TES Detectors and High-Resolution X-Ray Detection for μCF and Exotic Atom Studies

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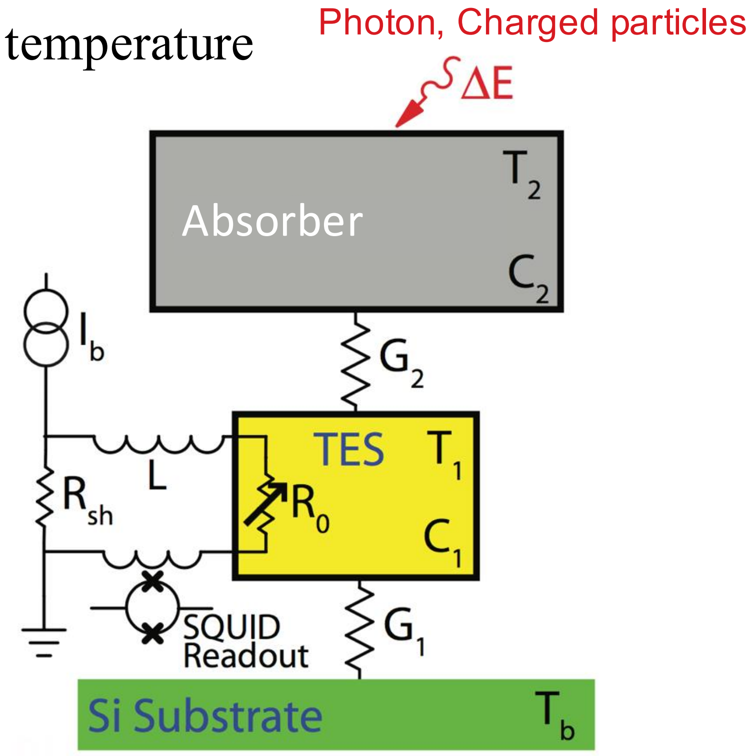
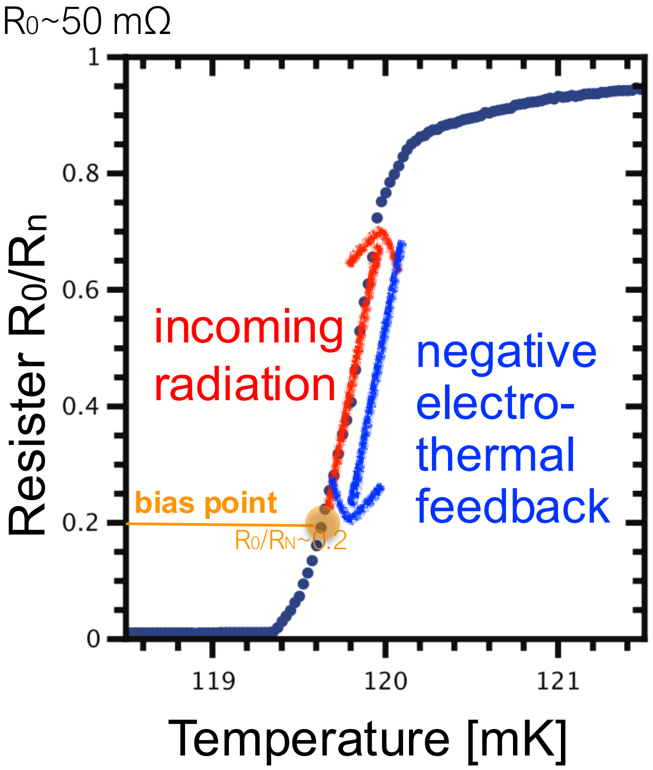
Transition Edge Sensor (TES) microcalorimeter

