Exotic Atom Spectroscopy and High-Resolution X-Ray Measurements

Chubu University
Yuichi TOYAMA

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- Solid D_2 target experiment
  - J-PARC
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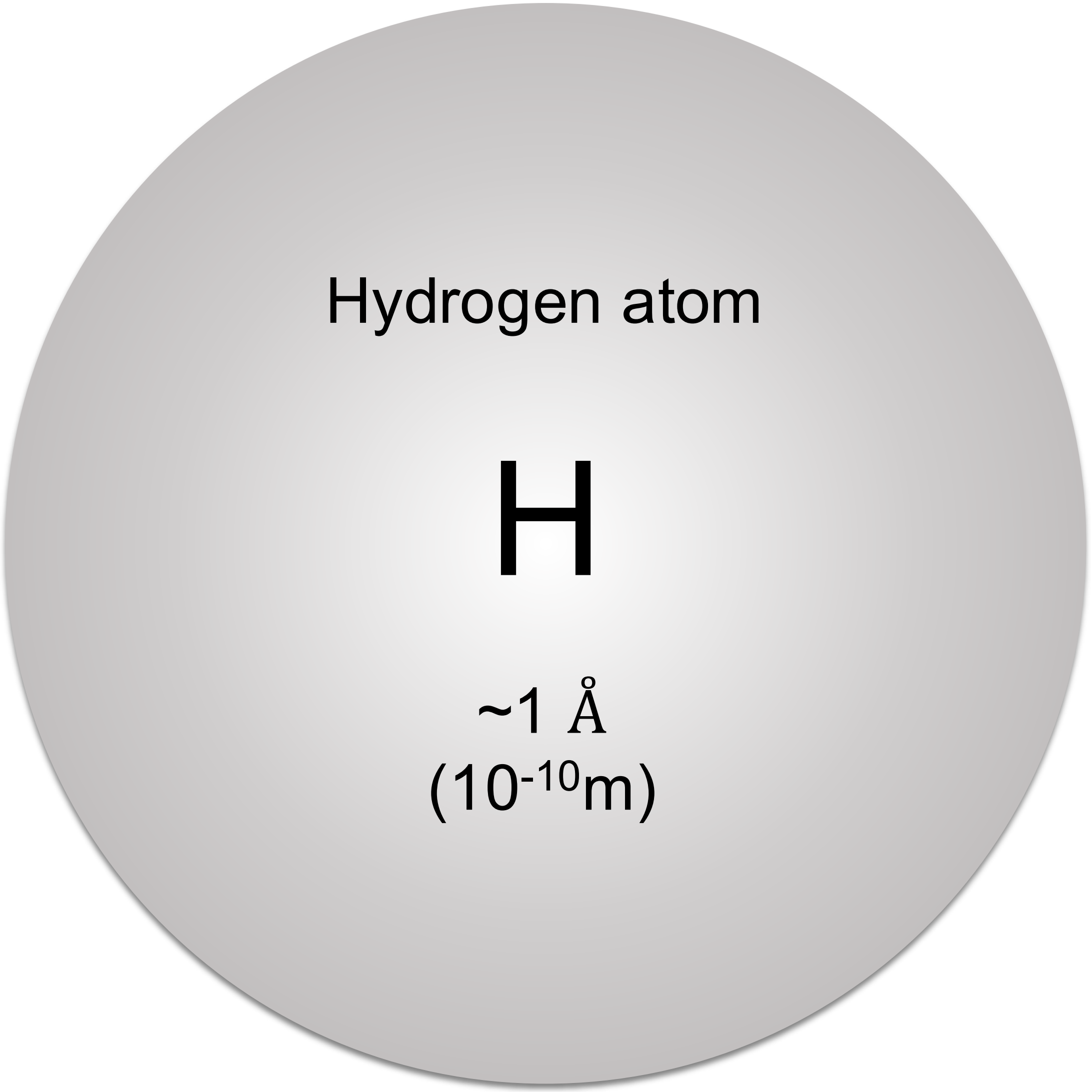
  - ddμ* X-ray spectrum
- Future measurement (dtμ*)

Muonic atom (scale)



Muonic Hydrogen

μH

~1/200 Å
(500 fm)

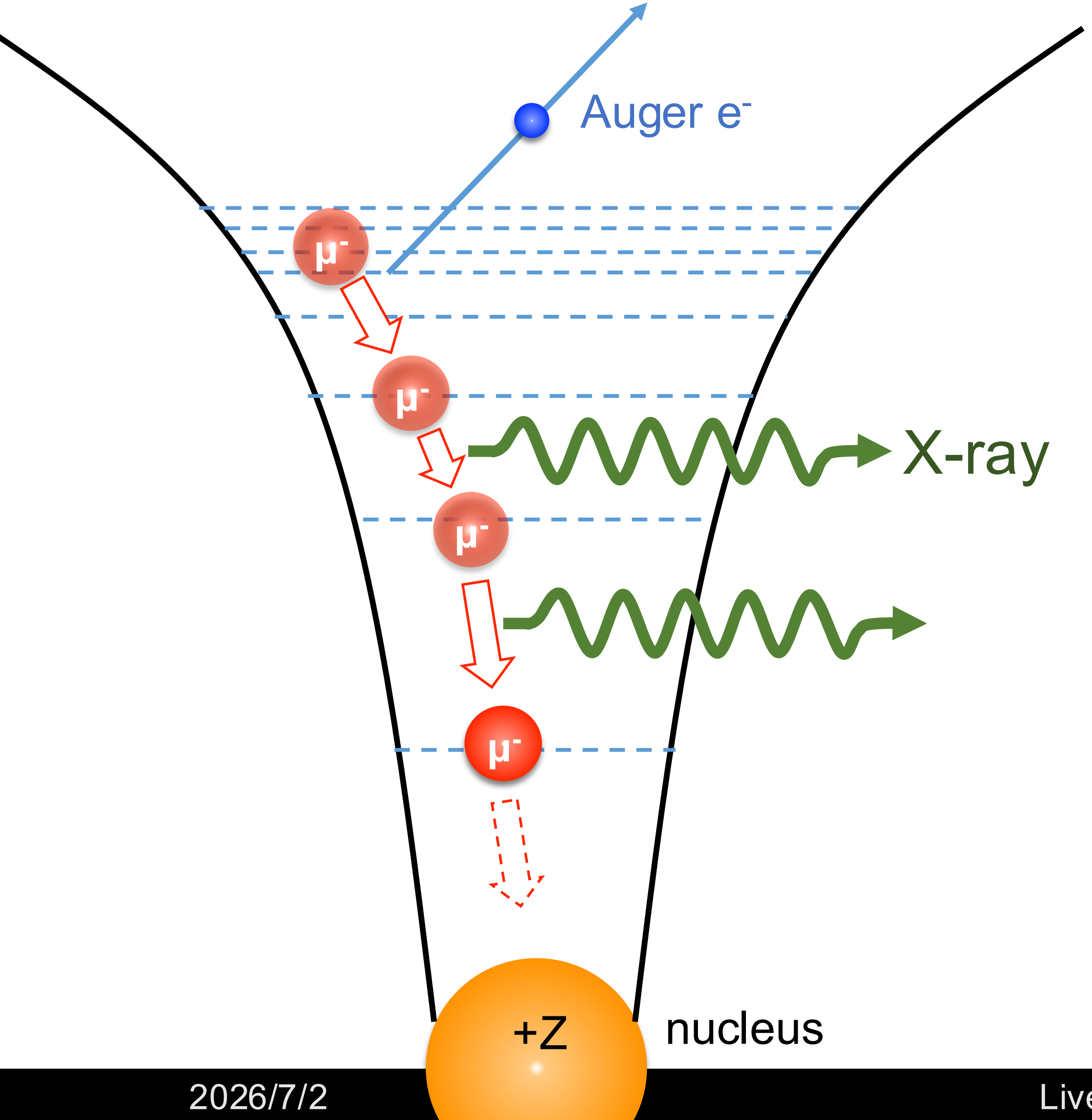
Bohr radius ($\frac{4\pi\epsilon_0\hbar^2}{me^2}$) 1/207 of normal atom

QED test at strong electric field

Non-destructive elemental analysis by X-ray measurement

muon catalyzed fusion (μCF)

Muonic atom (production process)

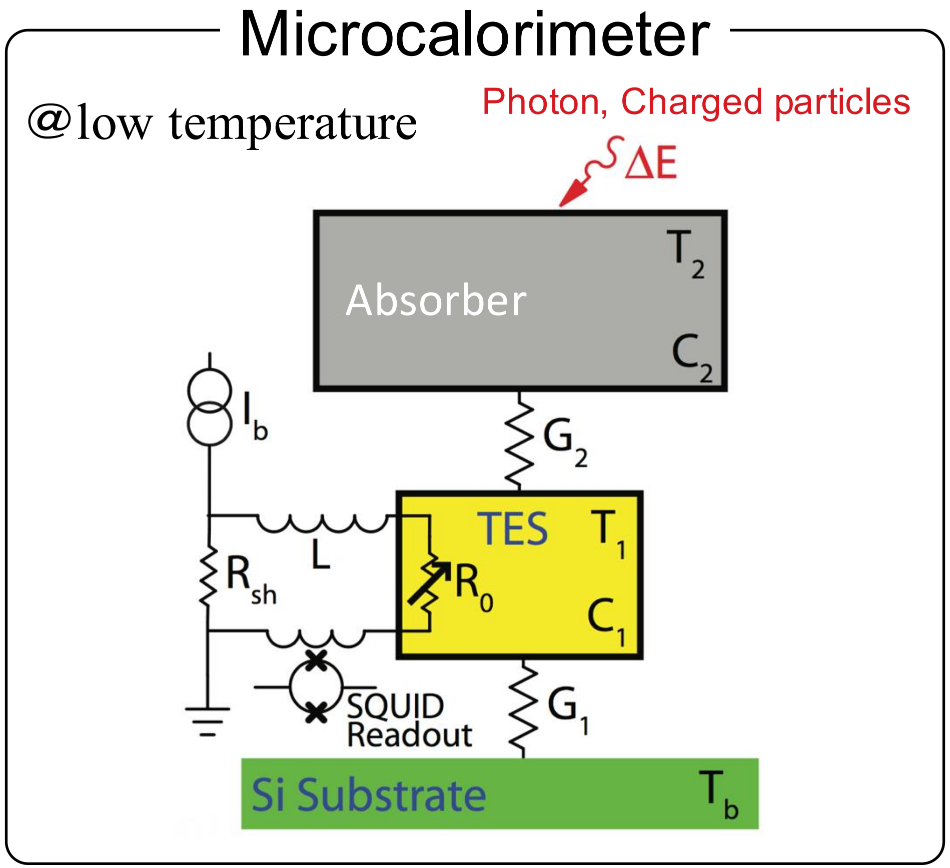


1. Decelerate & stop in a target material
2. Muon capture by an atom
   - n~20 (depending on atomic number)
3. Muon cascade (de-excitation)
   1. Auger electron emission
   2. Muonic X-ray emission

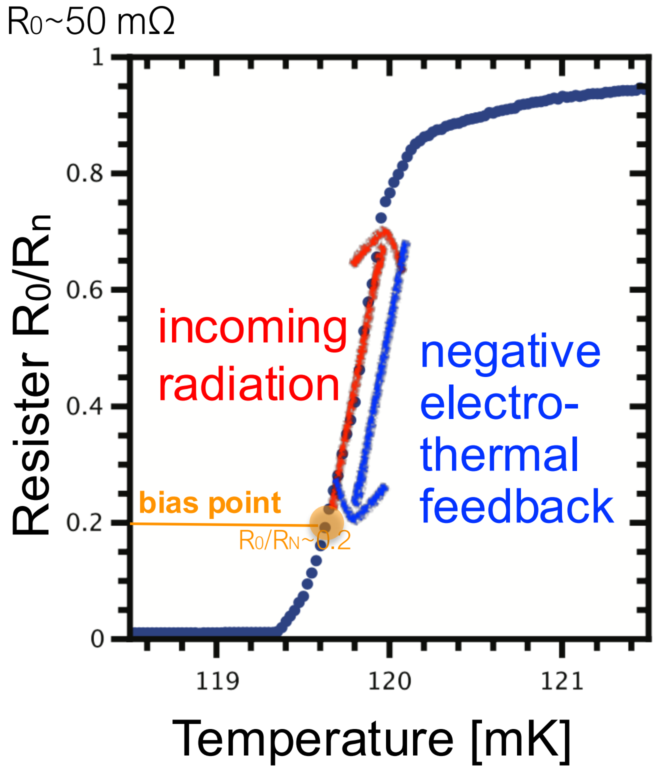
   time scale: 10 fs-1 ps
4. Muon decay or nuclear capture

   ~μs

Transition Edge Sensor (TES) microcalorimeter

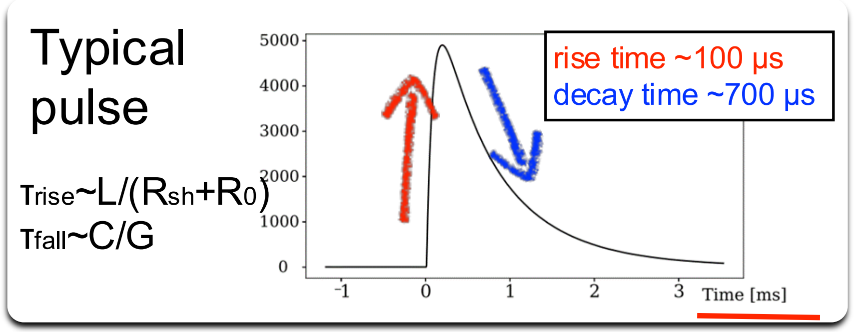


1. Incoming radiation
2. Temperature rise
 ⇒ Increasing resistance
3. Reducing bias current
4. Reducing Joule heat
5. Temperature fall
6. Back to original position



TES
for Low energy X-ray

Absorber: **Au** (965 nm)
Num. of pixels: 192



✓ High resolution (<10 eV @ 2 keV, FWHM)
- Ref.) SDD >100 eV @ 6 keV

$$\Delta E = 2\sqrt{2\ln 2}\cdot\sqrt{k_b {T_c}^2 C/\alpha}$$

☐ Effective area 0.1 mm^2/pixel
- Multi-pixelization to ~15 mm^2 (TDM readout)

