag. catalyst

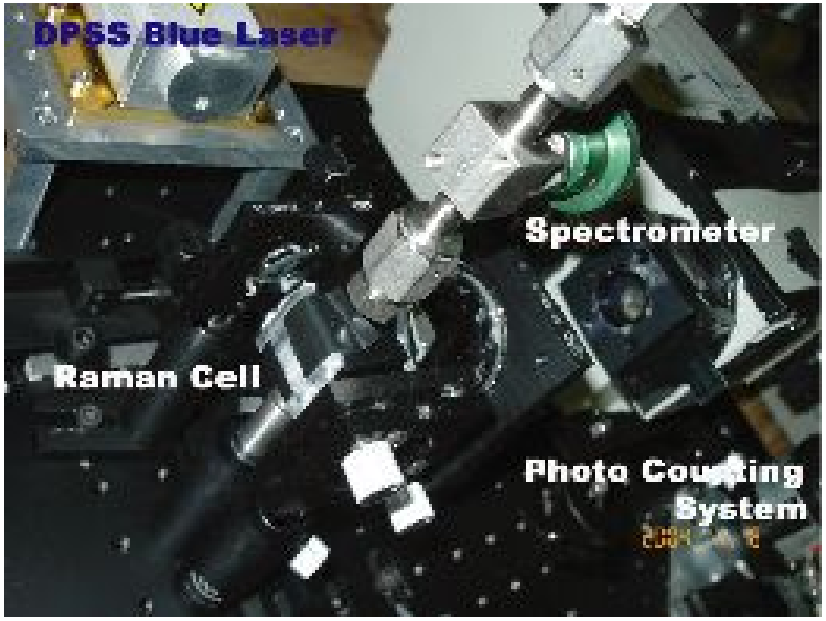


Raman Spectroscopy

For the complete controlling of OP state, absolute measurement of the composition of ortho-para mixture is essential.

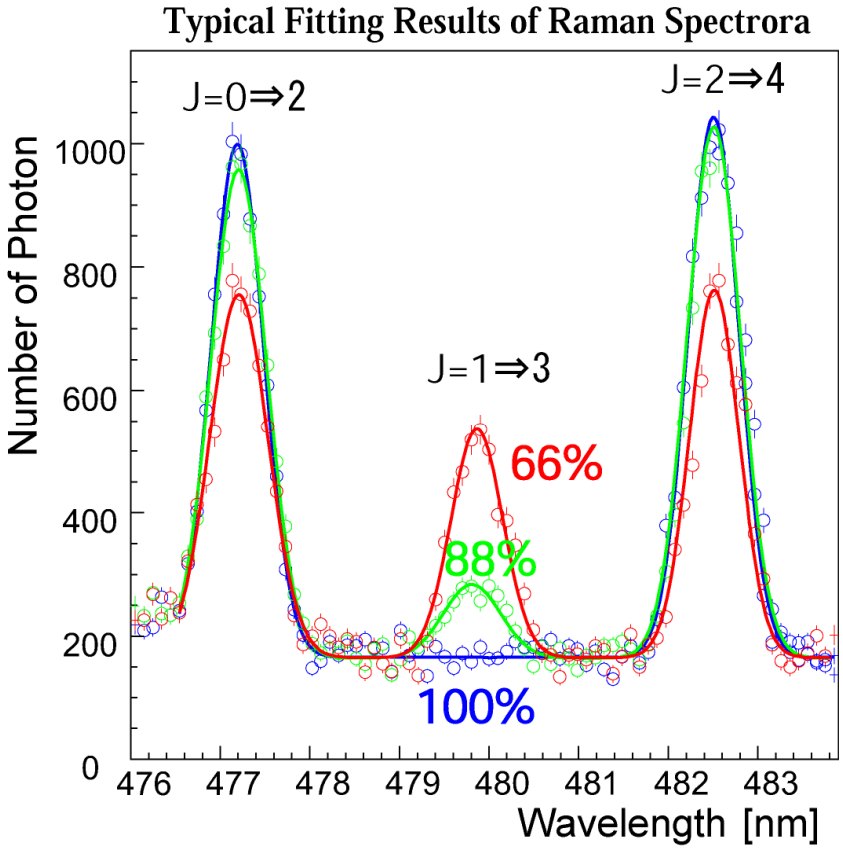
The Raman spectroscopy method was employed for the first time in μCF to determine the OP ratio of our target.

Raman Laser System



Placed near experimental area

for in-situ measurement



Hyperfine Transition Rate 1

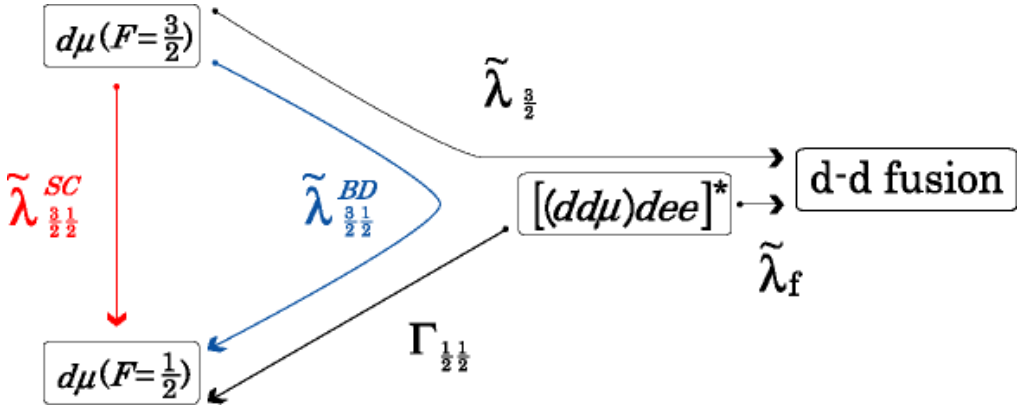
$\lambda^{SC}_{\frac{3}{2}\frac{1}{2}}$, $\lambda^{BD}_{\frac{3}{2}\frac{1}{2}}$ and $\Gamma_{\frac{1}{2}\frac{1}{2}}$ were derived by using the ortho-para dependence of $\lambda_{\frac{3}{2}}$ and $\lambda_{\frac{3}{2}\frac{1}{2}}$

No ortho-para dependence of $\lambda^{SC}_{\frac{3}{2}\frac{1}{2}}$ and $\Gamma_{\frac{1}{2}\frac{1}{2}}$ was assumed