Microcalorimeter

@low temperature



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

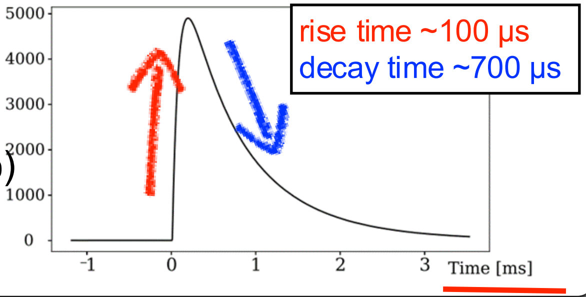


TES
for Low energy X-ray

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

Typical pulse

T_{rise}~L/(R_{sh}+R_0)
T_{fall}~C/G

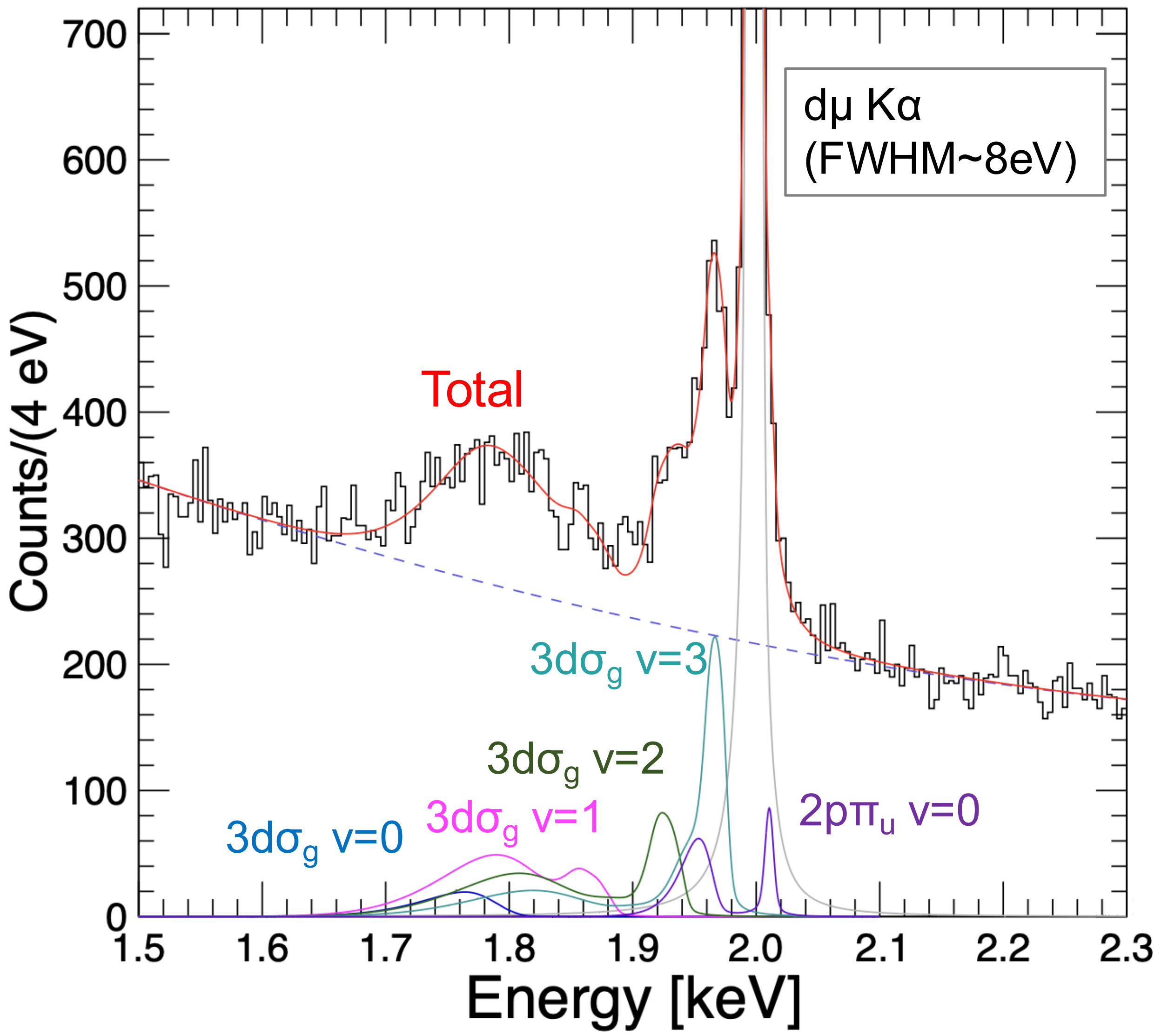


✓ High resolution (<10 eV @ 2 keV, FWHM)
- Ref.) SDD >100 eV @ 6 keV

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

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

Highlight: ddμ* dissociative X-ray

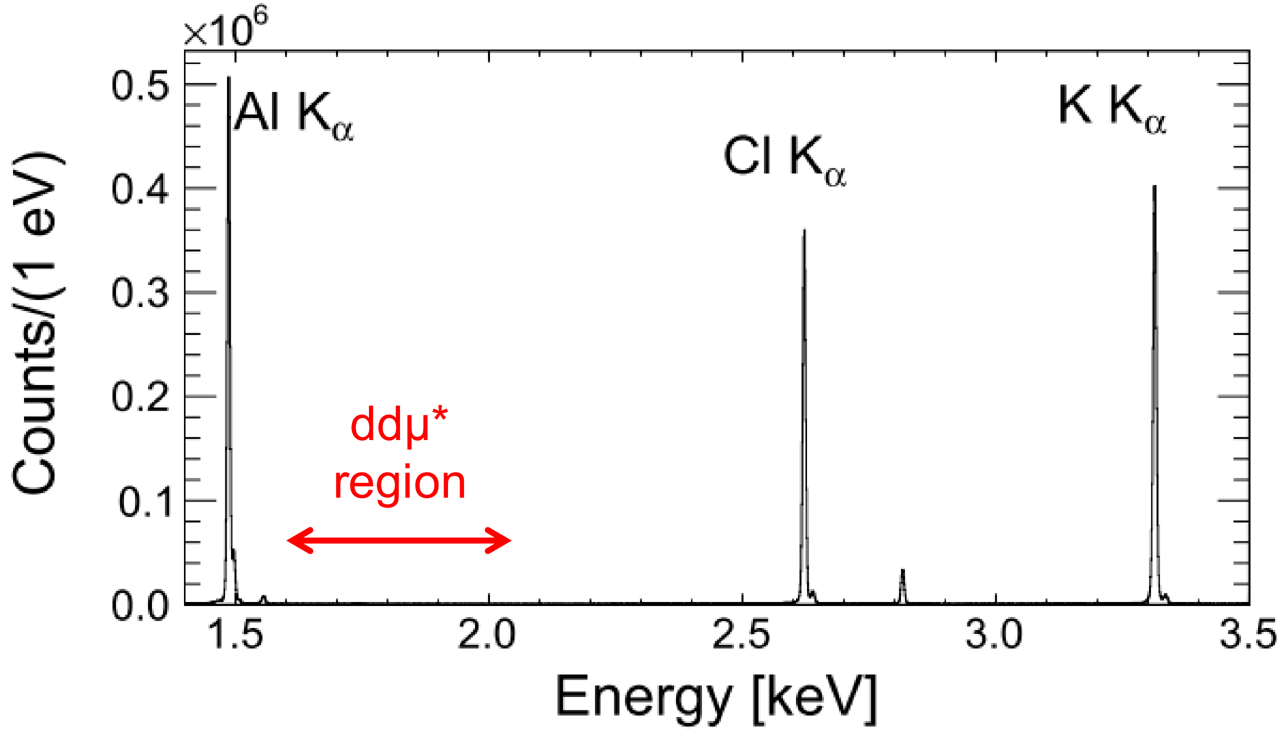


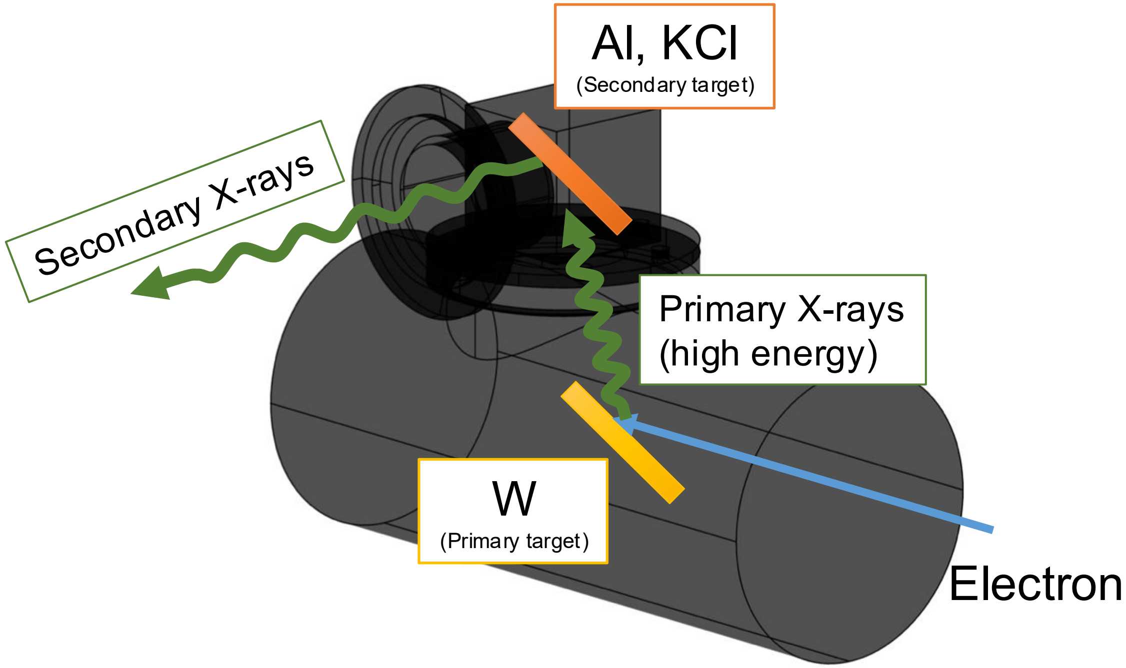
- χ^2 fit (Minuit)
- Spectra of Vesman + Auger processes
  - $3d\sigma_g$ v=0, 1, 2, 3, $2p\pi_u$ v=0
- dμ peak: Response function
  - Determined to be self consistent
- Brems. b.g.: Quadratic function

Spectrum is well reproduced!