HEATES collaboration

High-resolution **E**xotic **A**tom x-ray spectroscopy with **TES**

Scientists from many fields!
(Astro + (Nuclear & Hadron) + (Atomic & Muon)) physicists + TES experts

Challenge: Operate TES under severe condition

History

2013 Start collaboration with NIST

2014 Feasibility study with π^- atom @PSI — PTEP 2016

2015-2018 $\bar{K}N$ interaction with K^- atom @J-PARC hadron — PRL 2022

2019- μ^- atom/molecule @J-PARC MLF — PRL 2021, 2023, and 2025, Sci. Adv. 2026

2024- μ^- atom with γTES @J-PARC MLF

2024 Koshiba prize

High-resolution **E**xotic **A**tom x-ray spectroscopy with **TES**

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Challenge: Ope

History

2013 Start collaboration with NIS
2014 Feasibility study with π^- ato
2015-2018 $\bar{K}N$ interaction with K
2019- μ^- atom/molecule @J-PAR
2024- μ^- atom with γTES @J-PAI
2024 Koshiba prize

Process of muon catalyzed fusion

$$d t \mu \rightarrow \alpha + n + \mu + 17.6\ \mathrm{MeV}$$

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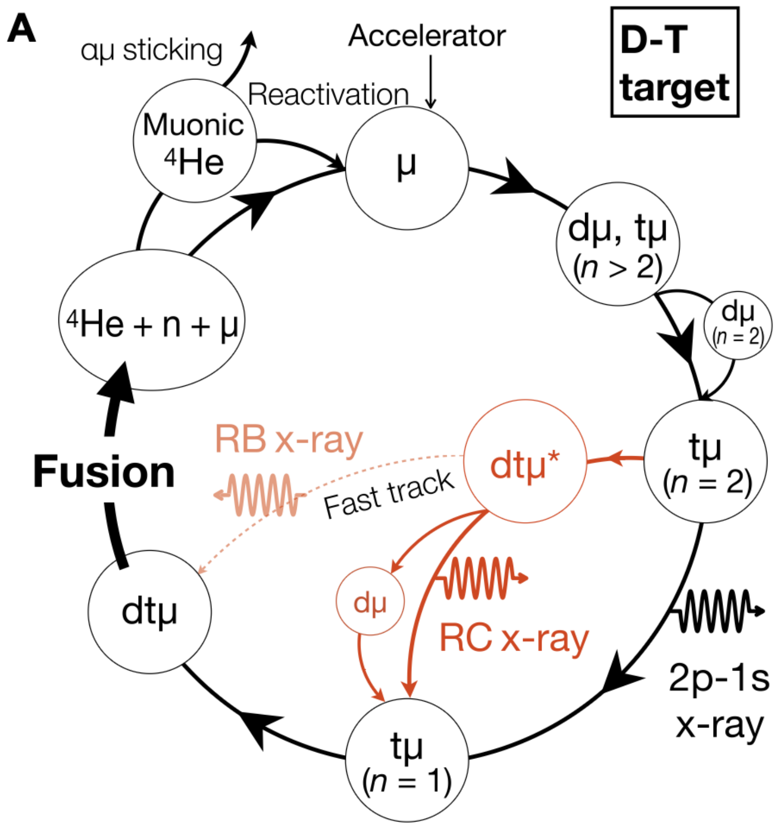
…

After fusion, μ- forms another dtμ molecule.

μ- does not directly react but acts like *catalyst.*

⇒muon catalyzed fusion

μCF cycle in D-T mixture target



- Recently, the reaction cycle via molecular resonance states proposed by Y. Kino et al. at Tohoku University → μCF rate (exp.) was explained

No direct measurement of resonance states of muonic hydrogen molecules.

⇒ X-ray spectroscopy of ddμ*

$$dd\mu^* \rightarrow d\mu + d + h\nu$$

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$$d t\mu \rightarrow \alpha + n + \mu + 17.6\ \mathrm{MeV}$$

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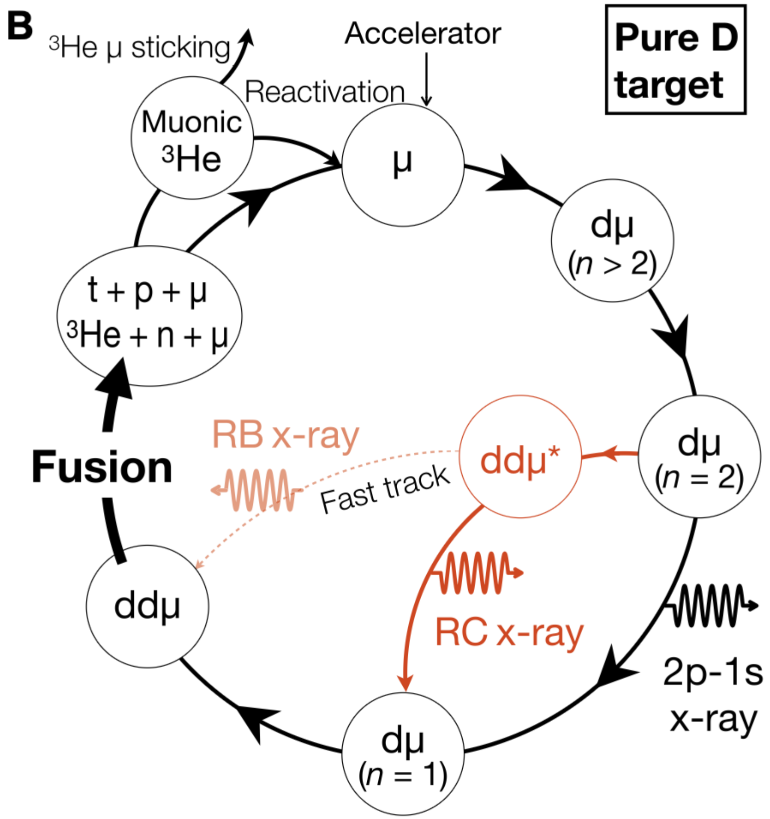
…

μCF cycle in pure D_2 target



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⇒ X-ray spectroscopy of ddμ*

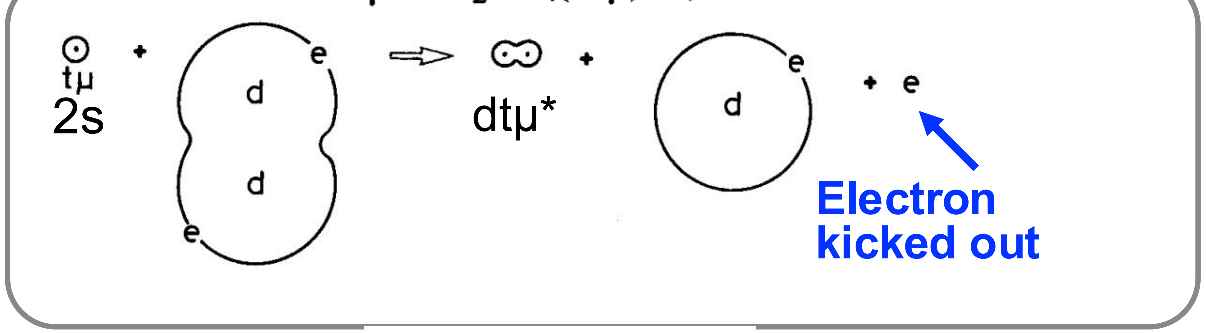
$$dd\mu^* \rightarrow d\mu + d + h\nu$$

Vesman mechanism

E. Vesman, ZhETF Pis. Red. 5, 113 (1967).
P. Froelich, Advances in Physics 41, 405 (1992).

①

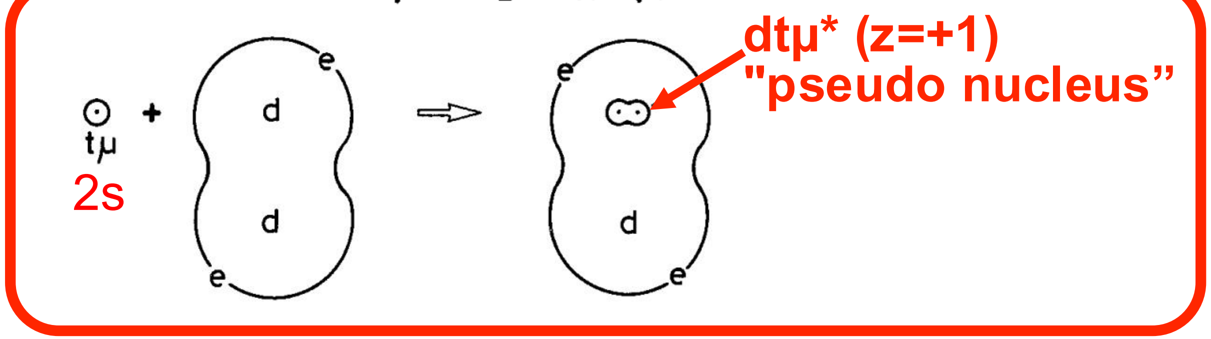
$t\mu + D_2 \rightarrow \langle (dt\mu)de \rangle + e$



Direct production

②

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



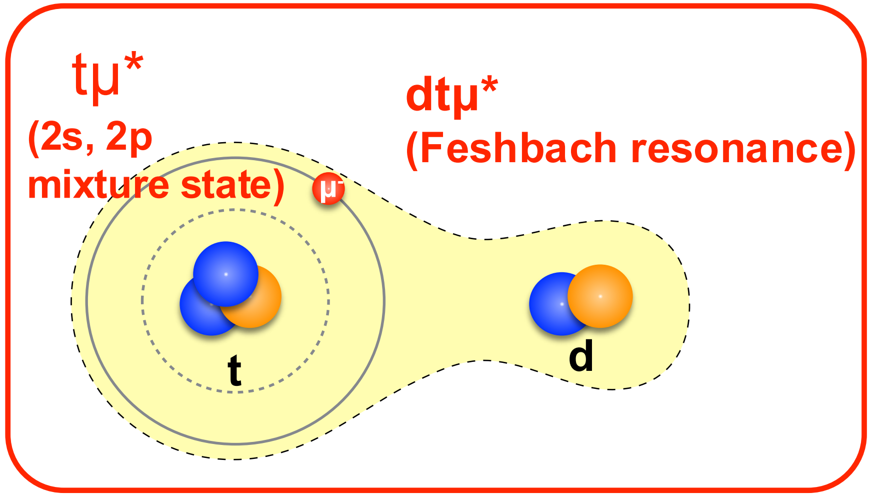
Resonant production

Vesman mechanism
(Feshbach resonance mechanism)

(μCF fusion rate suggests this process)

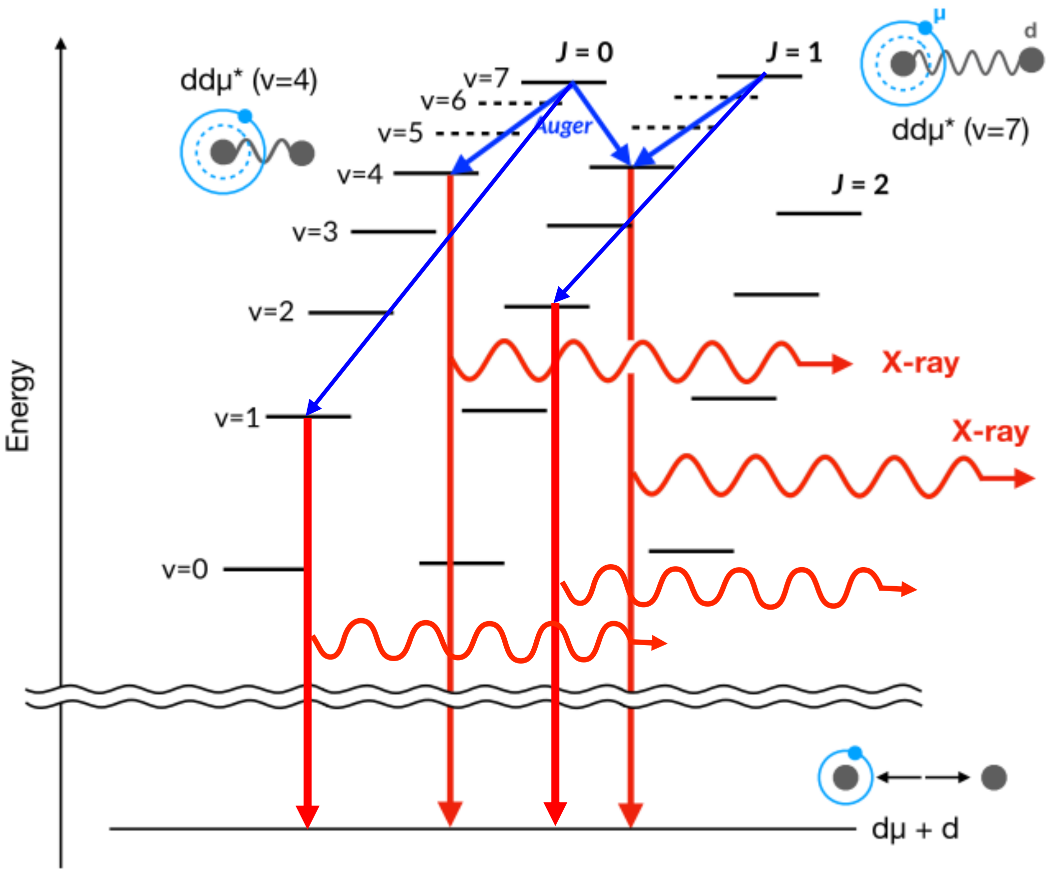
Excess energy of dtμ formation
→Vibrational/rotational energy of a D_2 molecule