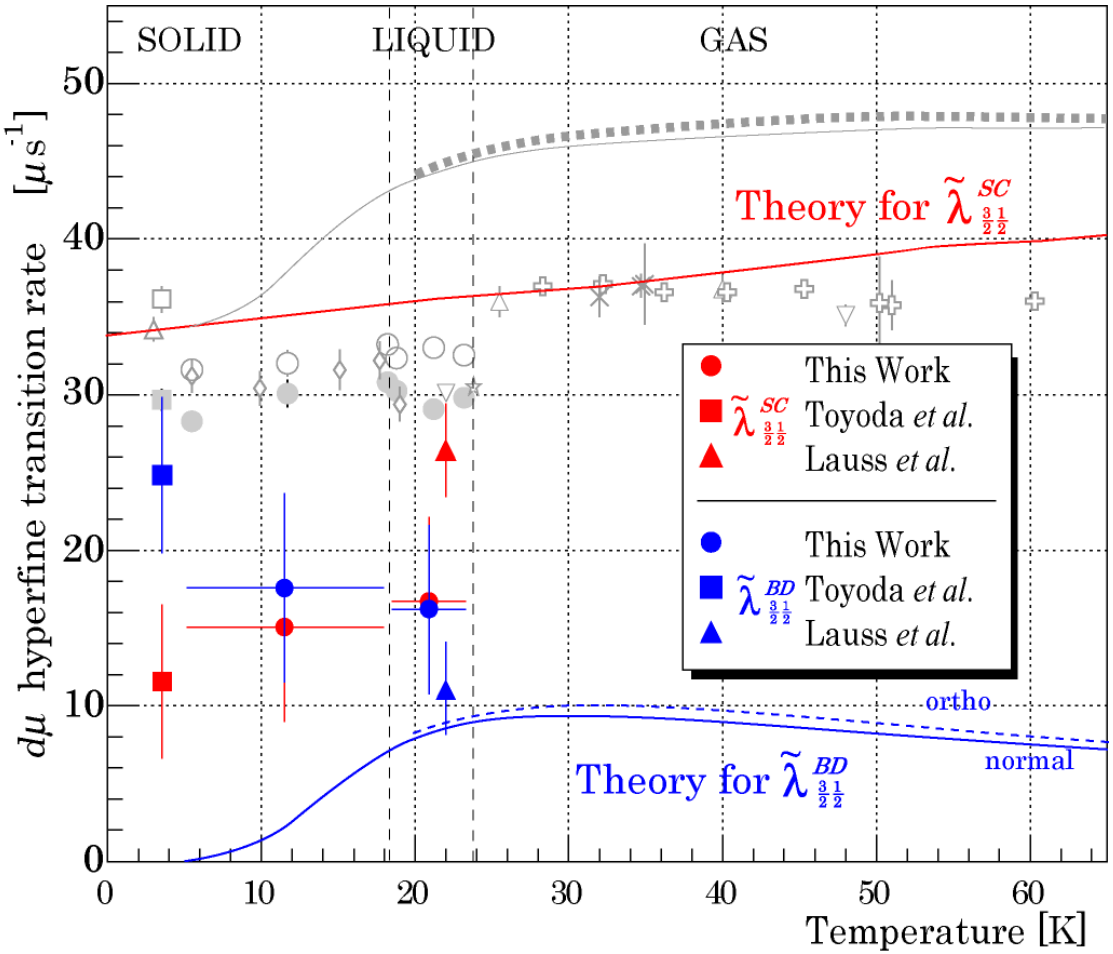
$$\lambda^{SC}_{\frac{3}{2}\frac{1}{2}} = \frac{\tilde{\lambda}^{ortho}_{\frac{3}{2}\frac{1}{2}}(\tilde{\lambda}^{normal}_{\frac{3}{2}} - \lambda_{nr}) - \tilde{\lambda}^{normal}_{\frac{3}{2}\frac{1}{2}}(\tilde{\lambda}^{ortho}_{\frac{3}{2}} - \lambda_{nr})}{\tilde{\lambda}^{normal}_{\frac{3}{2}} - \tilde{\lambda}^{ortho}_{\frac{3}{2}}}$$

$$\lambda^{BD}_{\frac{3}{2}\frac{1}{2}} = \tilde{\lambda}_{\frac{3}{2}\frac{1}{2}} - \lambda^{SC}_{\frac{3}{2}\frac{1}{2}}$$

$$\Gamma_{\frac{1}{2}\frac{1}{2}} = \frac{\tilde{\lambda}_f(\tilde{\lambda}^{normal}_{\frac{3}{2}\frac{1}{2}} - \tilde{\lambda}^{ortho}_{\frac{3}{2}})}{\tilde{\lambda}^{normal}_{\frac{3}{2}} - \tilde{\lambda}^{ortho}_{\frac{3}{2}}}$$