YT, YK, SO, TY et al., Sci. Adv. 2026

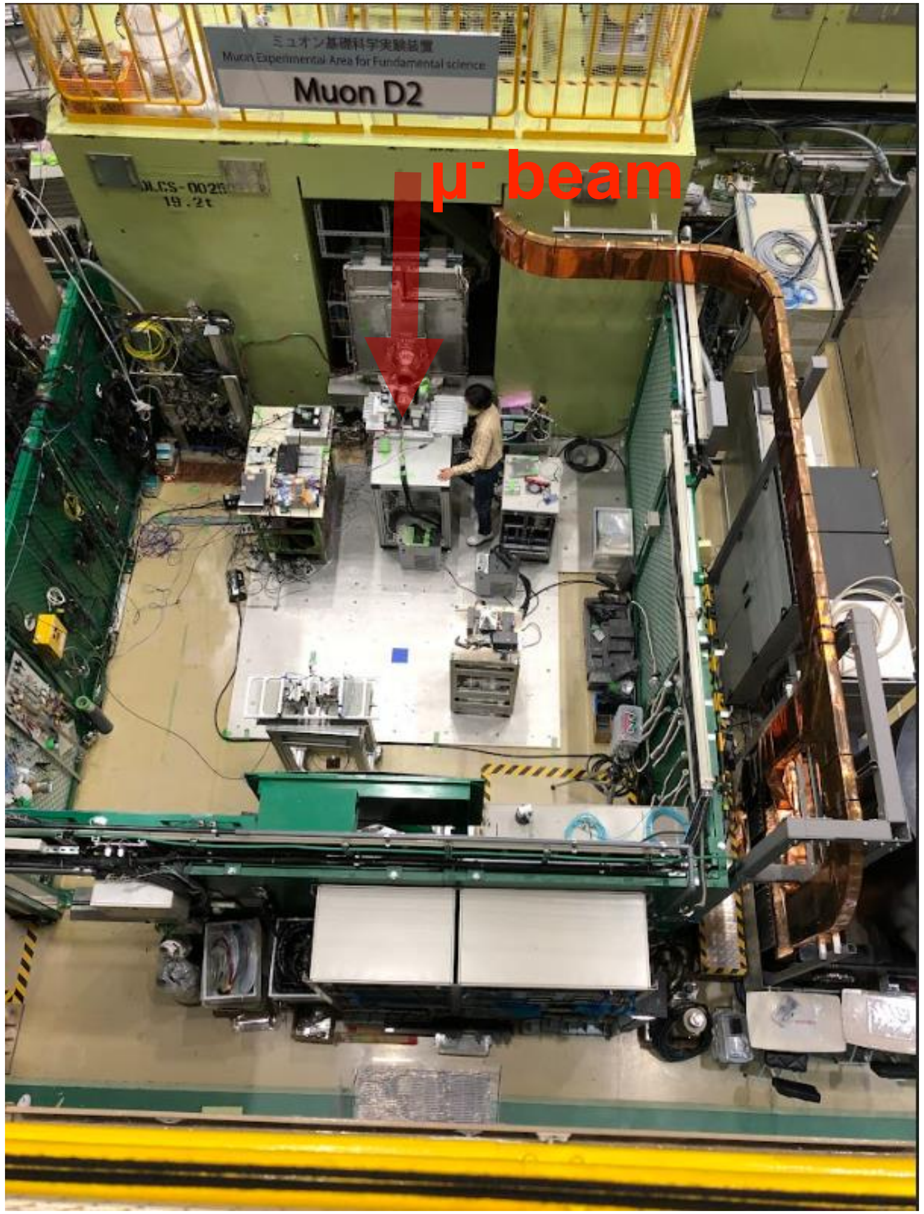
Energy calibration of TES

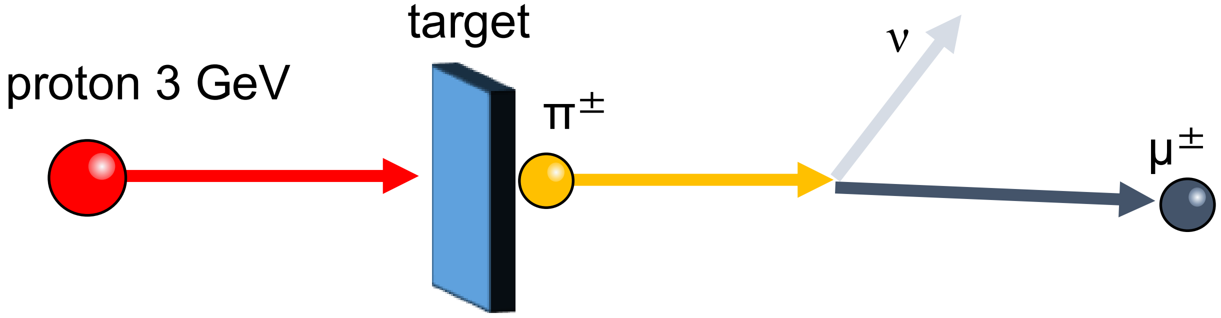




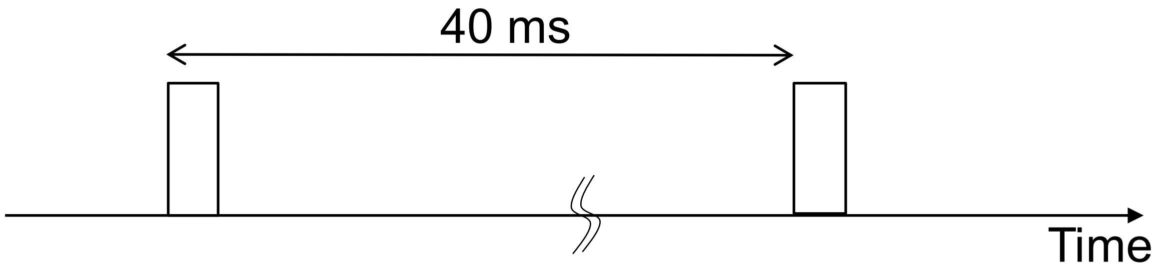
- X-ray tube
  - Kα X-rays of Al, Cl, and K
  - ROI (1.7—2.0 keV)
  - calibrated for each pixel, each run, and summed the spectrum
  - Stable response during the measurement

J-PARC MLF D2 beamline





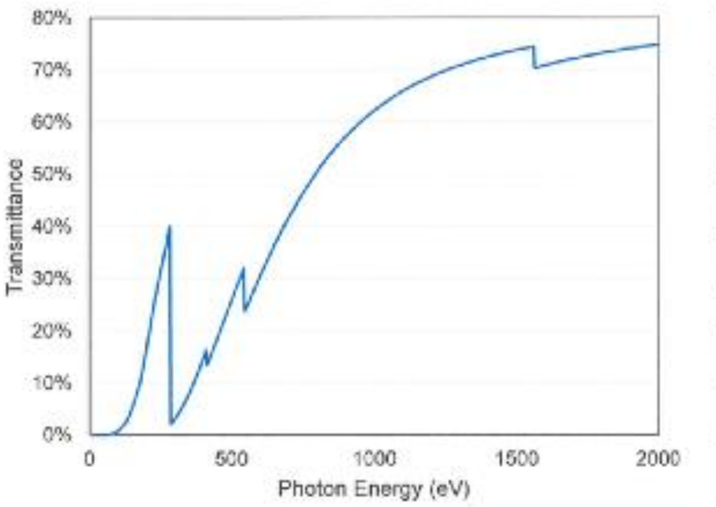
- Beam momentum: 27.5 MeV/*c* (max. 50 MeV/*c*)
- $\Delta p/p$~10% (FWHM)
- 25 Hz double pulse beam
- Intensity: ~5.0×10^{6} μ^{-}/sec
- Beam size: ~Φ50 mm