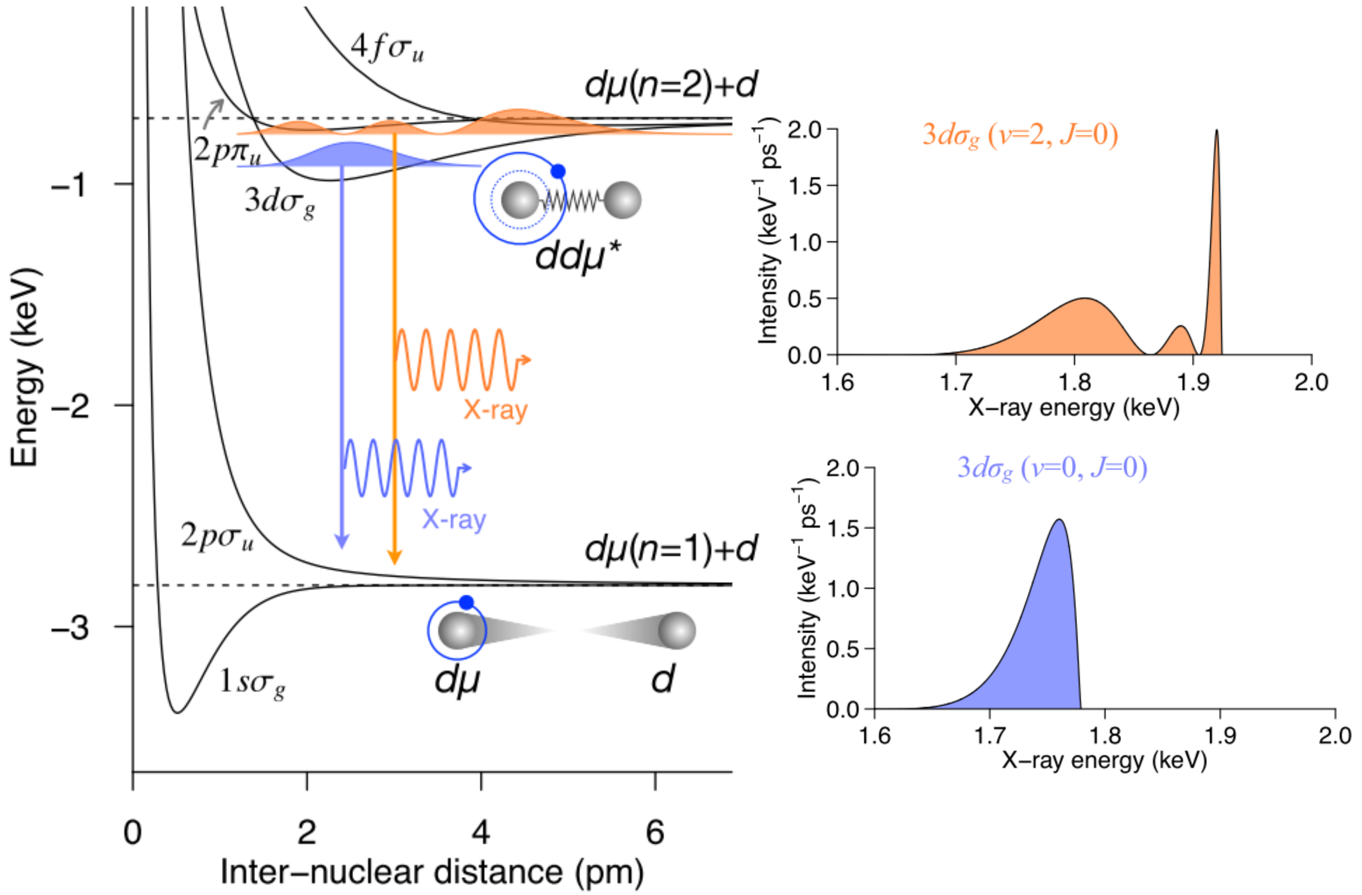
pure D system can be understood same analogues (ddμ*)



X-ray spectrum of ddμ*

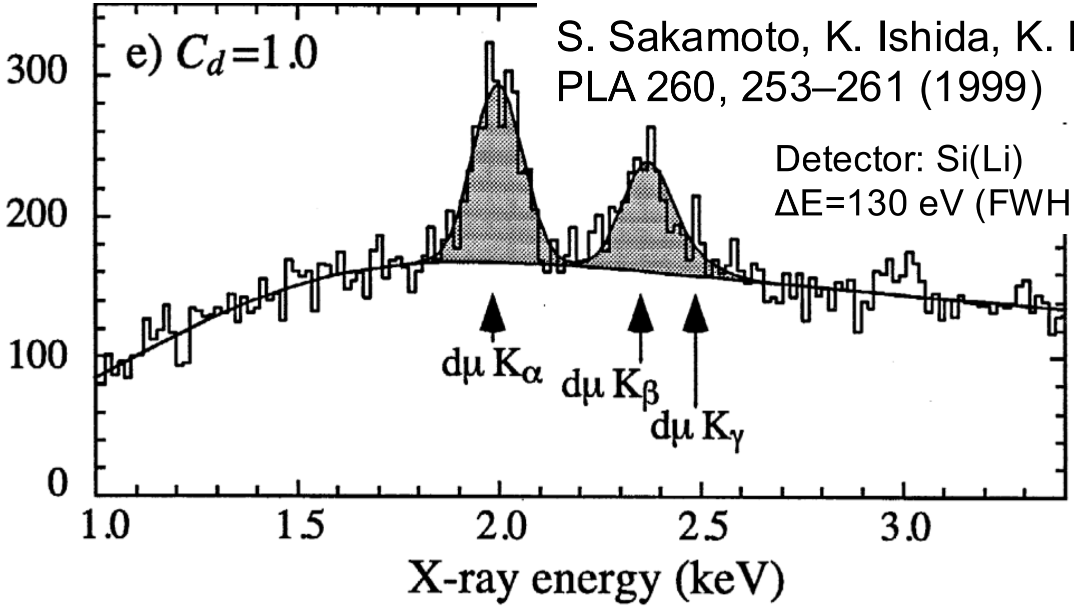
ddμ* produced at higher vibrational state (v≧7)
radiative decay occur at lower state (v≦4),after Auger process
⇒ Observable: Sum of several states' spectrum
X-ray of dμ atom 2p-1s (2 keV) cannot be avoided.
Measurement of low energy X-ray <2 keV is also challenging





Calculation by T. Yamashita (Tohoku Univ.)
Phys. Rev. A 111, 012811 (2025).

Previous muonic X-ray measurements with a deuterium target

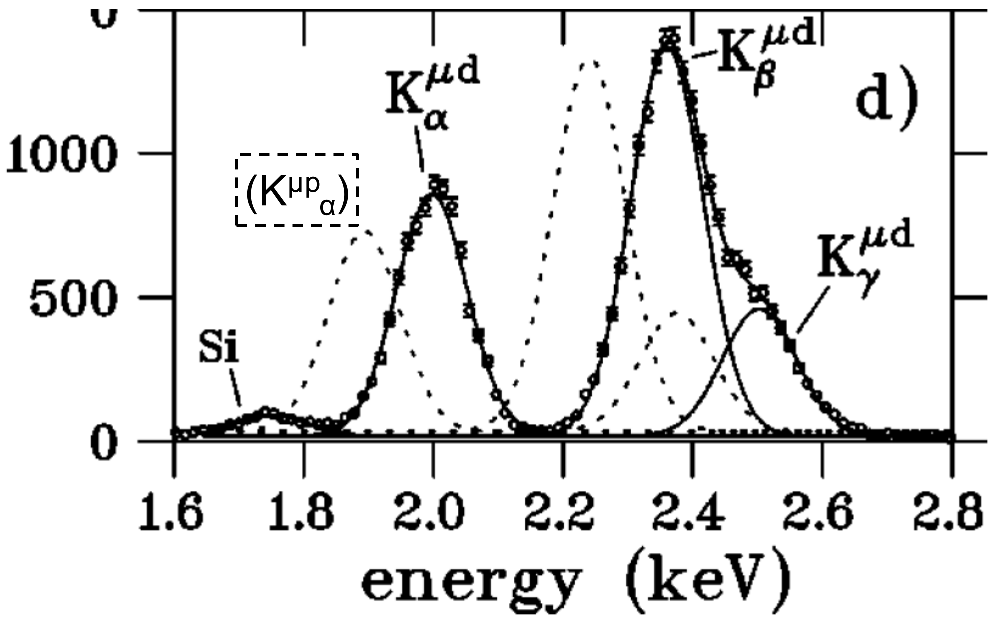


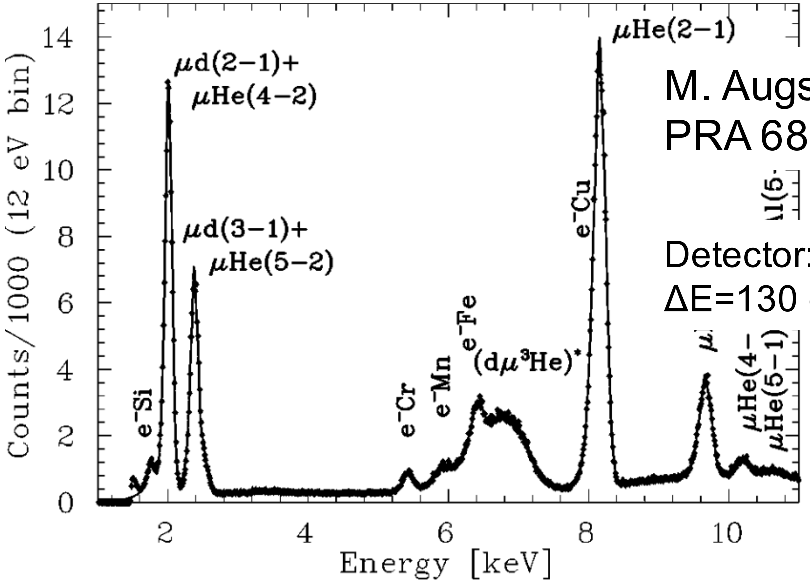
S. Sakamoto, K. Ishida, K. Nagamine, PLA 260, 253–261 (1999)

Detector: Si(Li)
ΔE=130 eV (FWHM)

B. Lauss et al., PRA 60, 209 (1999)

Detector: APD
ΔE~120 eV (FWHM)





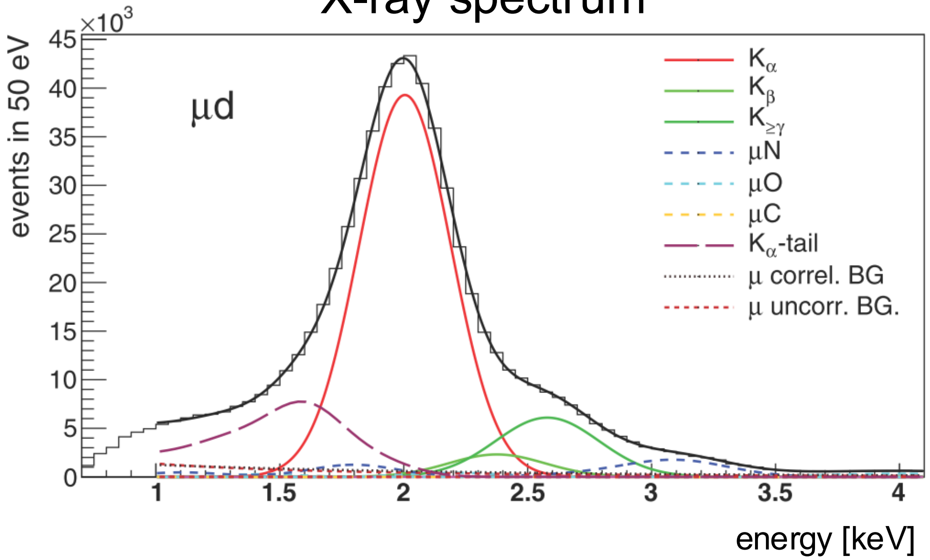
M. Augsburger et al., PRA 68, 022712(2003)

Detector: CCD
ΔE=130 eV (FWHM)

Conventional detectors cannot separate ddμ* (molecule) X-ray from μd (atom) X-ray!

Previous muonic X-ray measurements with a deuterium target

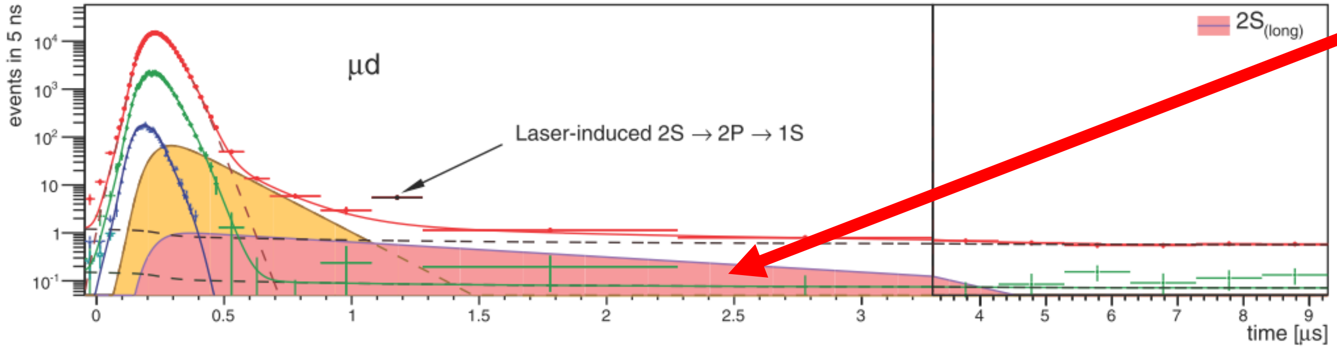
X-ray spectrum



M. Diepold et al., PRA88, 042520 (2013)
(CREMA Collaboration)

- Experiment at PSI
- Low pressure gas D_2 target (100 Pa)
- X-ray detector: APD
  - ΔE=400 eV (FWHM)
  - Δt=25 ns