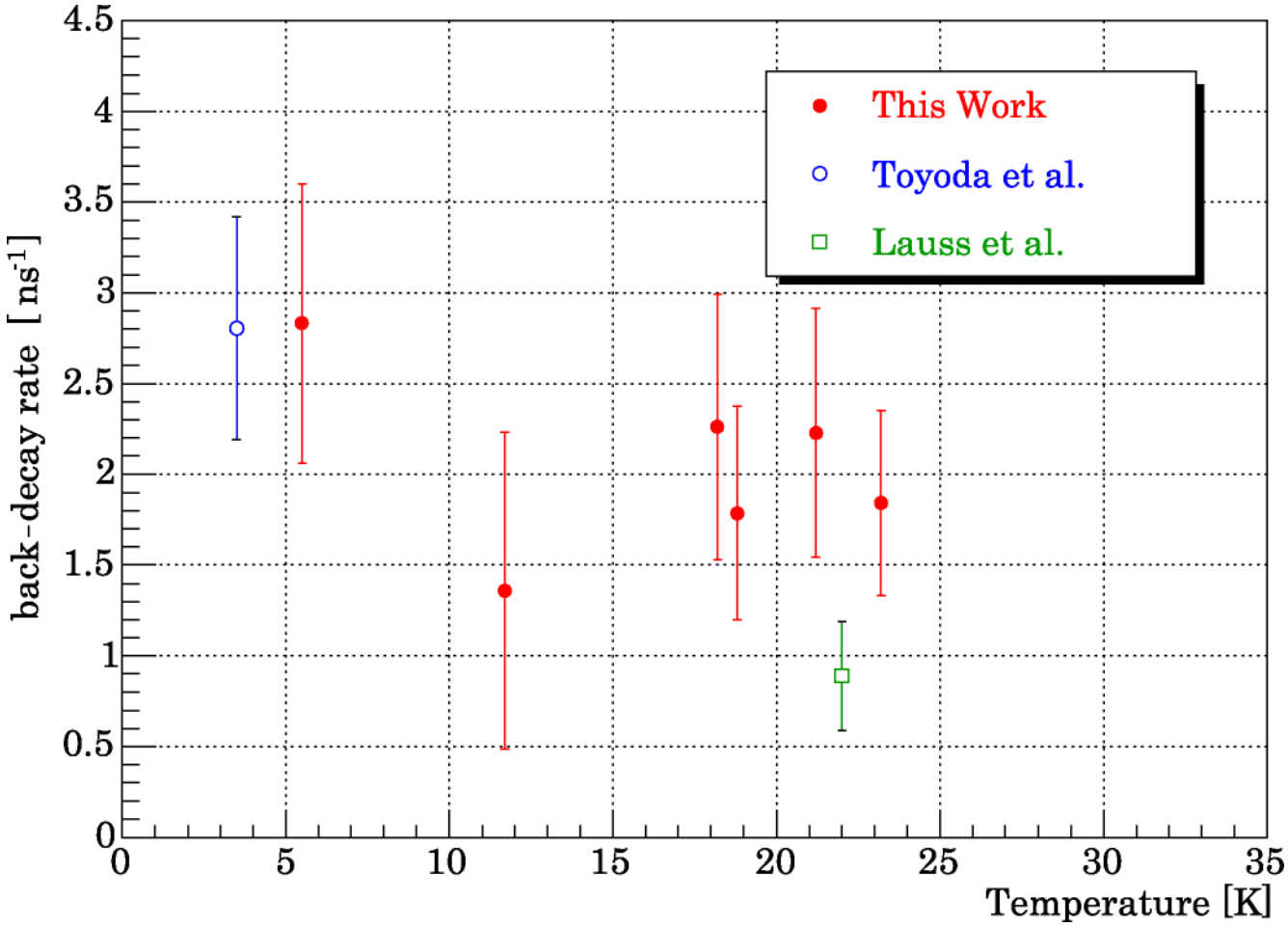
Hyperfine Transition Rate 2



$\lambda^{SC}_{\frac{3}{2}\frac{1}{2}}$ **is about 40% of the theoretical one**

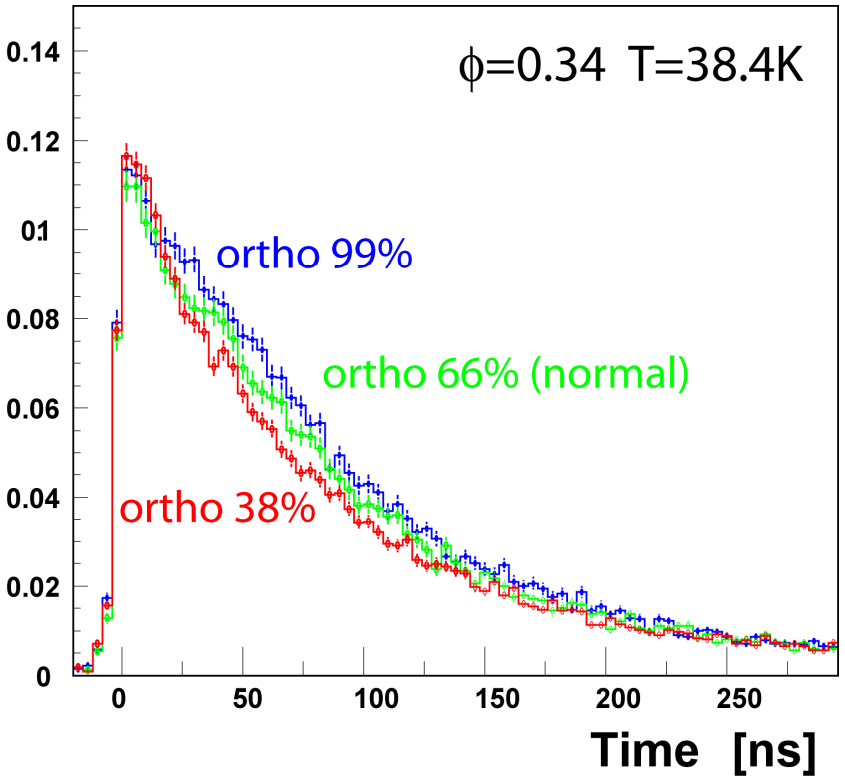
The reason for the discrepancy has not yet been explained

Back-Decay Rate



The back-decay rates $\Gamma_{\frac{1}{2}\frac{1}{2}}$ are consistent with the previously observed rates and the theoretical rate (1.5 ns^{-1})

Epithermal effect



Epithermal effect in d-t μCF

[*Jeitler et al. Phys. Rev. A51 (1983) 1757*]

Strong resonance ～hundreds eV

Acceleration mechanism

•muon transfer dμ→tμ

•spin flip

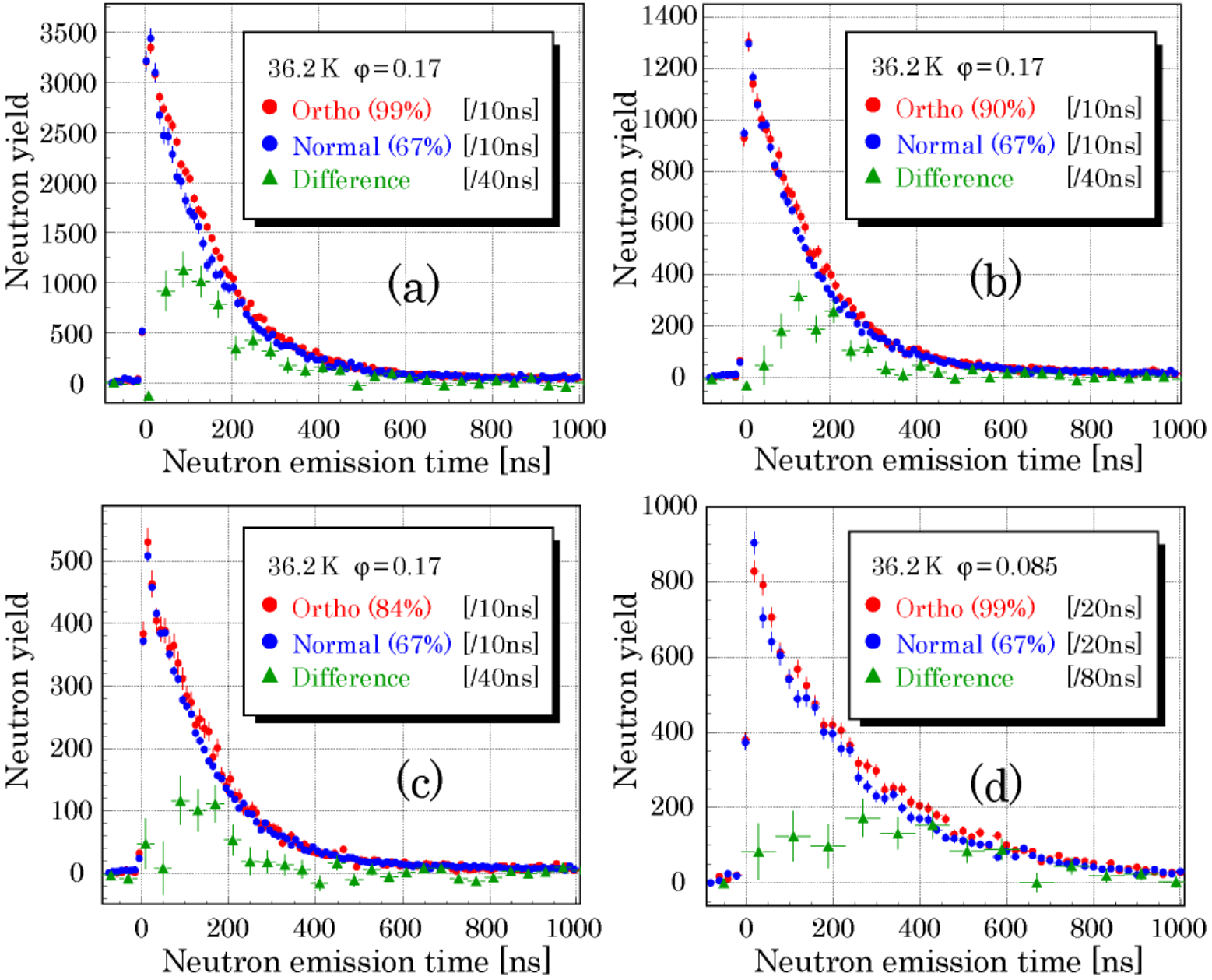
In our case, the structure is clearly depends on the ortho-para ratio!