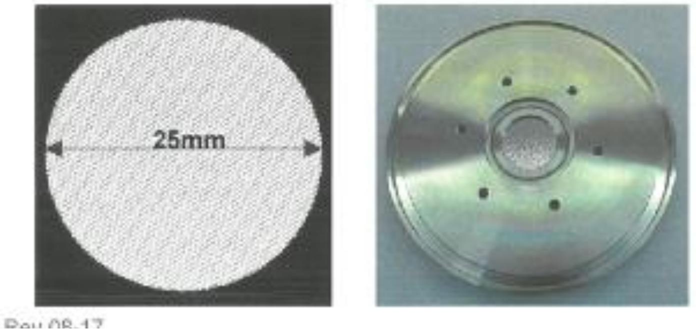


Gas D_2 target experiment

Mar 9 - 19, 2022

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



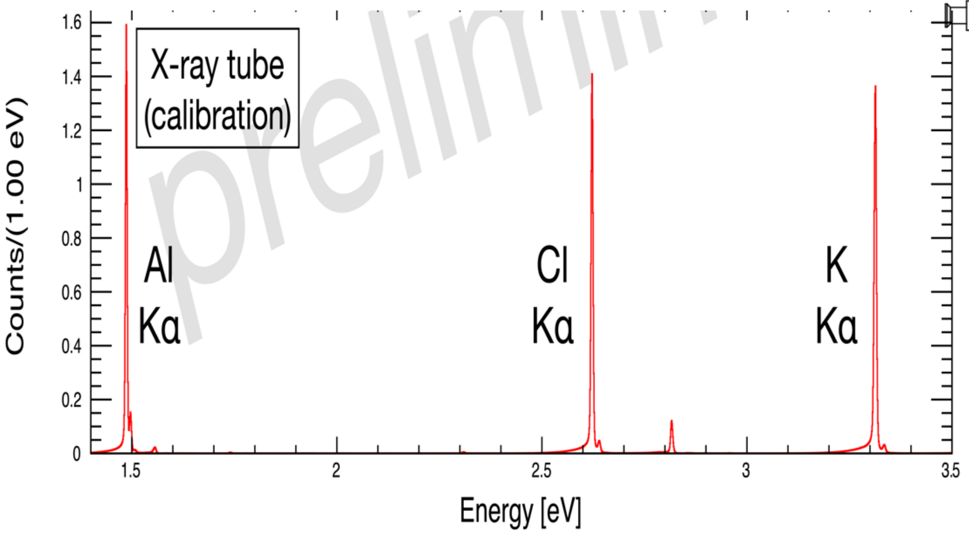


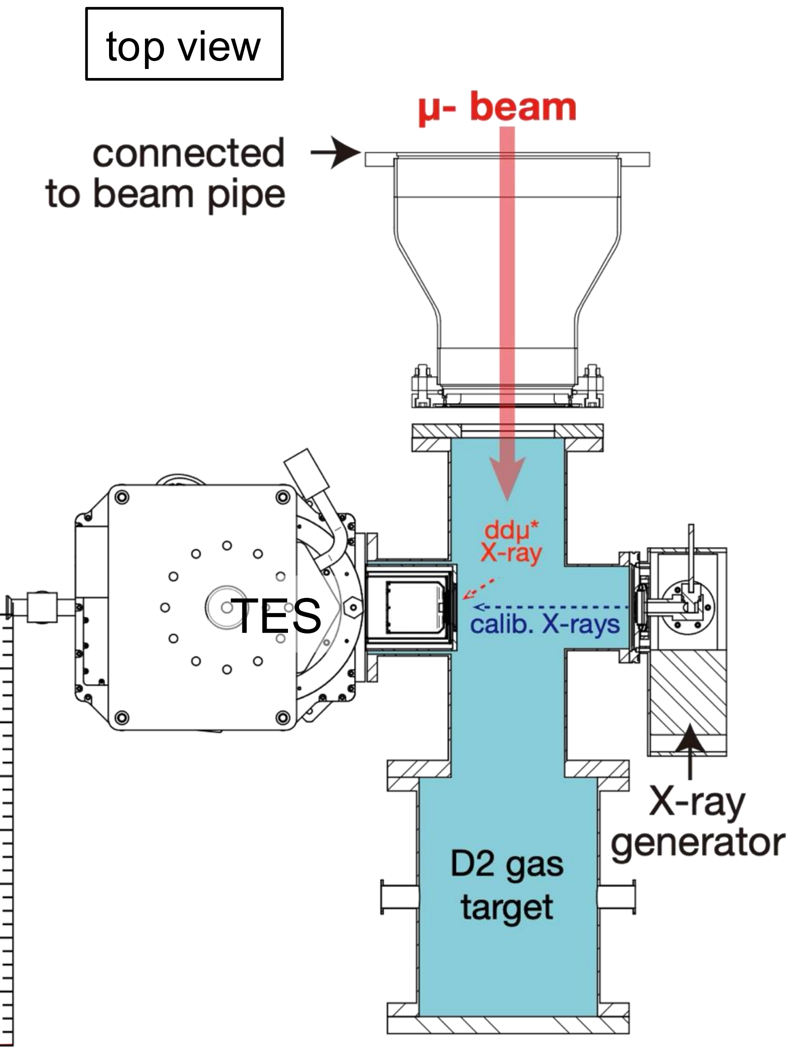
Radiation shields of TES

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

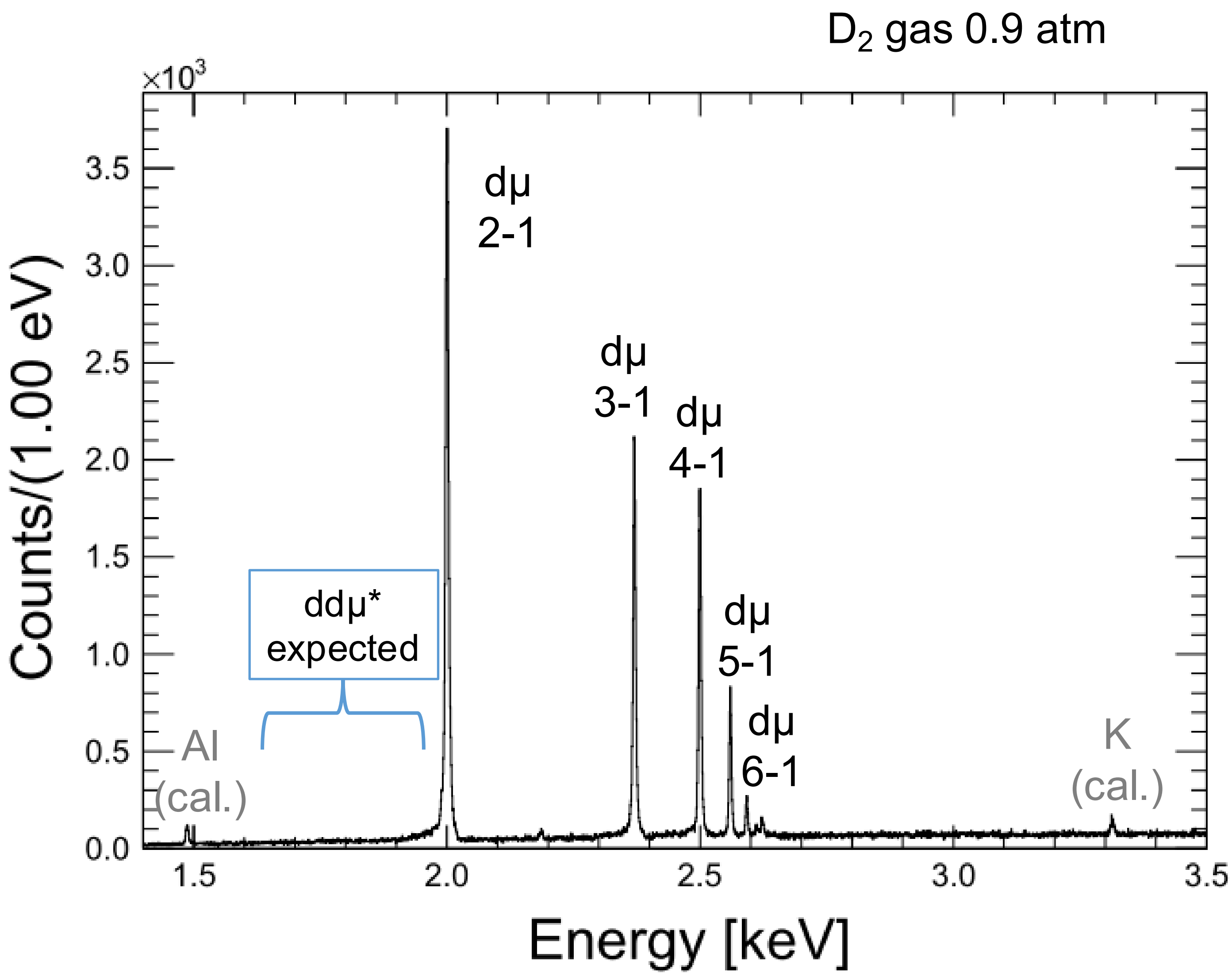
Transmission: ~60% at 2 keV

Energy calibration in <2 keV region





Gas D_2 target experiment



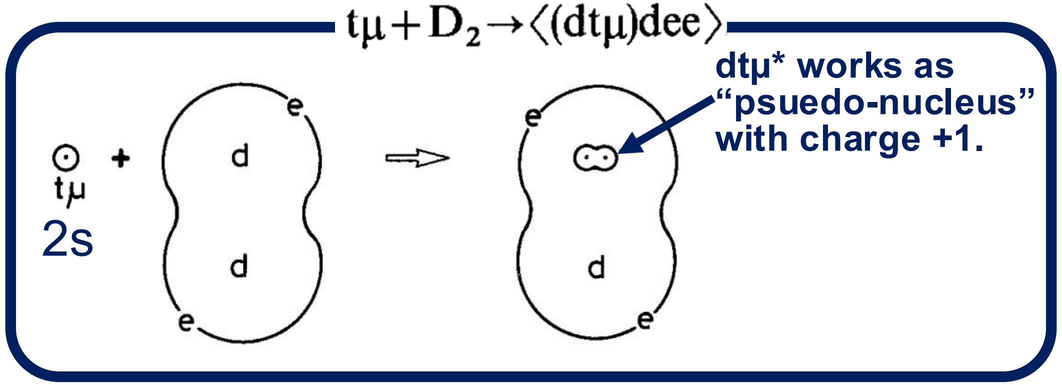
Mar 9 - 19, 2022

- Established energy calibration in <2 keV region