Time spectrum of μd X-ray

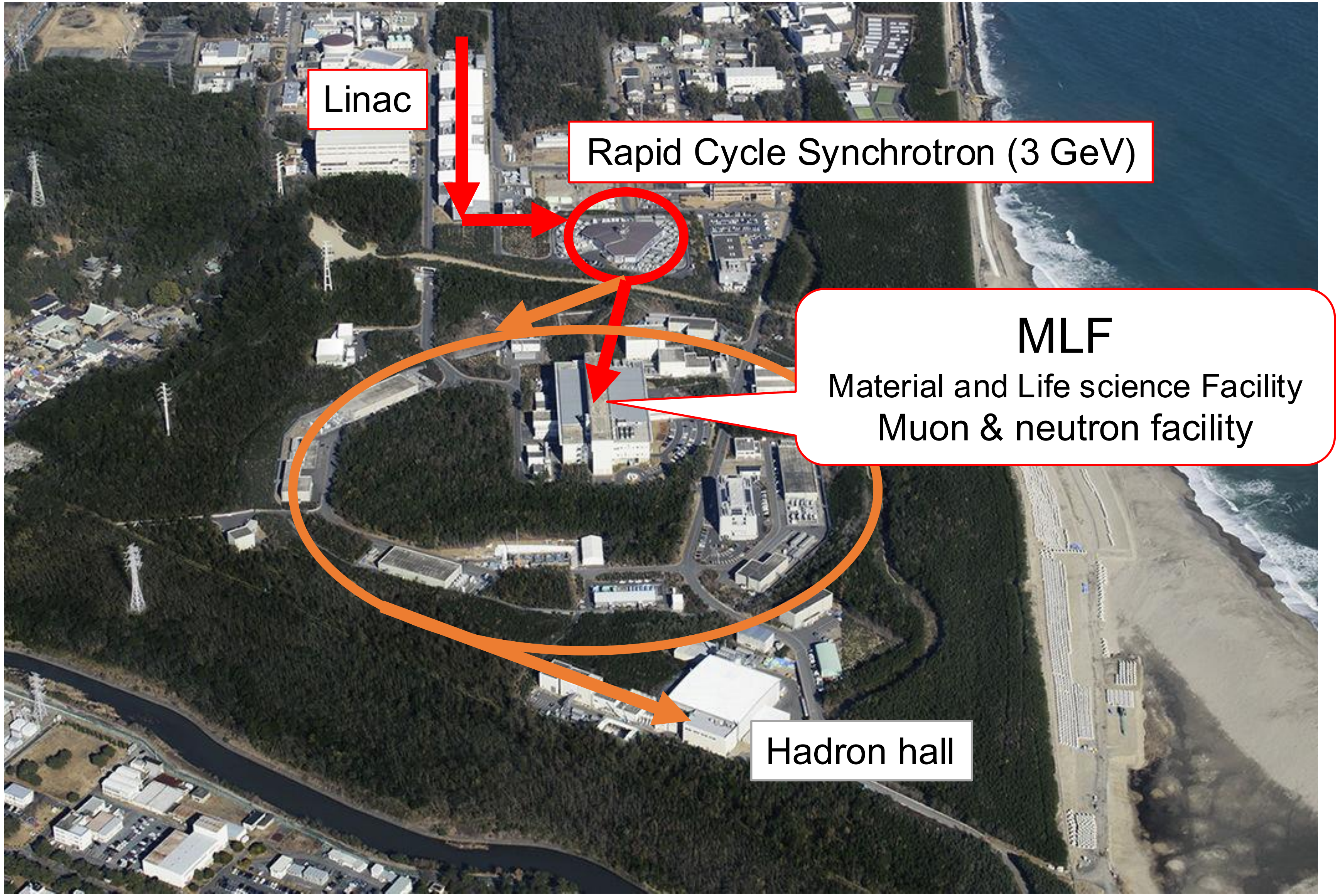


They interpret slow component of μd Kα is X-ray from ddμ*

But no spectral decomposition…

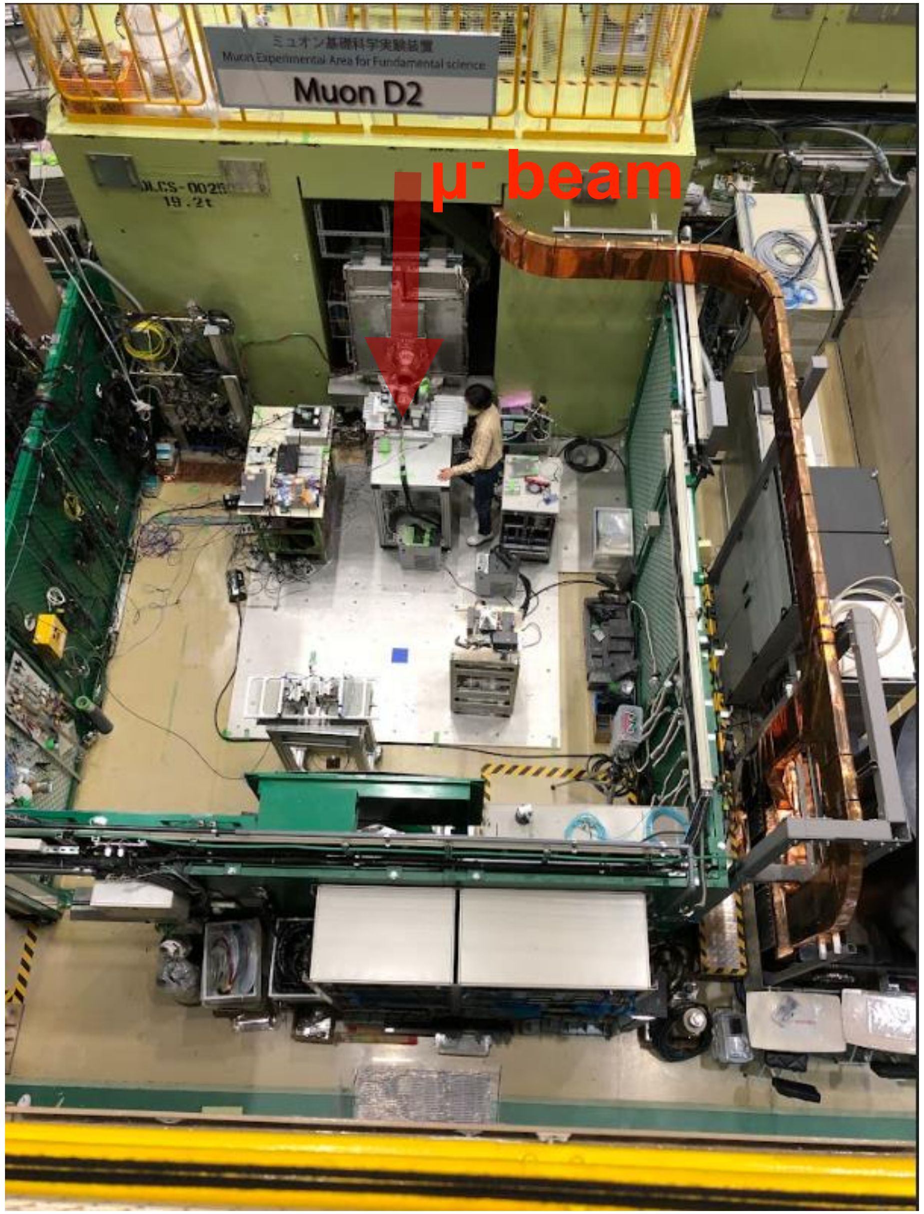
Higher energy resolution is necessary!

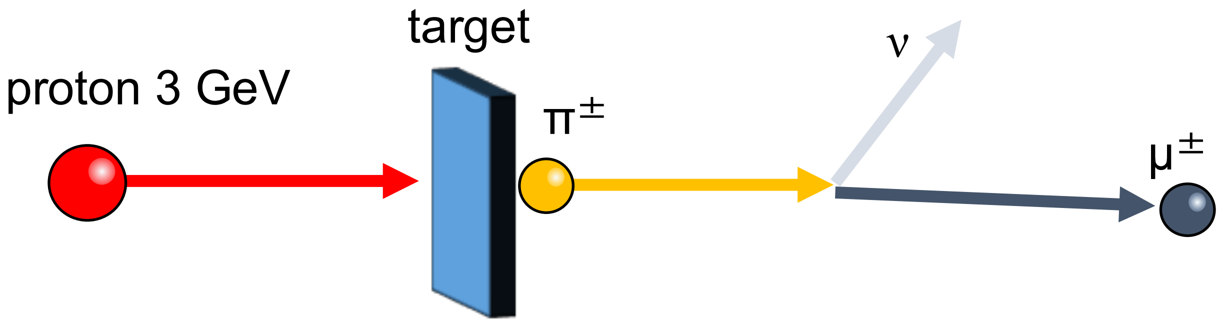
Japan Proton Accelerator Research Complex



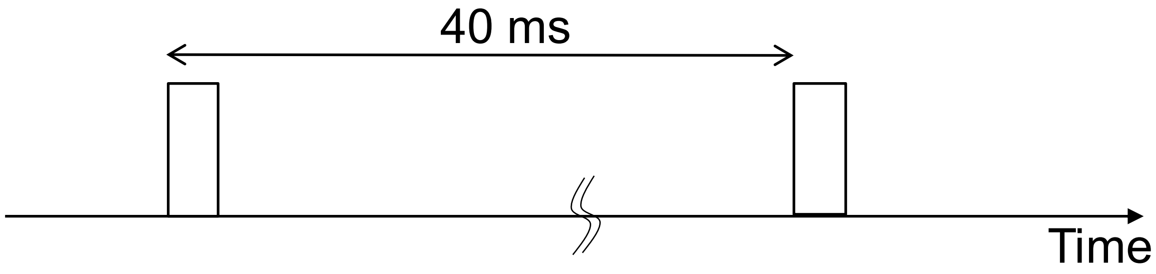
https://j-parc.jp

J-PARC MLF D2 beamline

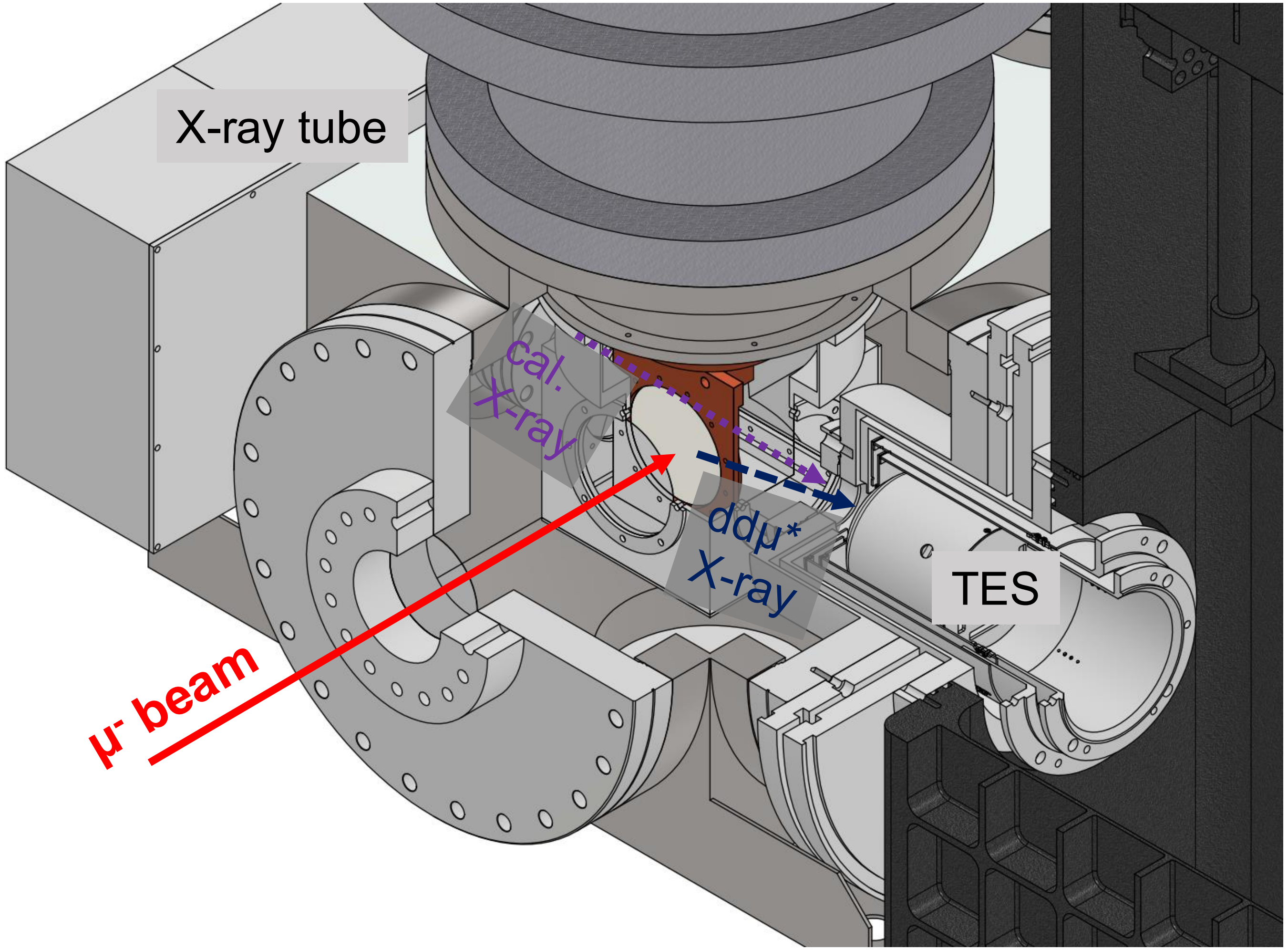




- Beam momentum: 27.5 MeV/*c* (max. 50 MeV/*c*)
- $\Delta p/p$~10% (FWHM)
- 25 Hz double pulse beam
- Intensity: ~5.0 x 10^6 μ^-/sec
- Beam size: ~Φ50 mm