Lowest resonance ～meV

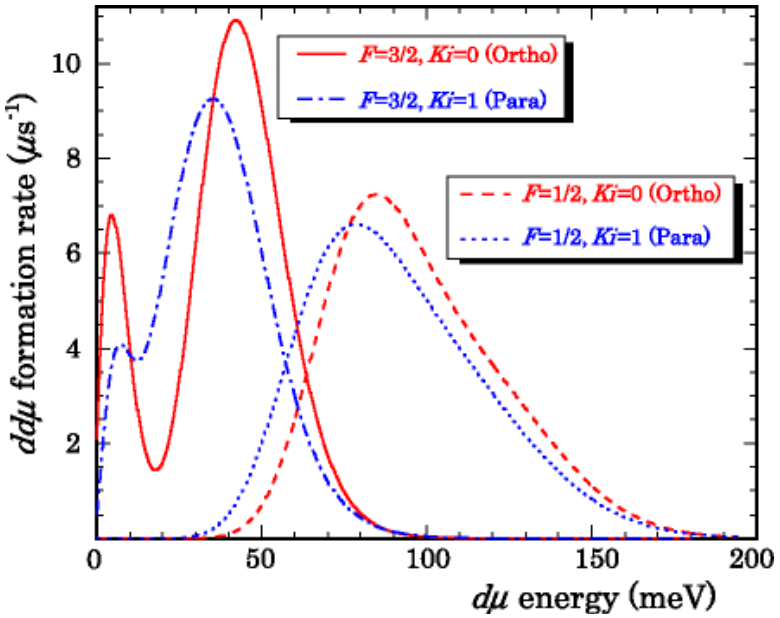
It is difficult to extract the exact rates of $\lambda_{\frac{3}{2}}$ and $\lambda_{\frac{3}{2}\frac{1}{2}}$

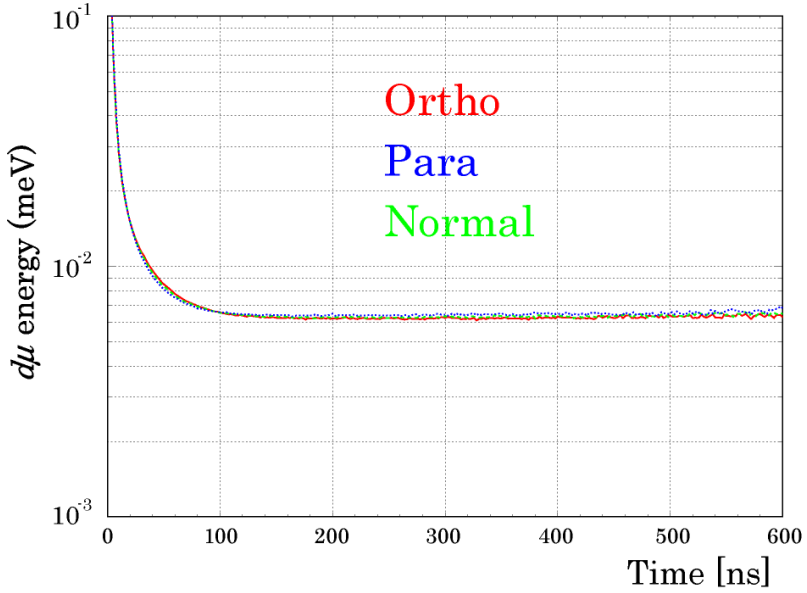
Competition between dμ thermalization and ddμ formation

Bump Structure 2



Origin of Bump Structure





•Molecular formation from epithermal dμ (F=1/2)

× Small OP dependence of the resonant condition for dμ with F=1/2

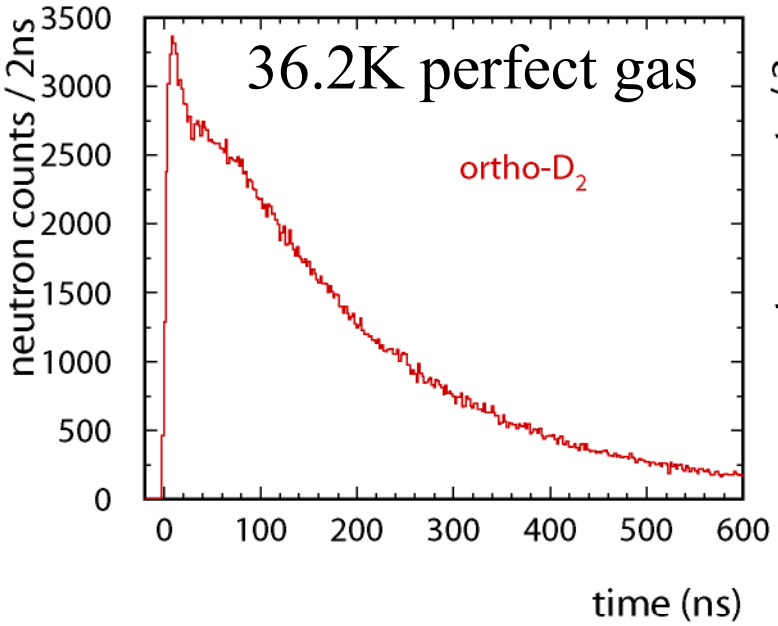
•Para heating

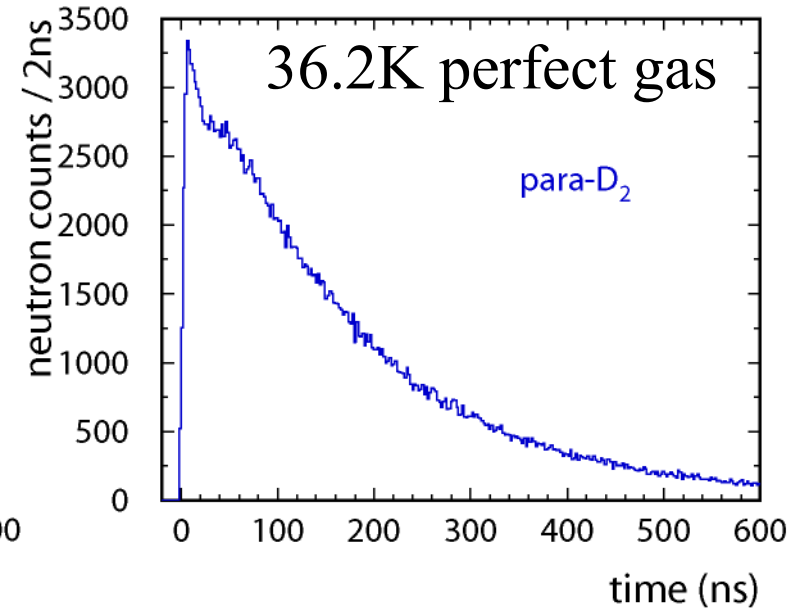
× Small OP dependence of dμ decelerating process