- Observed dμ K X-rays w/ ΔE= eV resolution
- **No signal from muonic molecules**

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

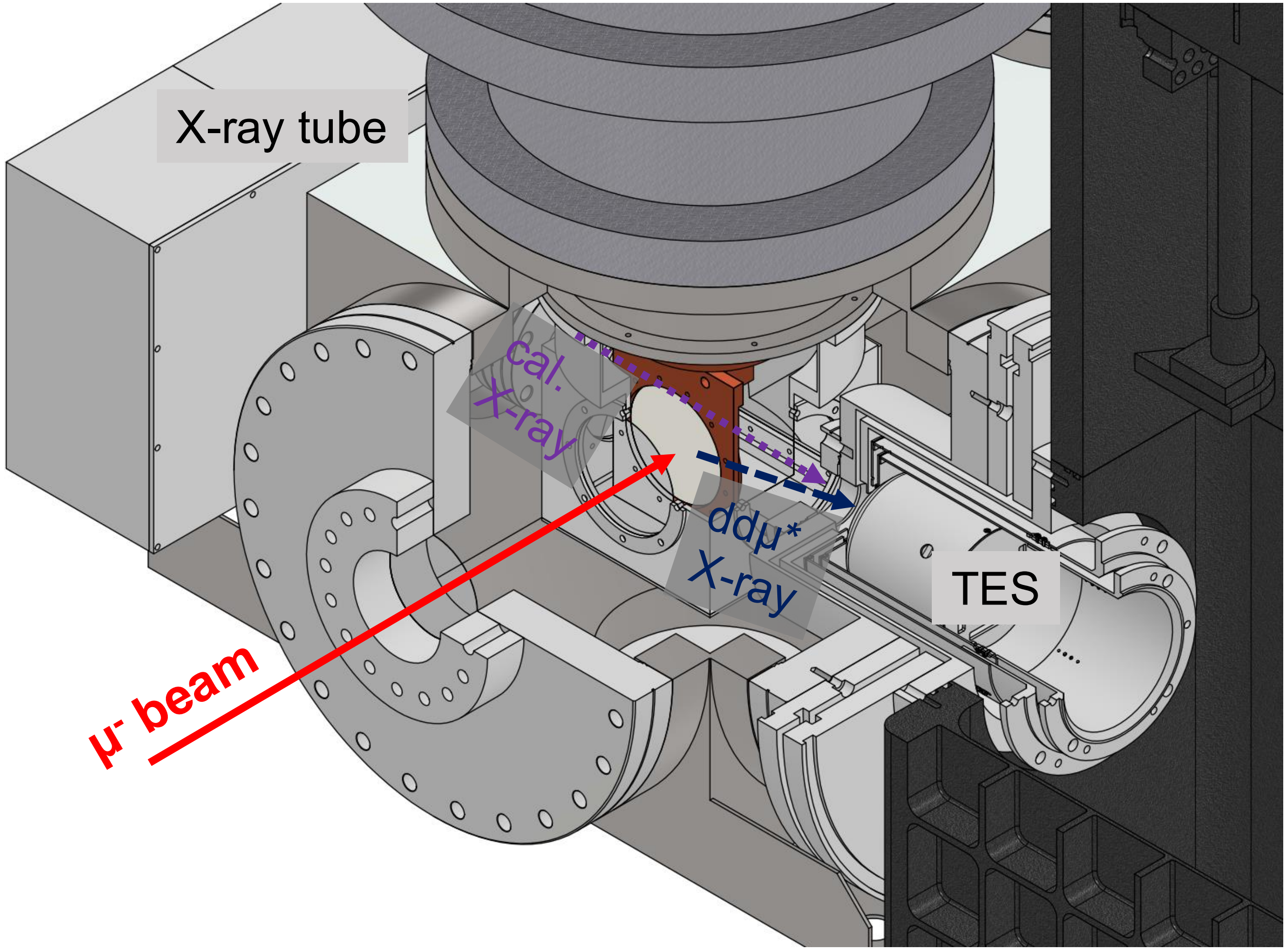
⇨ **Solid D_2 target**

Vesman mechanism



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

Experimental setup of a solid D2 target experiment

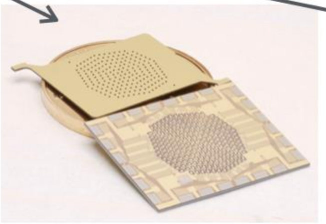


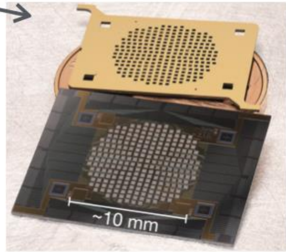
at J-PARC MFLD2 beam line
Feb 5 - 11, 2023

- 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^-)