Experimental setup of a solid D2 target experiment



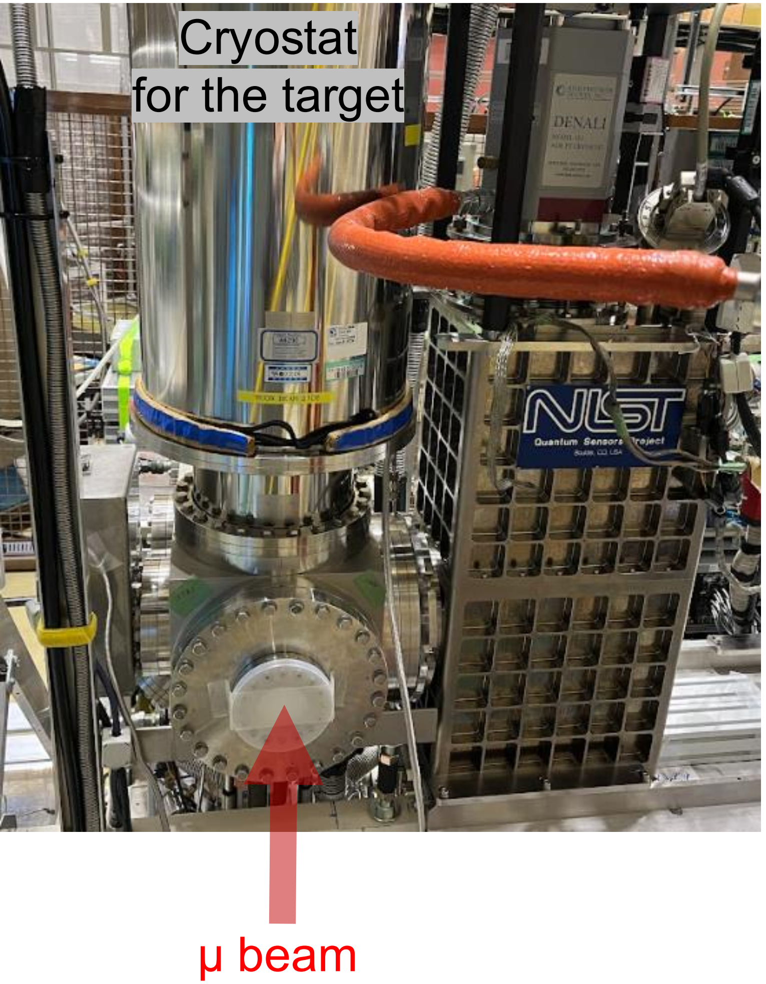
at J-PARC MFLD2 beam line
Feb 5 - 11, 2023

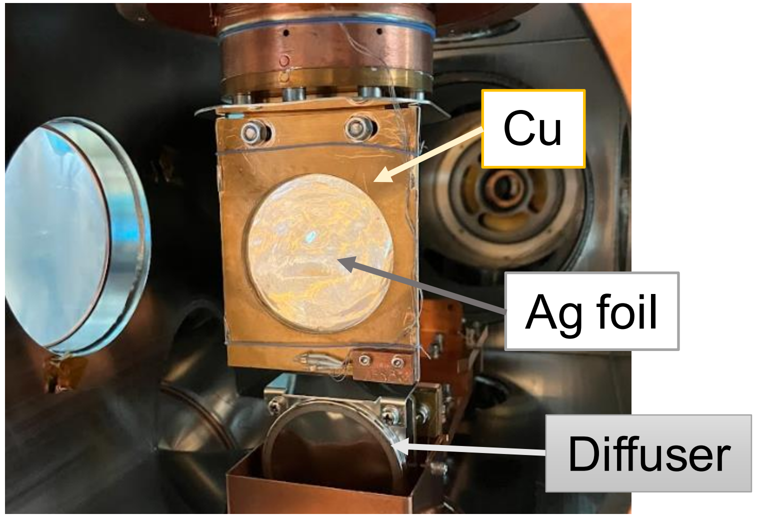
- μ⁻ beam (27.5 MeV/*c*) was irradiated to the solid deuterium target.
- ddμ* was produced in the target
- Dissociative X-rays of ddμ* were detected by TES detector
  - Transmittance: ~40%@2 keV
- Calibration X-rays from X-ray tube were measured simultaneously.

- Other detectors
  - Plastic scintillator + PMT (for decay e^-)
  - SDD (for reference)
  - MiniPIX (for proton, scattered μ^-)

Solid deuterium target system

P. Strasser et al. Nucl. Instrum. Meth. Phys. Res. A **460**, 451 (2001).



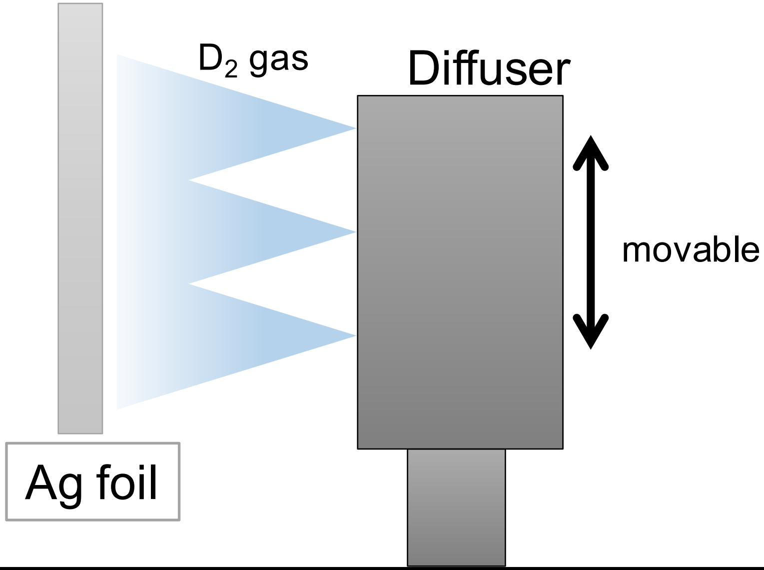


Al thermal shield
(before attaching window)

Solid deuterium target system

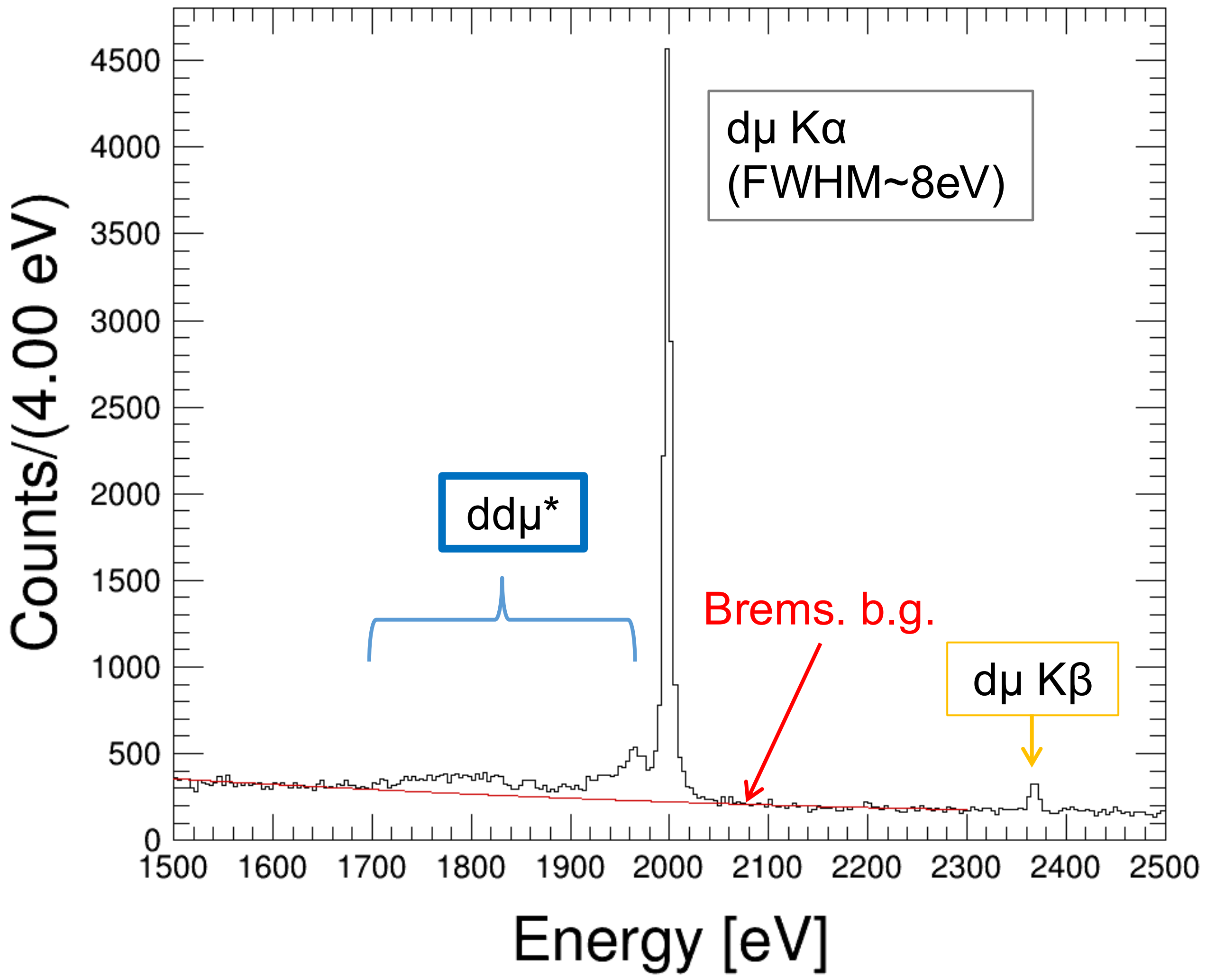
- Base: Ag foil (100 μm)
- Target size: ~Φ50 mm
- Thickness: ~1 mm
- Temperature: ~3 K (Liq. He coolant)
- Chamber pressure: 1x10^{-6} Pa

✓ Stable operation during the measurement.



ddμ* dissociative X-ray

In-beam spectrum (-1.0 μs, 1.5 μs)



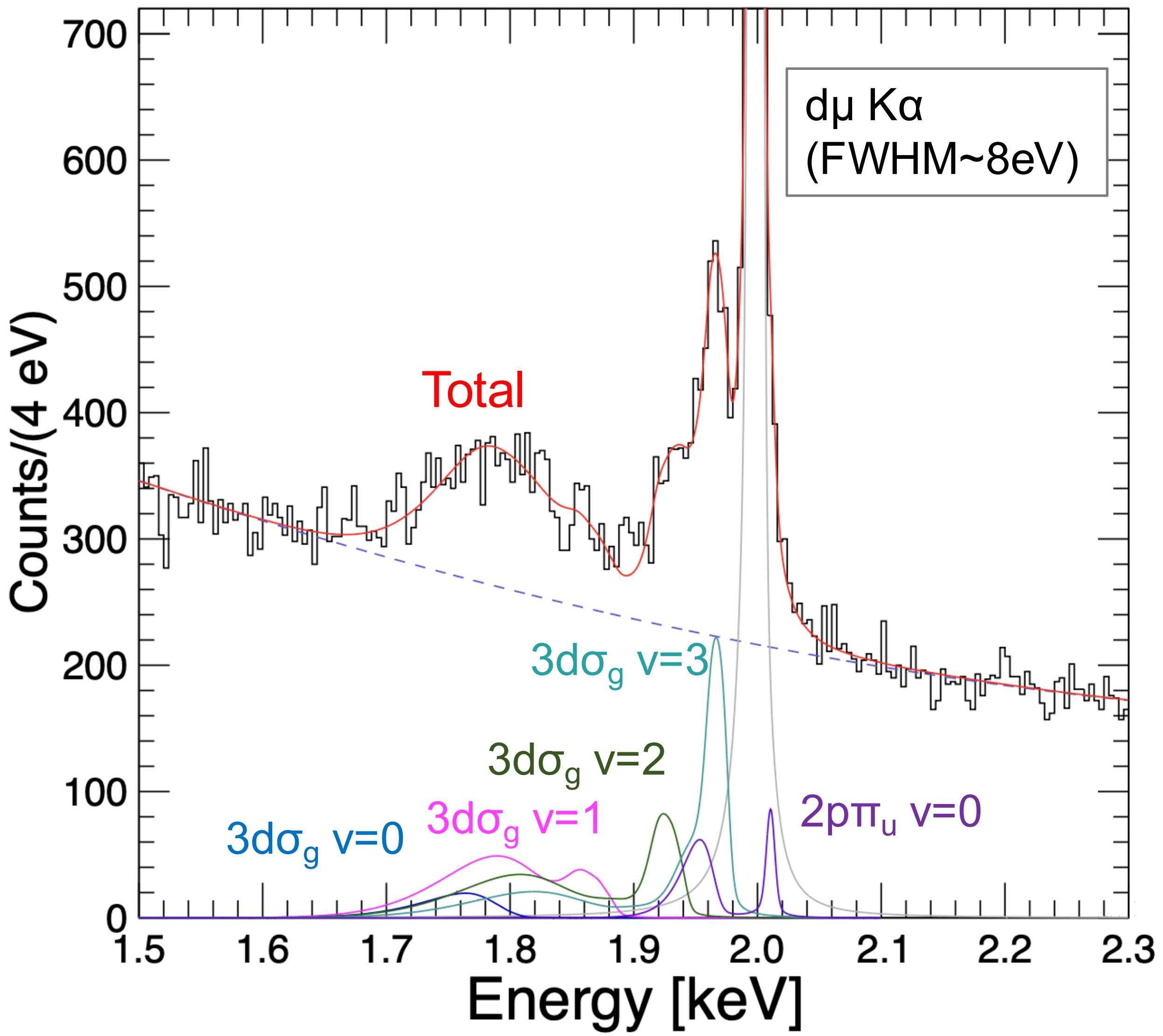
First observation of ddμ* X-rays!

dμ Kα:ddμ* = 6:4

⇨ ddμ* formation rate is comparable to the dμ(2p) de-excitation rate (1.2×10^{11} s^{-1})

※Brems. b.g.: Bremsstrahlung from decay e^-

Fitting of ddμ* dissociative X-ray



- χ^2 fit (Minuit)
- Spectra of Vesman + Auger processes
  - $3d\sigma_g$ v=0, 1, 2, 3, $2p\pi_u$ v=0
- dμ peak: Response function
  - Determined to be self consistent
- Brems. b.g.: Quadratic function

Spectrum is well reproduced!