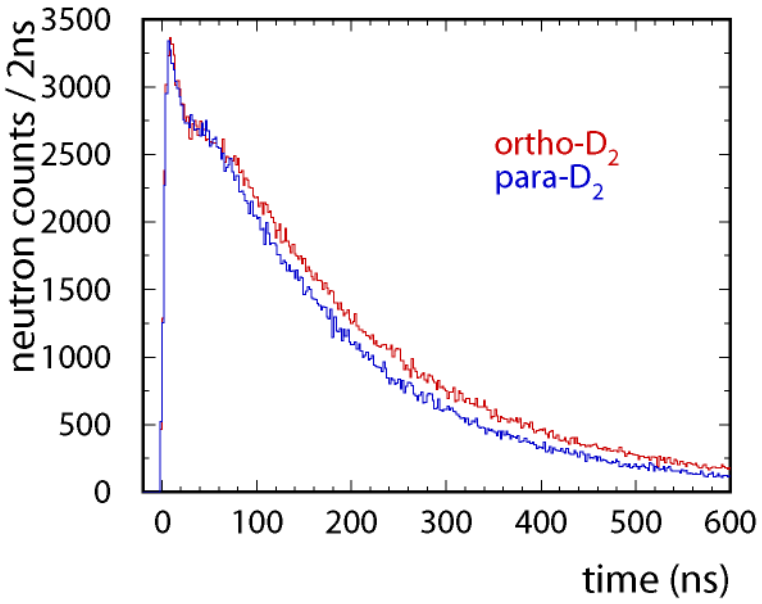
•Molecular formation from epithermal dμ (F=3/2)

slow thermalization

Preliminary Calculations by Adamczak





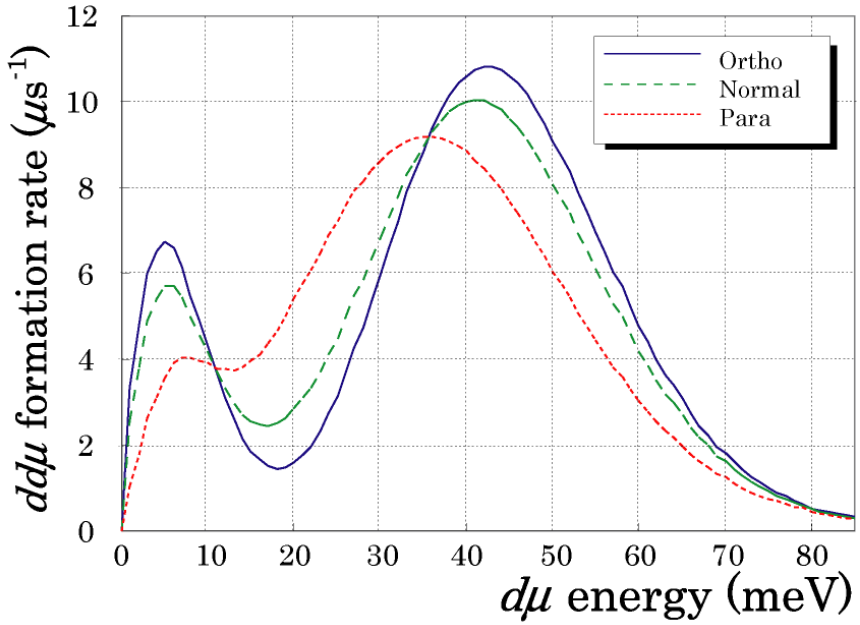


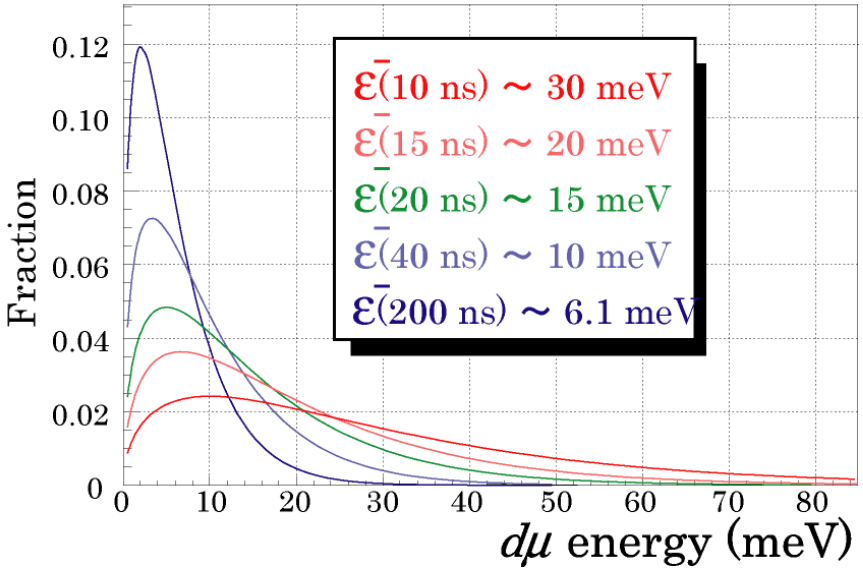
- ○ **Bump structure for ortho**
- ○ **Neutron yield**
- × **Bump structure for para**

The calculation does not reproduce correctly our experimental results concerning neutron time spectra.

Condensed-matter effects in the dense gaseous deuterium of our target (0.17LHD)?

Time-Dependent ddμ Formation Rate 1





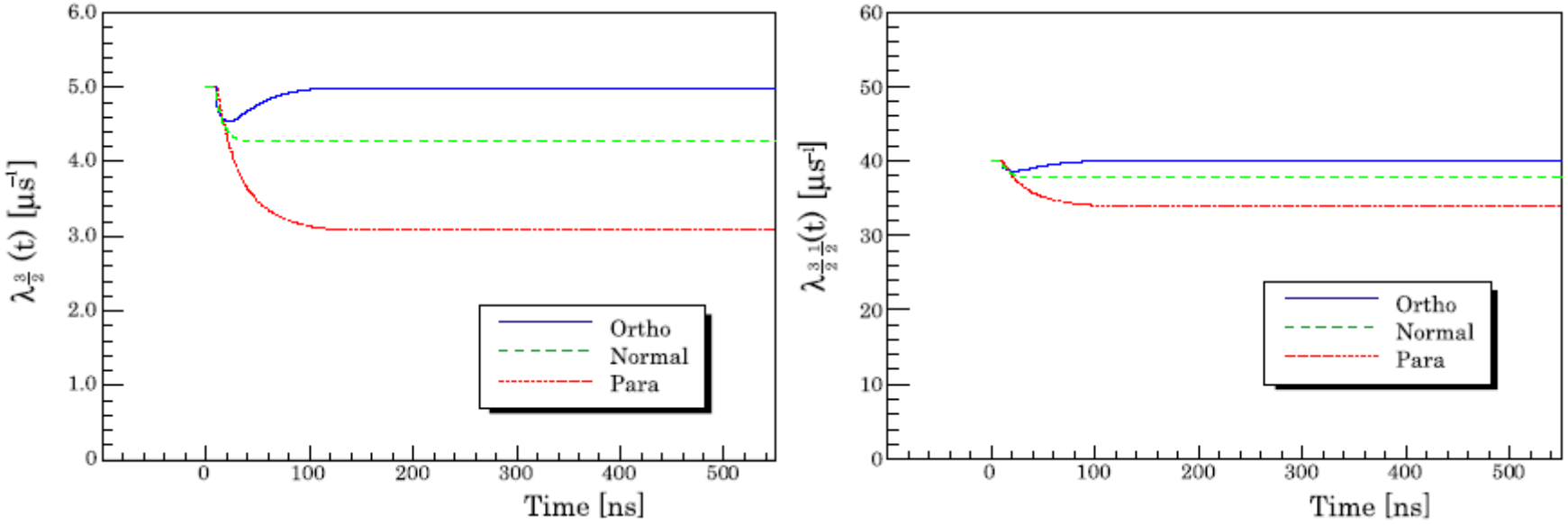
We calculated the "time-dependent" ddμ formation rates