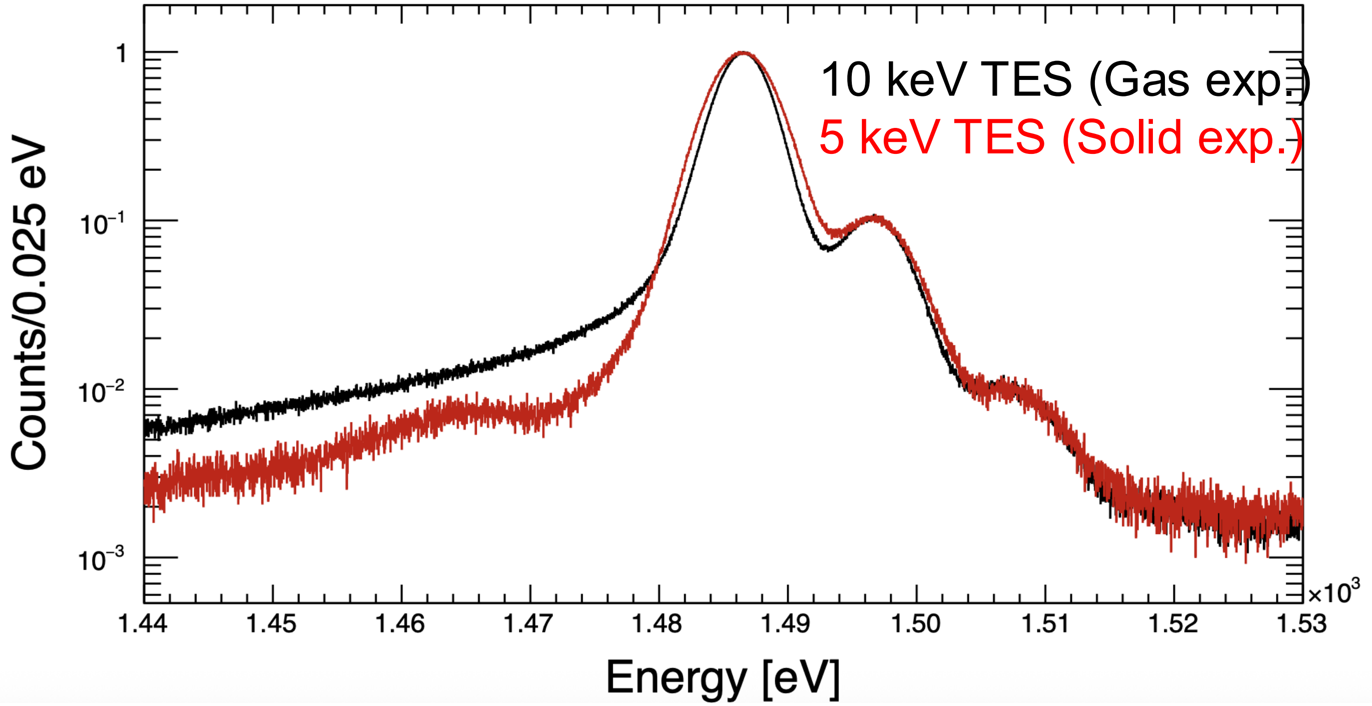
TES upgrade from gas exp to solid exp

Name	Solid D_2 exp 5 keV TES	Gas D_2 exp 10 keV TES
Saturation energy	10 keV	20 keV
Readout system	TDM	TDM
Absorber thickness (material)	0.965 μm (Au)	4.1 μm (Bi)
Absorber area	0.34 x 0.34 mm^2	0.320 x 0.305 mm^2
Absorber collimated area	0.28 x 0.28 mm^2	0.305 x 0.290 mm^2
Number of pixel	192	240
Total collection area	15.1 mm^2	21.2 mm^2
ΔE (FWHM)	5 eV @ 6 keV	5 eV @ 6 keV