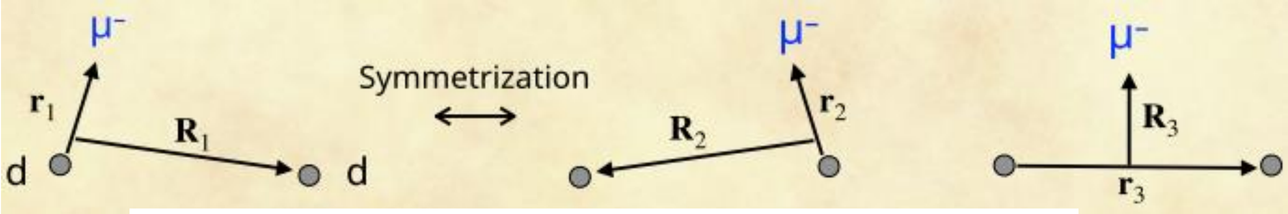
YT, YK, SO, TY *et al.*, Sci. Adv. 12, eaed3321 (2026)
doi: 10.1126/sciadv.aed3321

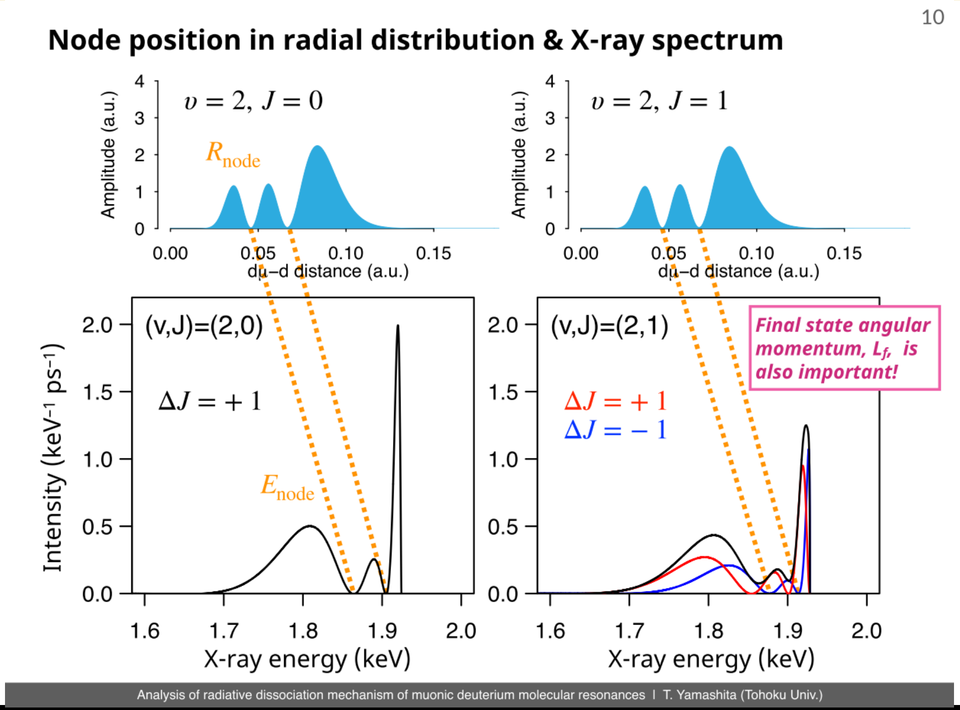
Experimental study of μCF cycle dynamics beyond fusion products (p, n, α…)

Necessity of precise few body calculation

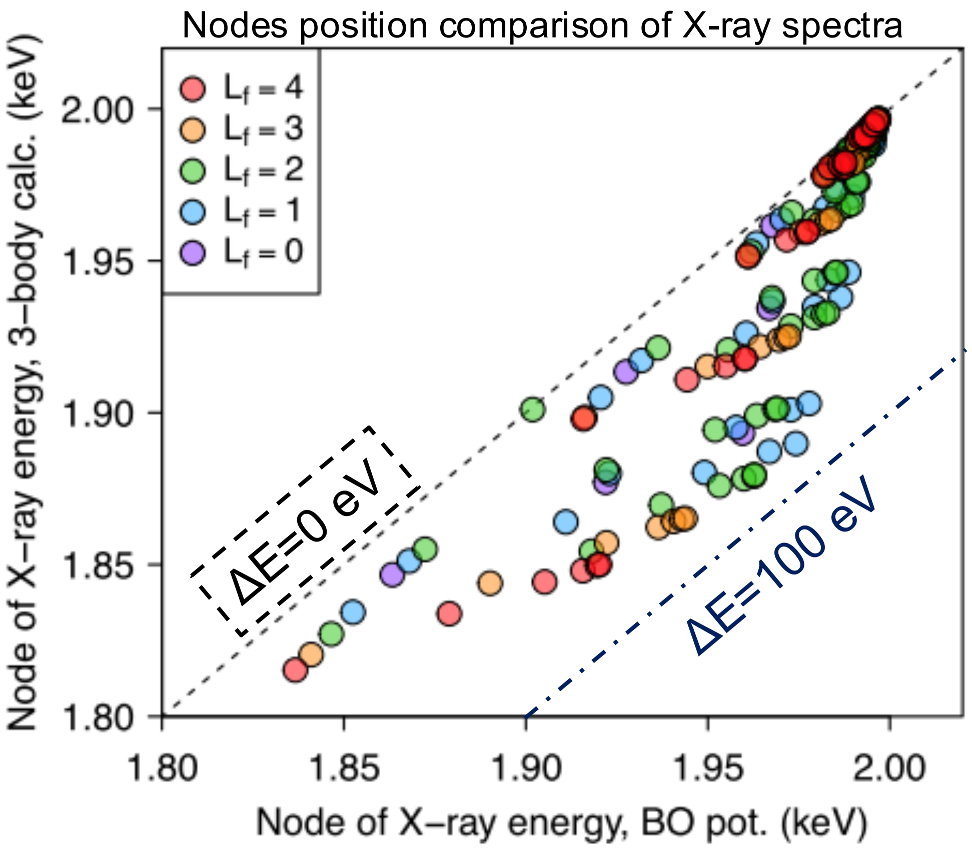
Adiabatic approximation (separate the motion of nuclei and that of electron (muon)) is not good due to large mass of muon.

Requires precise few body calculation that treat the three particles equally using Jacobi coordinates.





3-body calculation

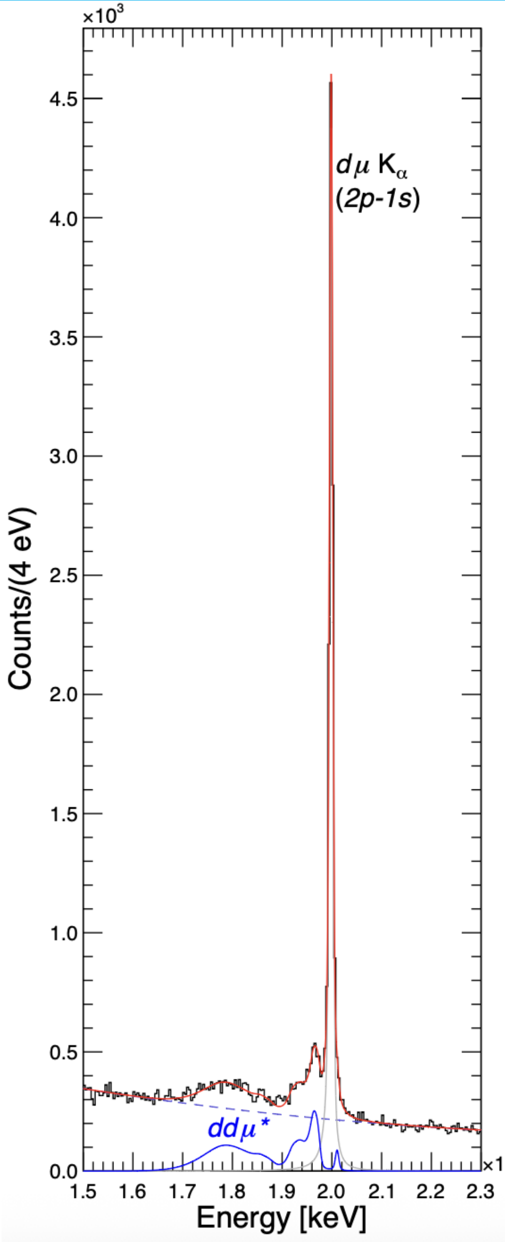


adiabatic approximation

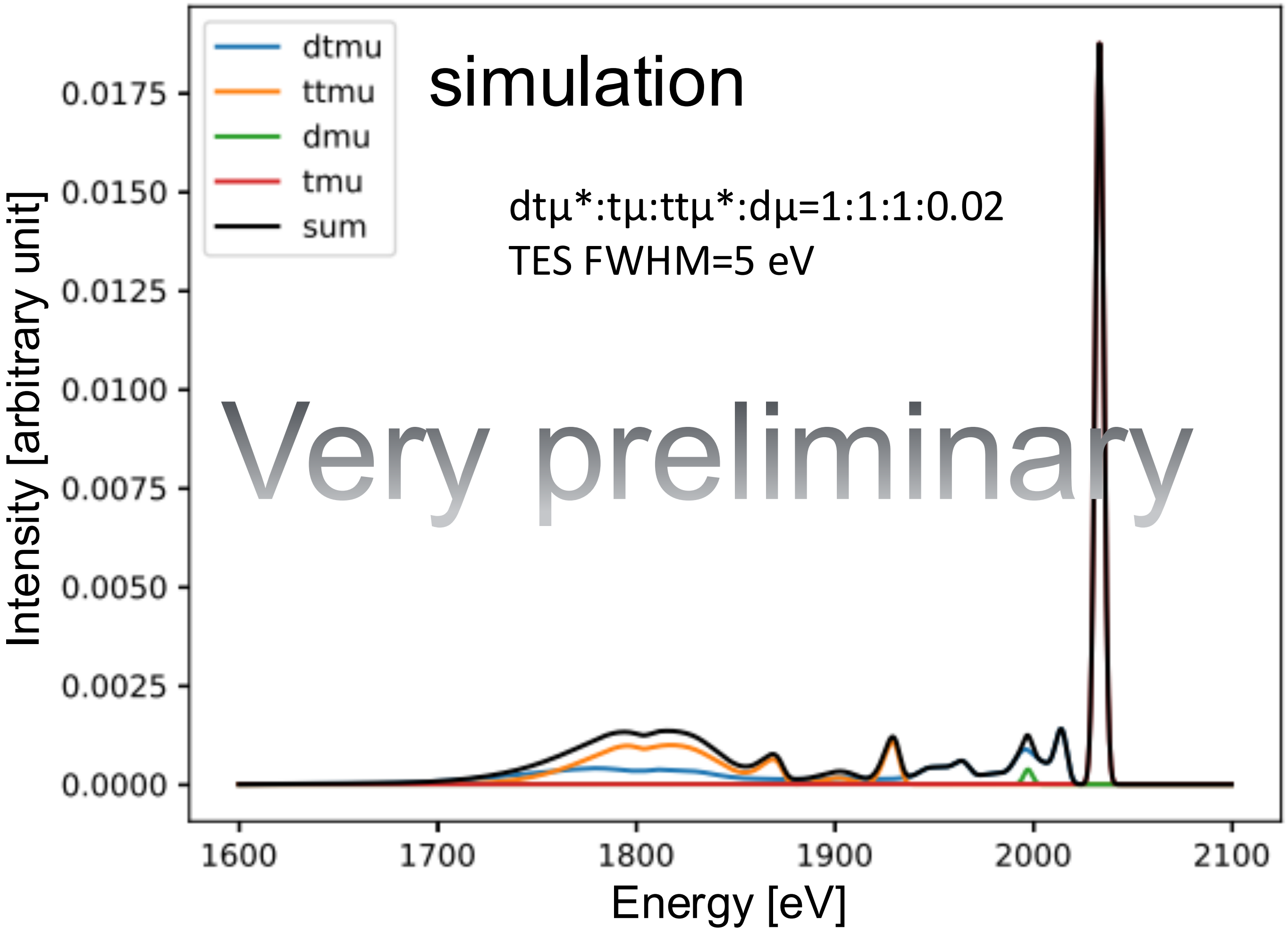
<100 eV difference between 3-body calc. and adiabatic approx.

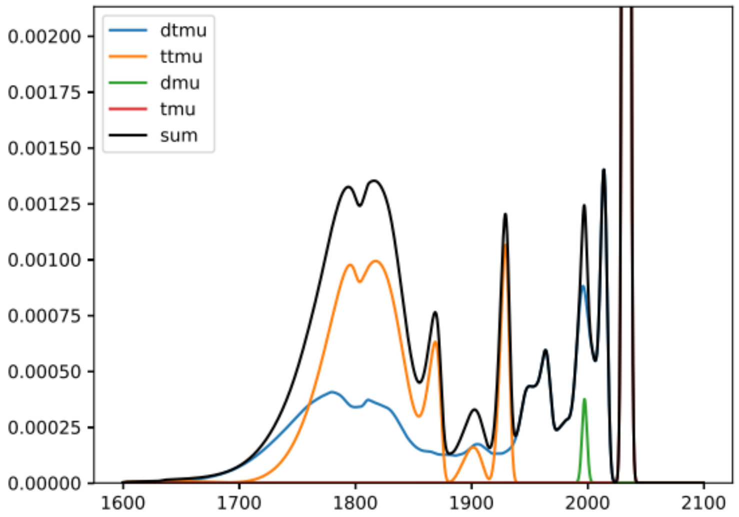
Summary

- Muon catalyzed fusion (μCF)
  - Nuclear fusion inside muonic molecules
  - Resonance states of muonic molecules play key roles
- X-ray spectroscopy of resonance states of muonic molecules ddμ*
  - Solid deuterium target & TES in 2023
- **First observation of ddμ* dissociative X-ray**
  - X-ray spectra of 3dσ_g v=1, 2, 3 and 2pπ_u v=0 reproduce the experimental result
    - Precise few body calculation by Tohoku Univ.
  - Production mechanism: Vesman mechanism + Auger process



Future TES experiment with a tritium target





Spectroscopic studies of the dtμ* molecule, which directly contributes to the fusion reaction rate.