Time evolution of overlap integral between Maxwellian dμ energy distribution and the resonant condition

$$\lambda_{\frac{3}{2}}(t) = \int \mathrm{d}\epsilon f(\epsilon, \epsilon_{avg}(t))\lambda_{\frac{3}{2}}(\epsilon)$$

Mean energy has time dependence

Time-Dependent ddμ Formation Rate 2

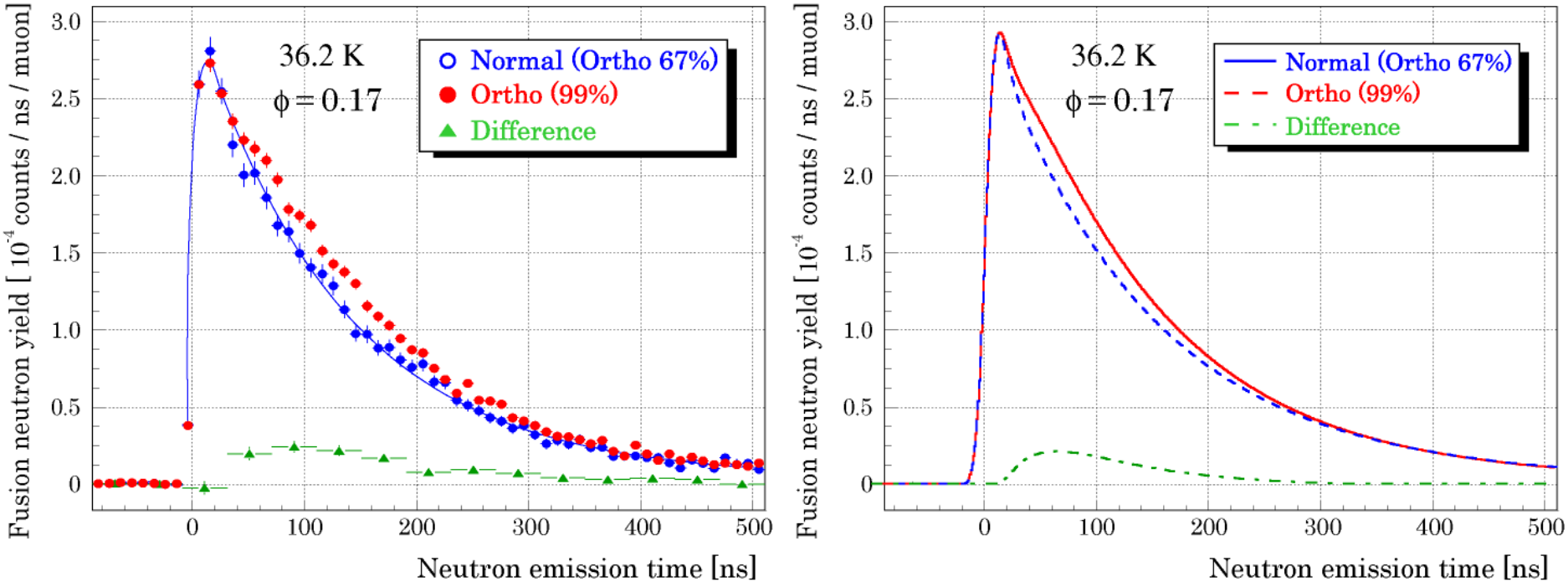


•The "time-dependent" rates in ortho-, normal-, and para-D2 were calculated

•The time dependence of the hyperfine transition rate was considered as the following;

$$\tilde{\lambda}_{\frac{3}{2}\frac{1}{2}}(t) = \lambda^{SC}_{\frac{3}{2}\frac{1}{2}} + \frac{\Gamma_{\frac{1}{2}\frac{1}{2}}}{\tilde{\lambda}_f}(\tilde{\lambda}_{\frac{3}{2}}(t) - \lambda_{nr}) \qquad \lambda^{SC}_{\frac{3}{2}\frac{1}{2}} = 24\ \mu s^{-1} \text{ and } \Gamma_{\frac{1}{2}\frac{1}{2}} = 1.5\ ns^{-1}$$

Time-Dependent ddμ Formation Rate 3



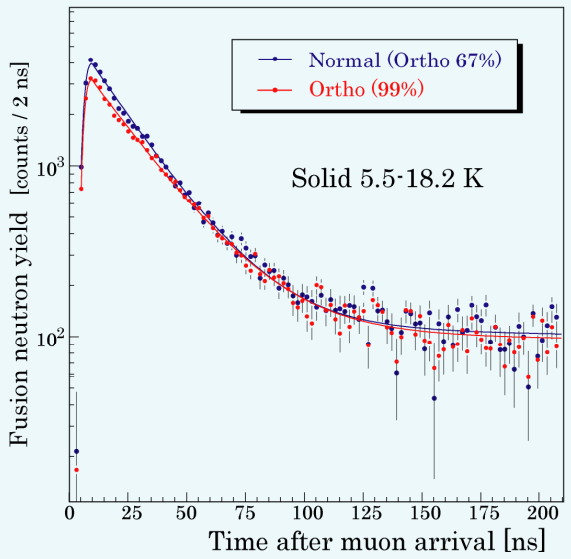
The calculated neutron time spectra for o-D2 and n-D2 reproduce the experimentally observed spectra

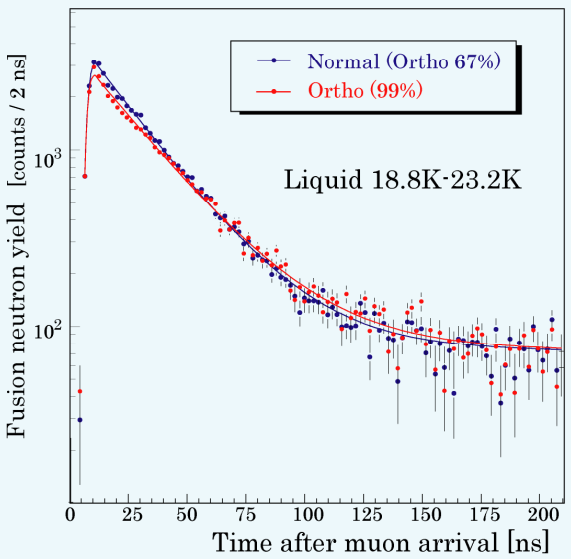
All previously observed rates in normal targets should be reviewed taking the time-dependence into account ???