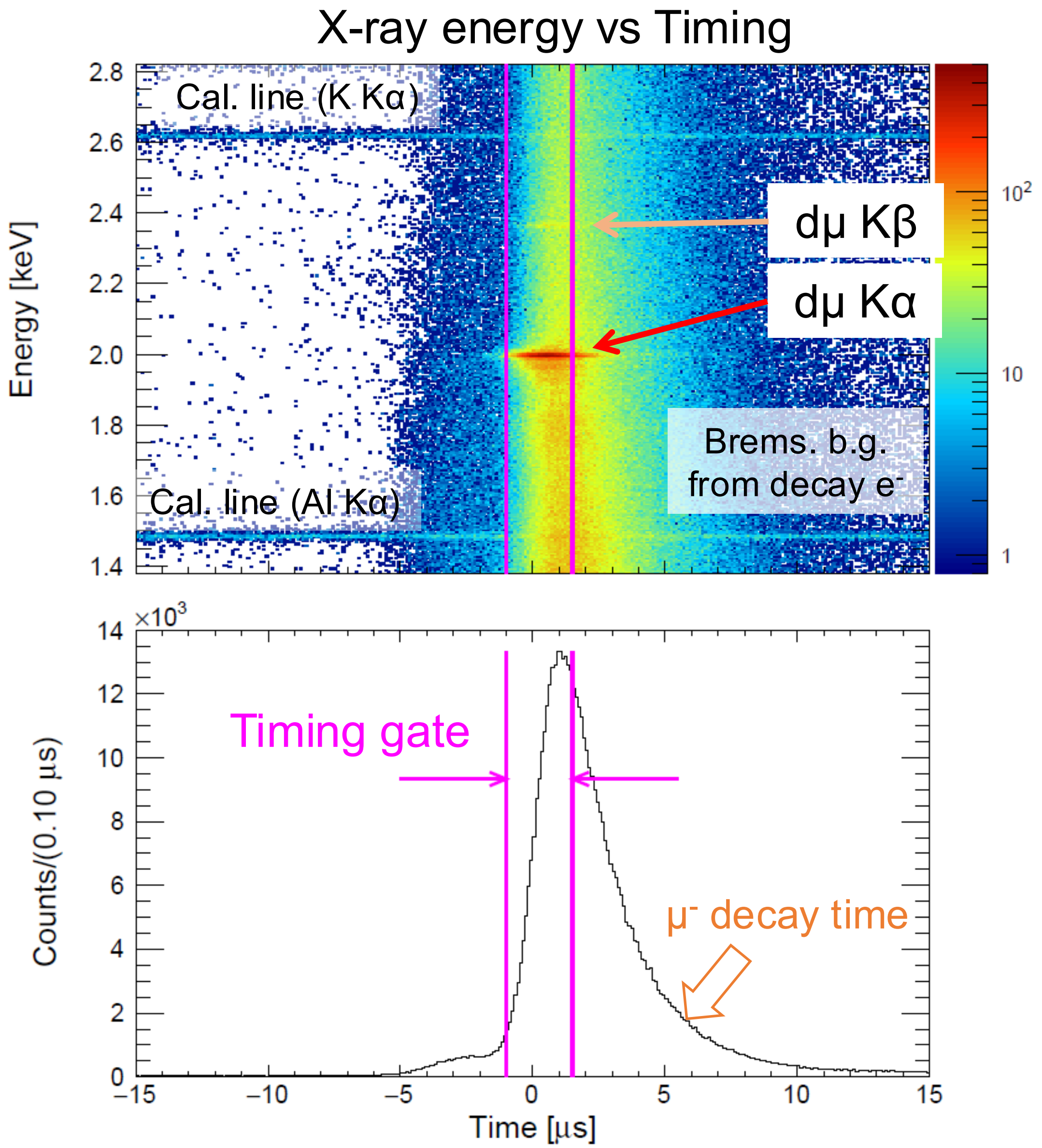


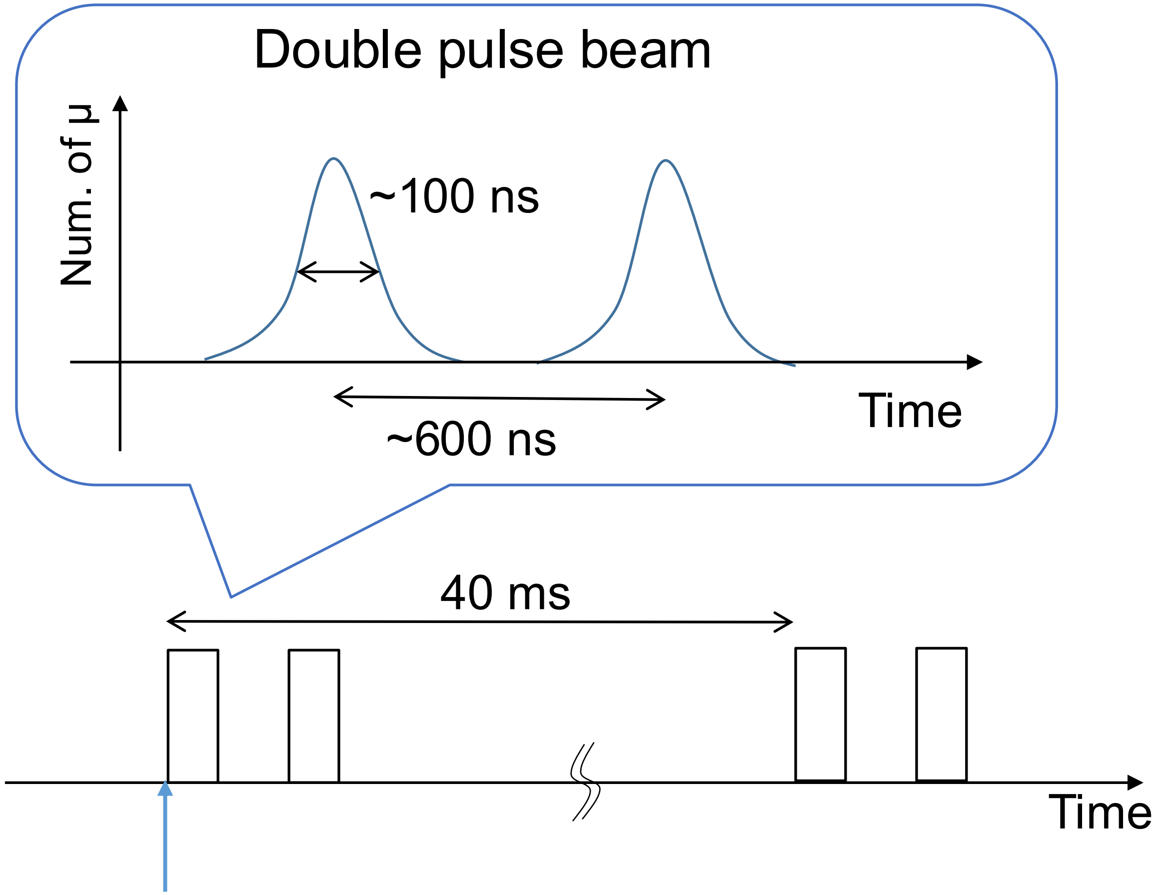
Rev. Sci. Instrum. 90, 123107 (2019)



- 5 keV TES (Au absorber) was used in solid D_2 exp
  - small tail components

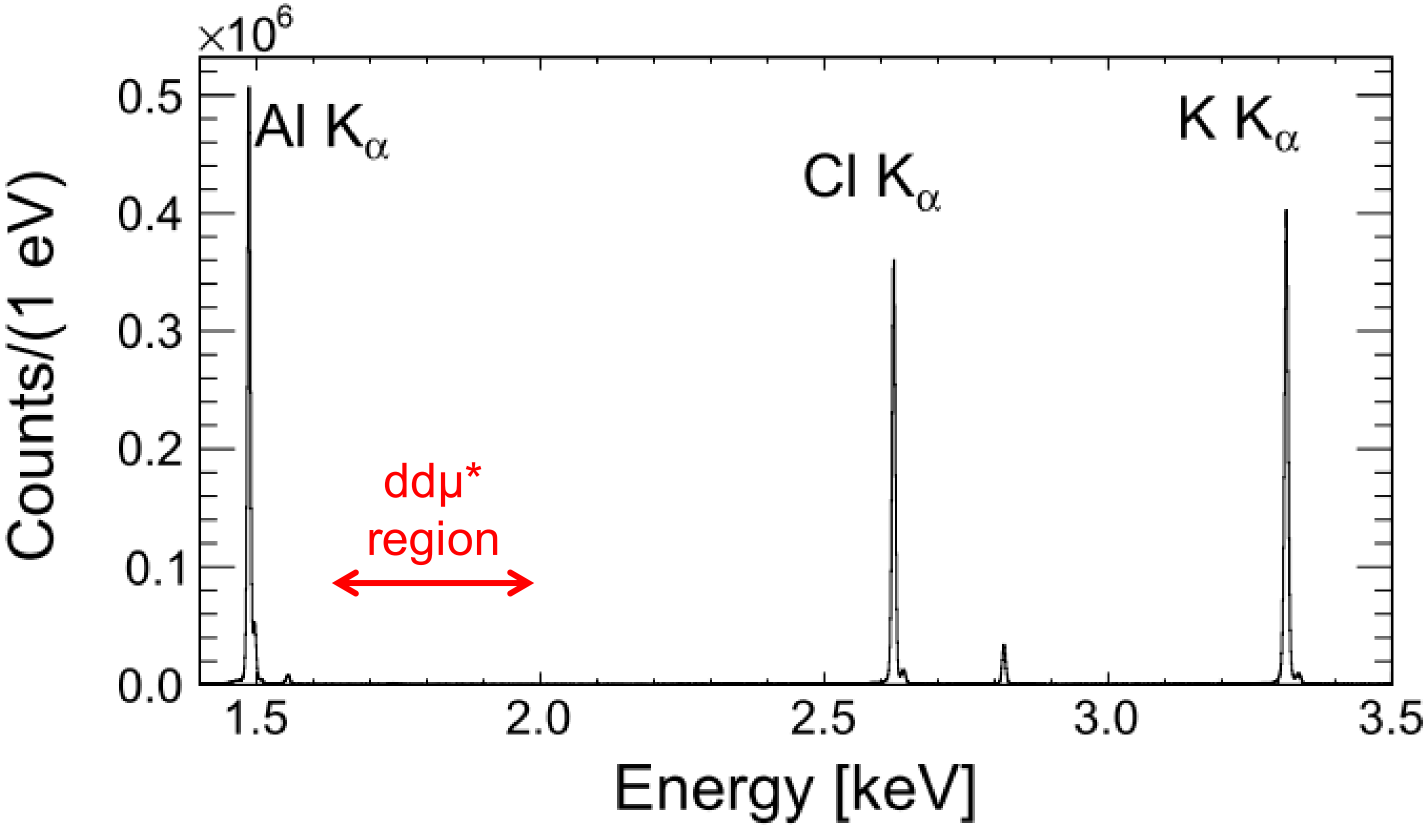
Event selection (Timing cut)



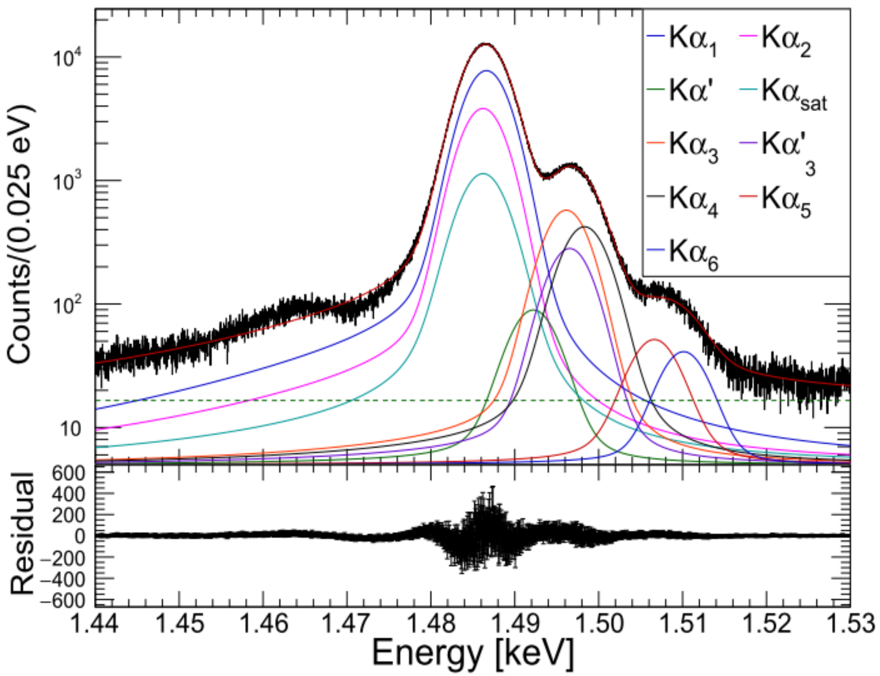


- Time=0: μ beam incoming timing
- Timing gate: [-1.0 μs, 1.5 μs]