Very preliminary expected spectrum without any backgrounds

- Only limited states are considered
- Theoretical calc. by T. Yamashita

Pulse beam or CW beam

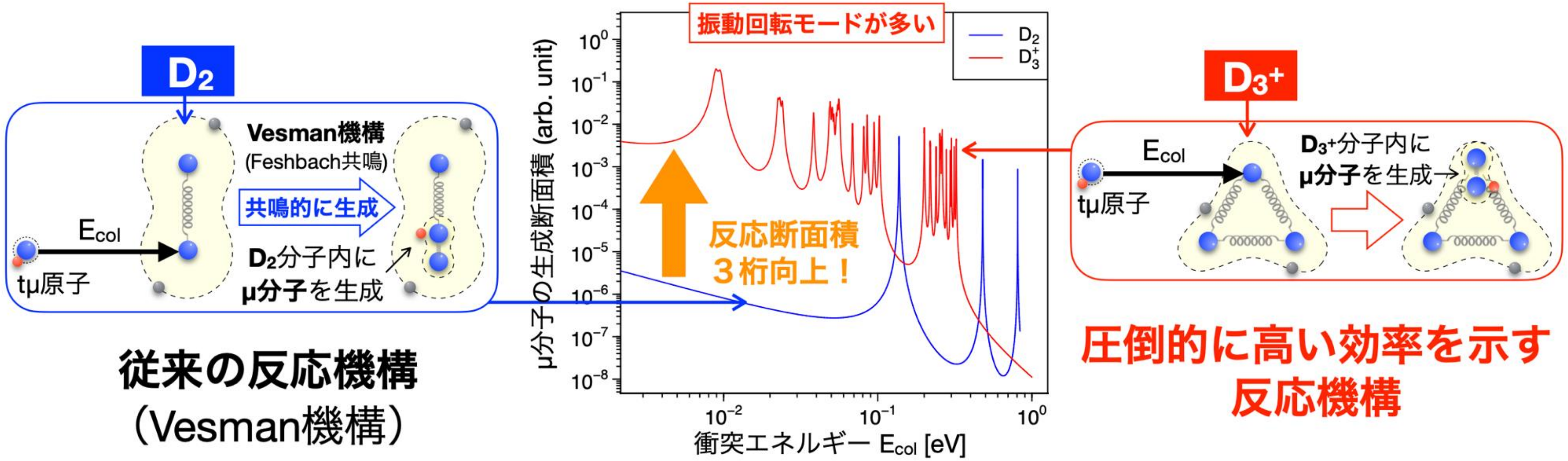
- In experiments using tritium, beta rays are continuously emitted due to tritium decay, so pulsed beams have traditionally been considered advantageous. However, based on the results of the previous J-PARC experiment, even when this disadvantage is taken into account, the temporally intense background generated by muon beam bunches could pose a problem, particularly in TES experiments.

- Brems b.g. from decay electron would be estimated from prev. data and simulation in the future
- Brems from tritium beta rays also need to be estimated

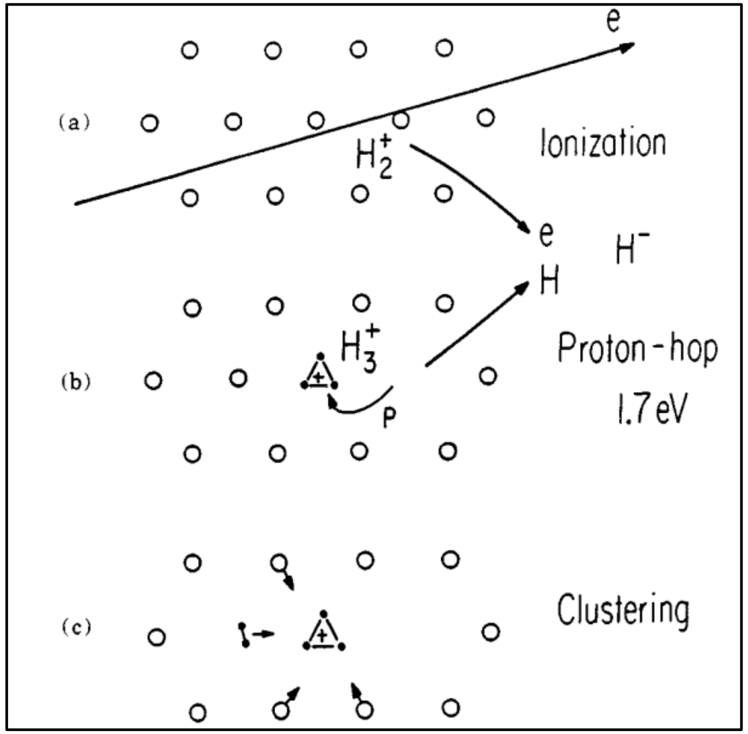
Simulation conditions
Assuming same setup w/ J-PARC Feb. 2023
Target size: Φ50 mm, t=1 mm
Target material: pure T_2
TES effective area: can be assumed Φ4 mm region

Backup

Proposed measurement: Radiochemical effect



J. Phys. Chem. A 2000, 104, 3775-3779

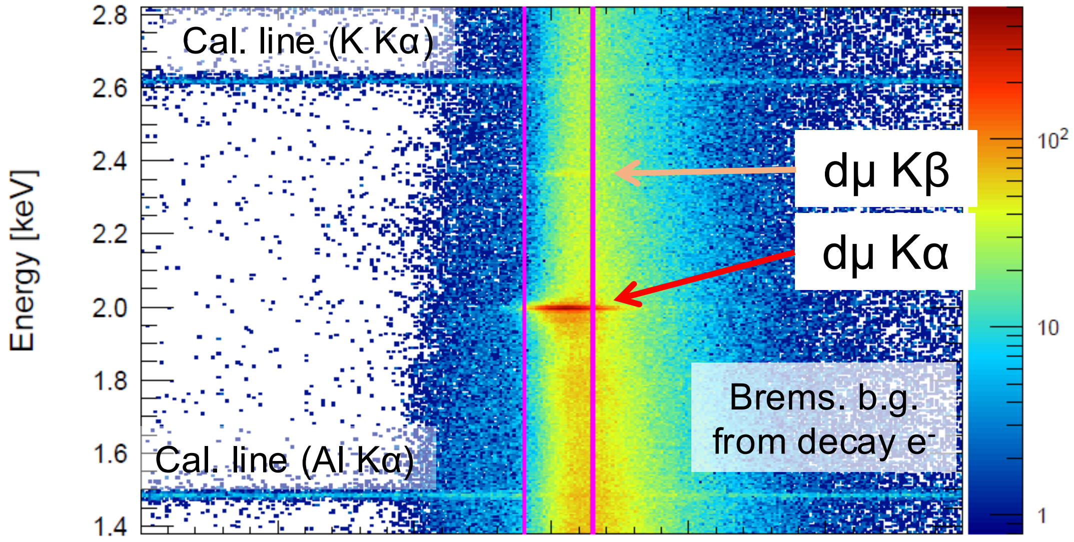


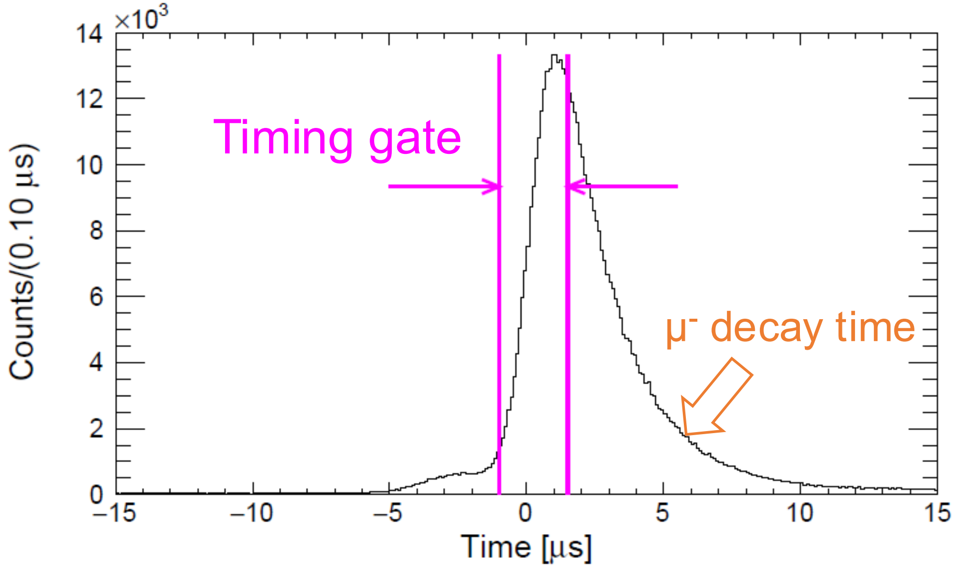
- D_3^+ has 3 order higher cross section of molecular formation
  - can accelerate μCF cycle
- Unknown parameter: lifetime of D_3^+ in solid D_2
  - will be measured off-line (FTIR measurement, collaboration with Okayama Univ.)
  - H_3^+ produced by ^{60}Co(T. Momose et al., J. Chem. Phys. 100 (10) 1994), by electron beam (M.C. Chan et al., J. Phys. Chem. A 2000, 104, 3775-3779)

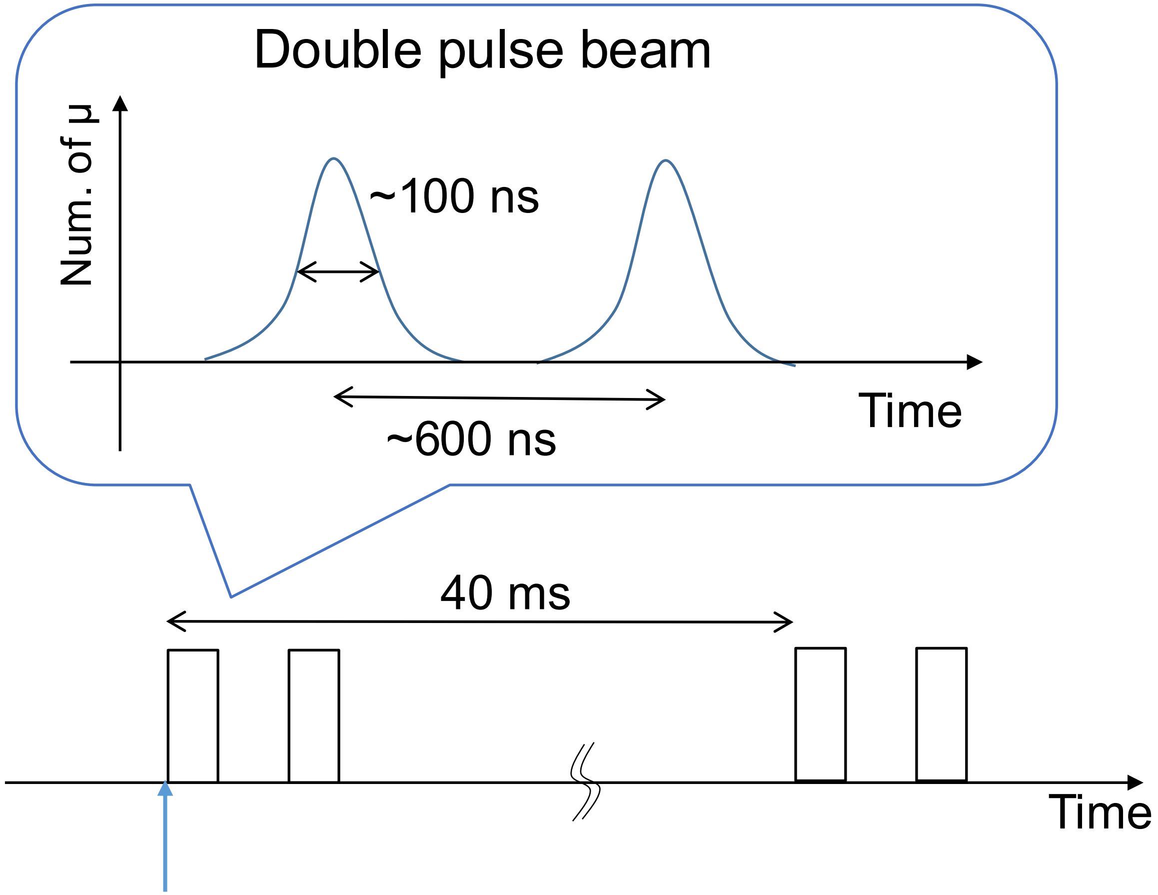
⇒ Change initial states of ddμ* → X-ray spectrum will be changed

Event selection (Timing cut)

X-ray energy vs Timing





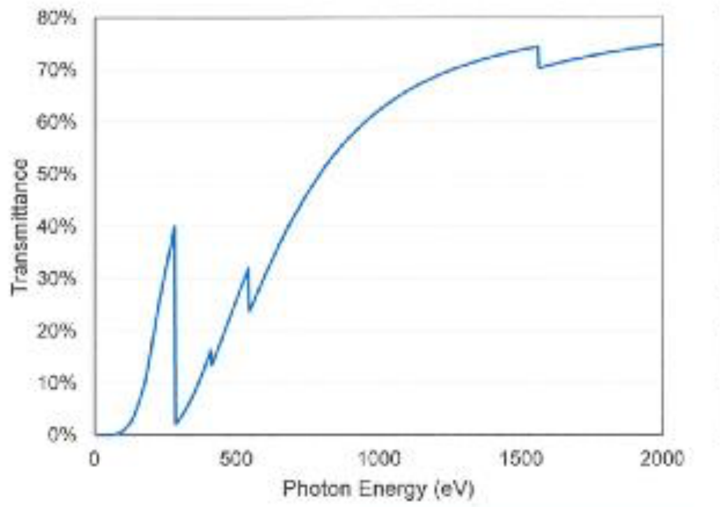


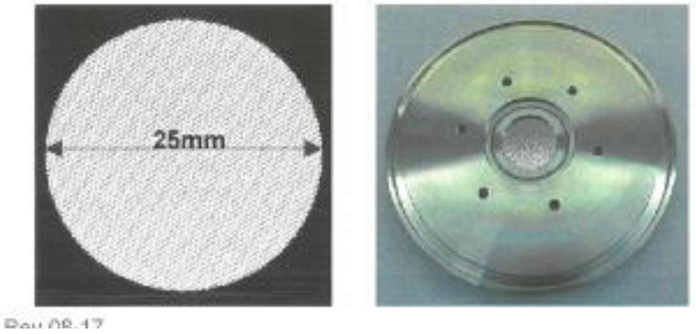
- Time=0: μ beam incoming timing
- Timing gate: [-1.0 μs, 1.5 μs]