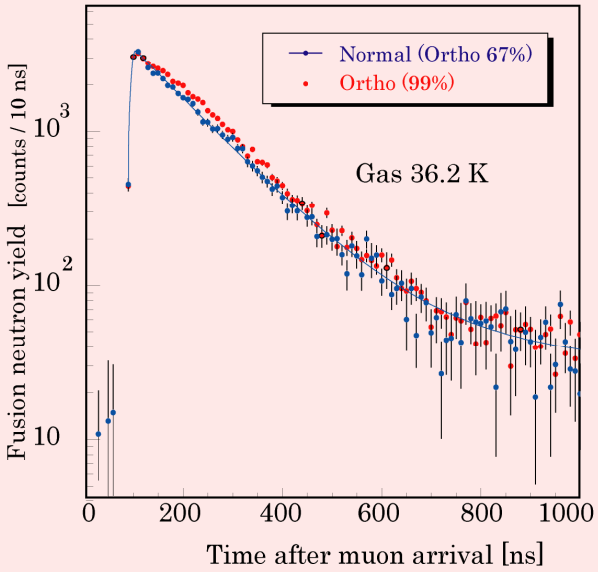
Stronger resonance in o-D2 is consistent with theory

Condensed Matter Effect

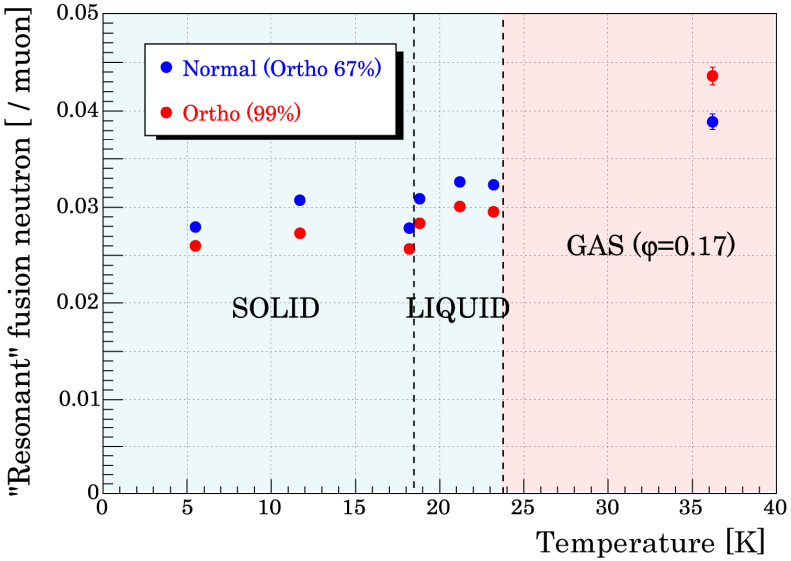
Ortho-para effect of spectra





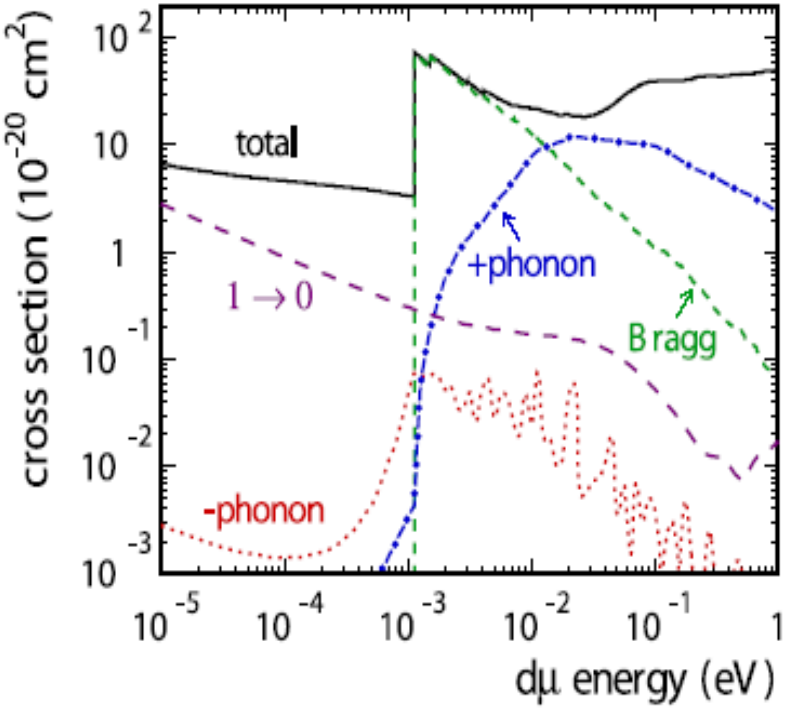


The effect is obviously different between the condensed target and gas target

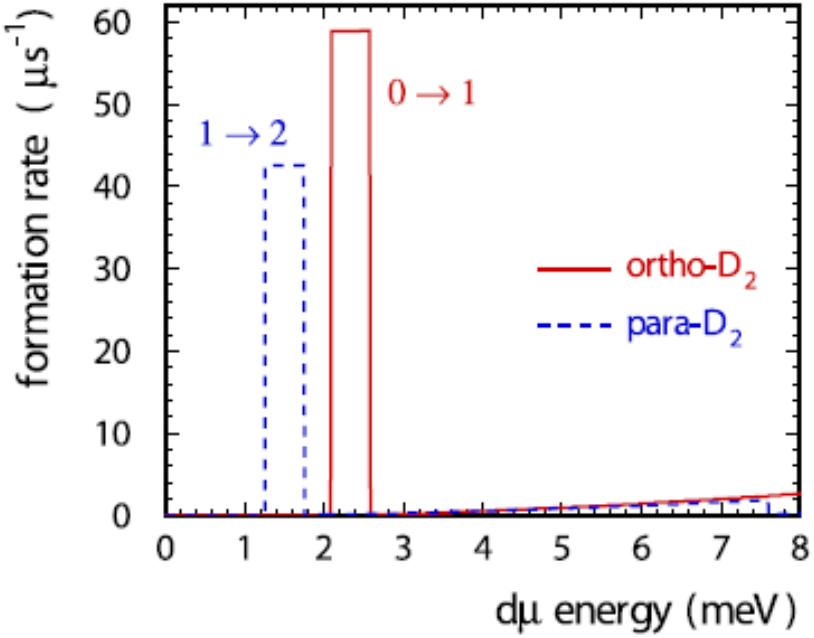


Ortho-para effect of neutron yield

Condensed Matter Effect by Adamczak



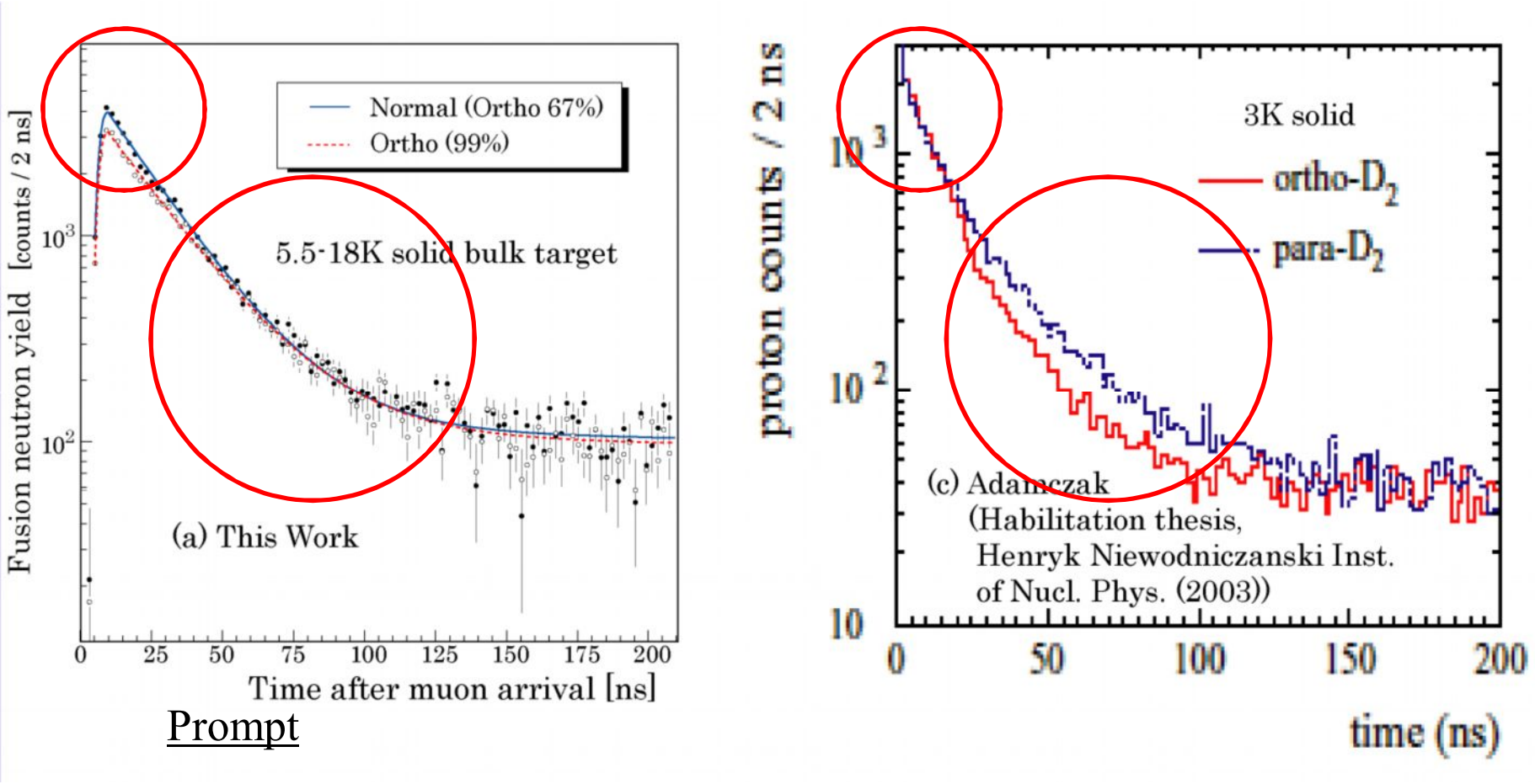
$d\mu(F=\frac{3}{2})+\mathrm{nD}_2, \quad T=3\ \mathrm{K}$



[A. Adamczak et al., PRA 64 (2001)]

- slow dμ thermalization in solid
- Phonon effect ⇒ small
- Resonance energy shift ⇒ -1.8 meV
- Resonance broadening ⇒ 0.5 meV

Comparison with theory by Adamczak



Prompt