Gas D_2 target experiment

Mar 9 - 19, 2022

Vacuum window (LUXEL)
(Al based mesh window)
~70% transmission at 2 keV



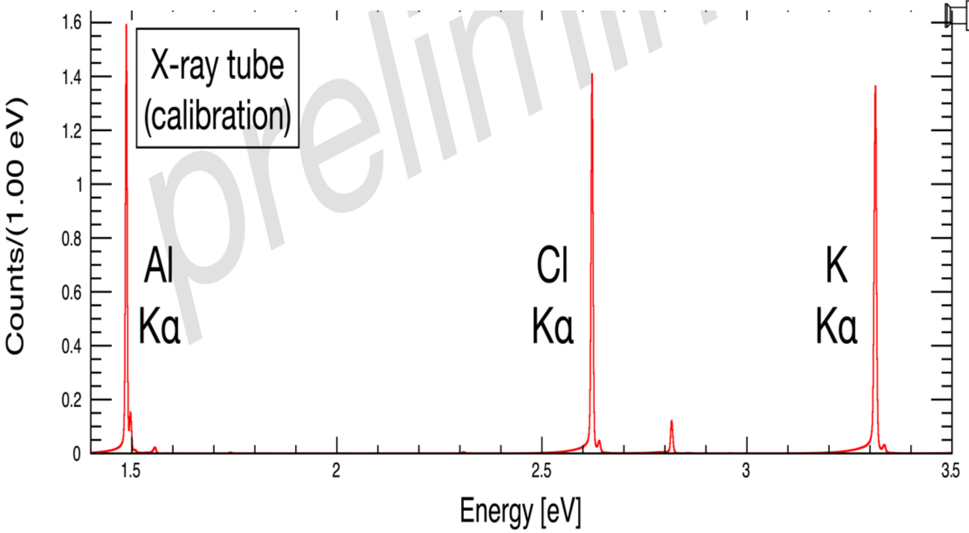


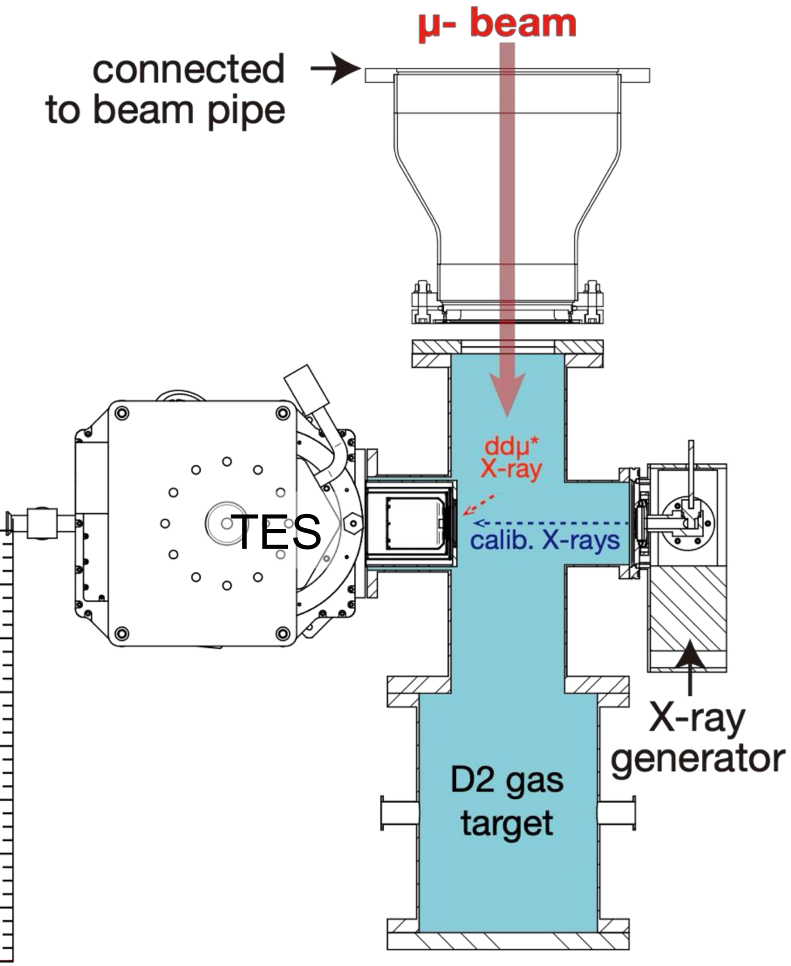
Radiation shields of TES

110nm Al &
200nm LUX polymide
x 3 (50 mK, 3 K, 50 K)

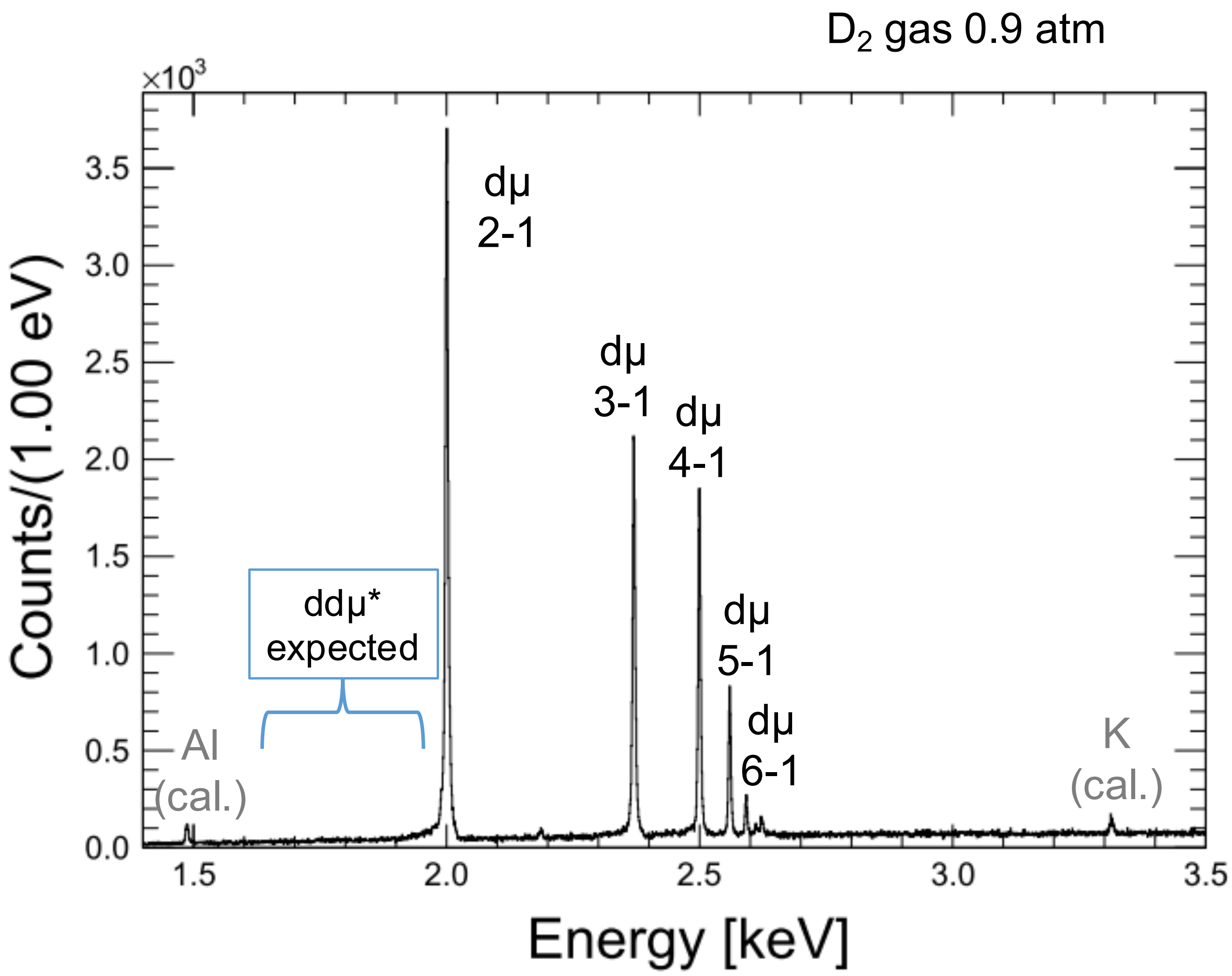
Transmission: ~60% at 2 keV

Energy calibration in <2 keV region





Gas D_2 target experiment



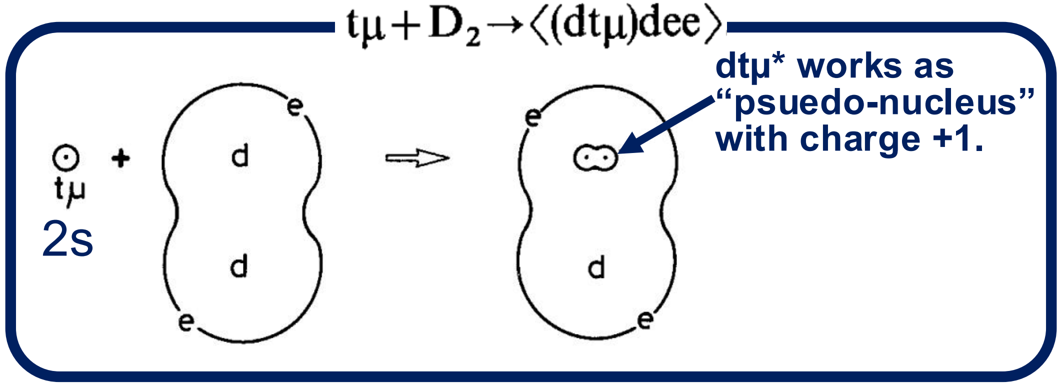
Mar 9 - 19, 2022

- Established energy calibration in <2 keV region
- Observed dμ K X-rays
- **No signal from muonic molecules**

➡ Vesman mechanism did not work well in low density gas environment due to insufficient thermalization of dμ atom?

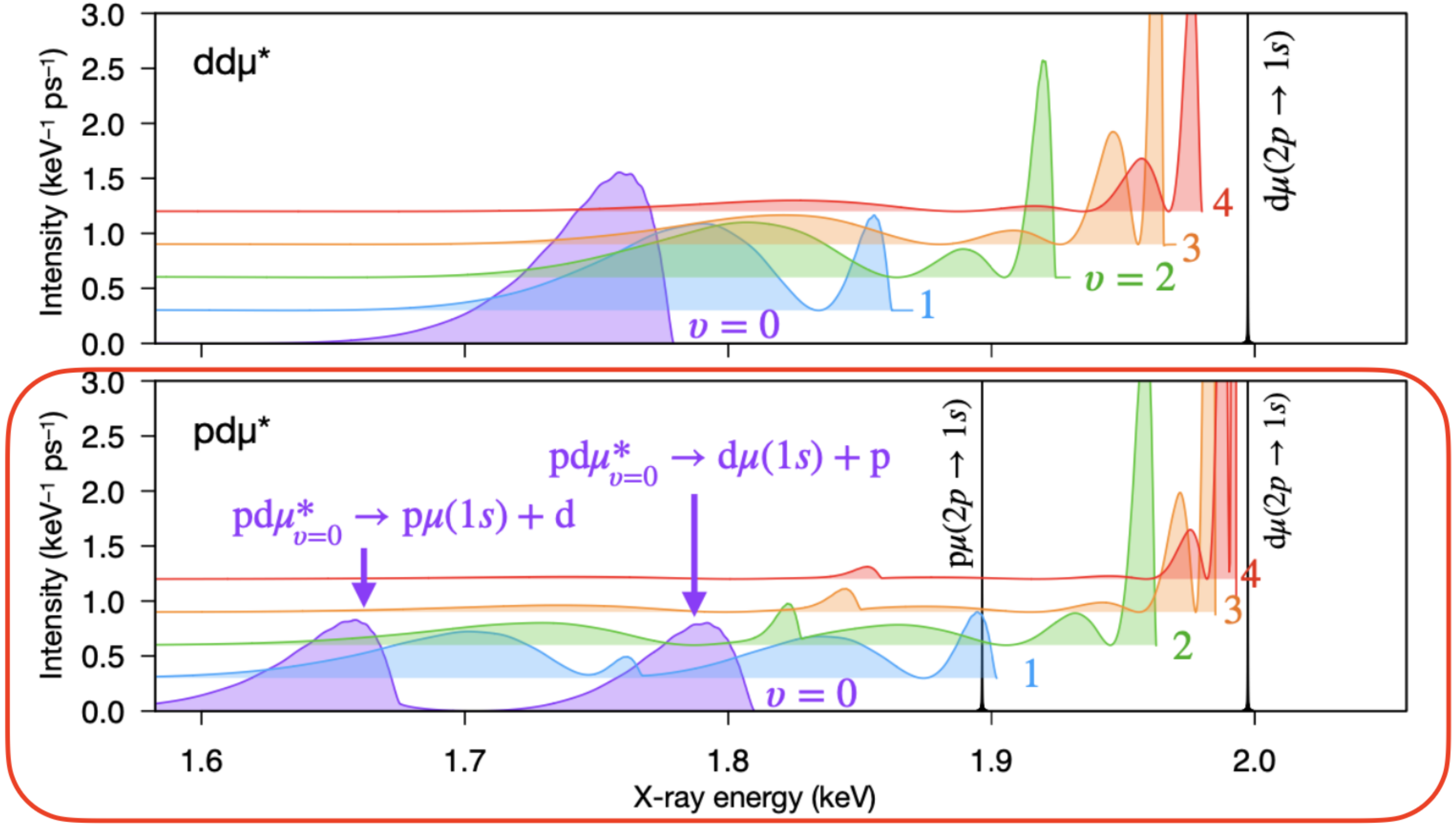
⇨ **Solid D_2 target**

Vesman mechanism



P. Froelich, Advances in Physics 41, 405 (1992).

Proposed measurement: pdμ* measurement



- H/D mixture (1:9) target
- Isotope effect will be clearly seen

solid D/T target

D line assumption (w/o additional focus)

		Activity (Ct=0.5)		
Diameter [mm]	Thickness [mm]	[TBq]	[Ci]	stop muon/pulse
50	1	94	2500	1.0E+03
25	1	24	600	2.5E+02
25	0.8	19	500	2.0E+02
10	1	4	100	4.0E+01
5	0.5	0.5	10	5.0E+00

RAL 1cc target, 60 stop mu/pulse