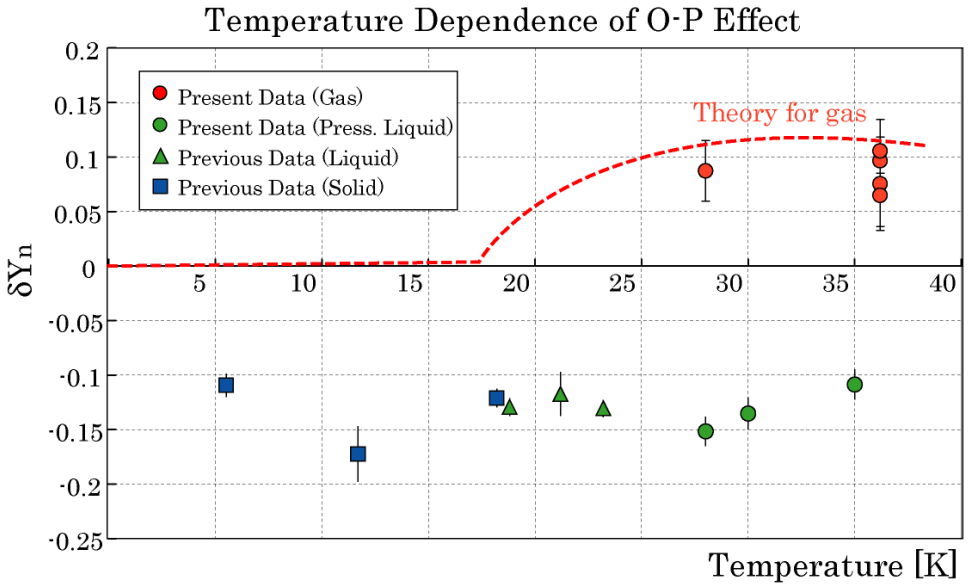
The effect of epithermal dμ atoms is too strong in theory

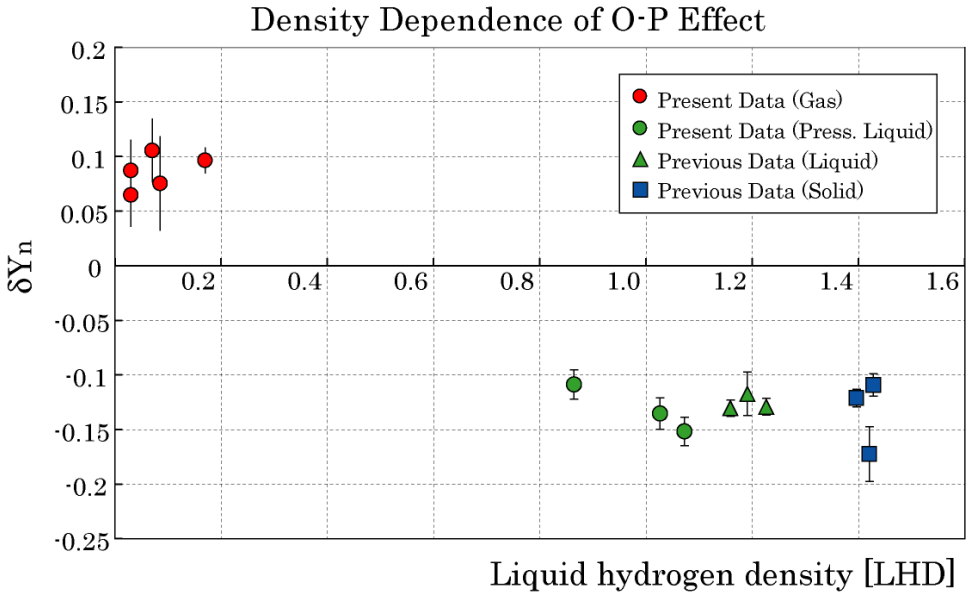
Slope

Exchange resonance energy in o-D2 for that in n-D2

Further effect in the condensed-matter is required to reproduce experiment

Resonant Fusion Neutrons Yield per Muon





Difference of neutrons yield between ortho (Y^o_n) and para (Y^p_n) targets are defined as

$$\delta Y_n = \frac{1}{c^o_o - c^p_o} \frac{Y^o_n - Y^p_n}{Y^o_n + Y^p_n}$$

C^p_o: Ortho concentration for para target

C^o_o: Ortho concentration for ortho target

Even at the same T, OP effect is inversion between gas and liquid.

Strong density dependence is clearly observed.

Effect of the surrounding D_2 molecule on the resonance condition is strong.