Calibration lines (Solid D_2)

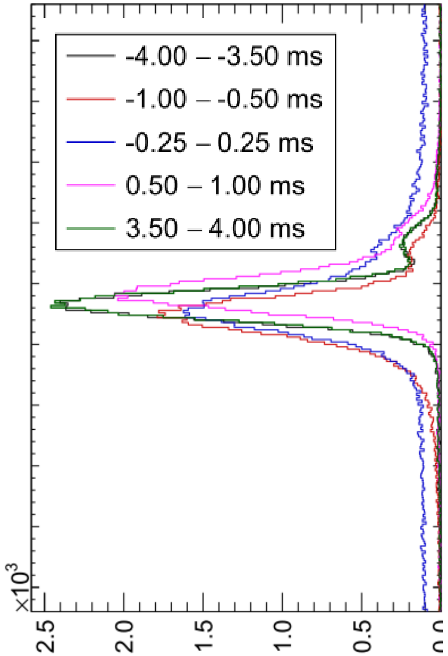


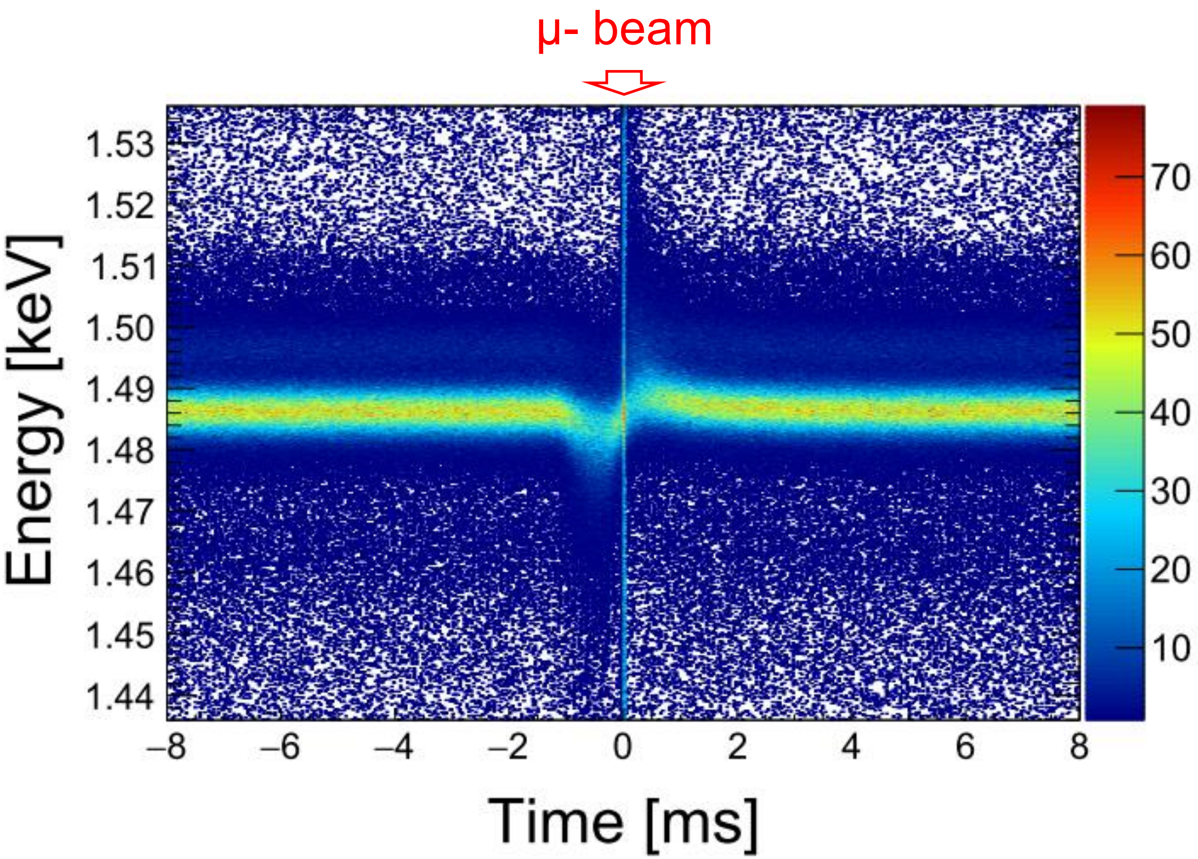
Al K X-rays (off-beam)



- Calibration of TES by Kα X-rays of, Al, K, and Cl.
- FWHM=5.7 eV at 1.5 keV (off-beam)
  - Voigt (peak) + Voigt⊗Exp (low energy tail)

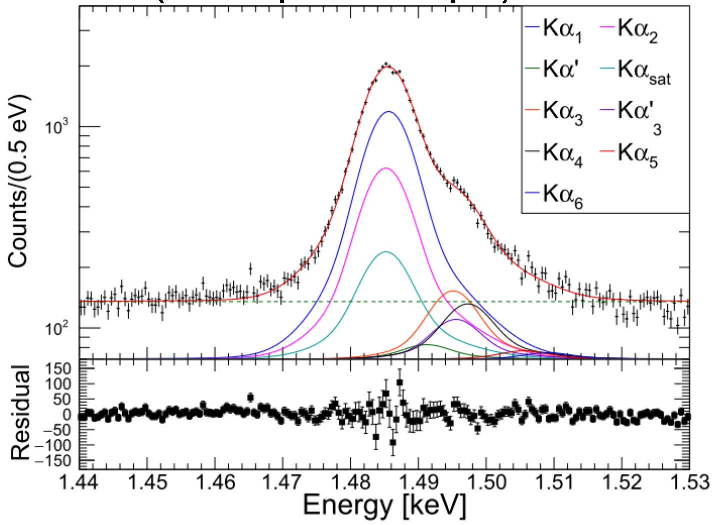
Time structure of TES response (Solid D_2)

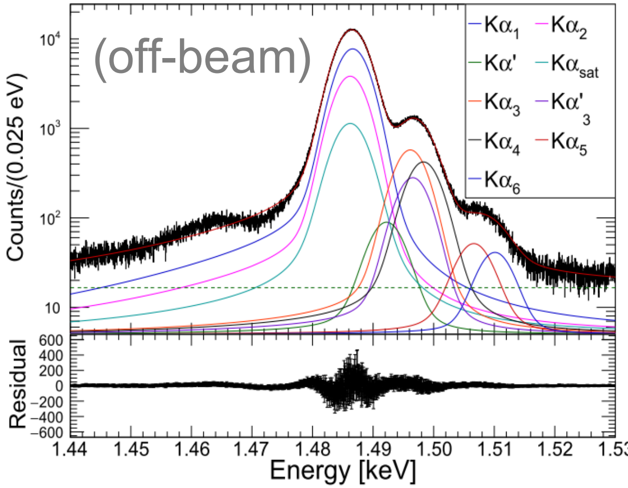




Al K X-rays (in-beam)

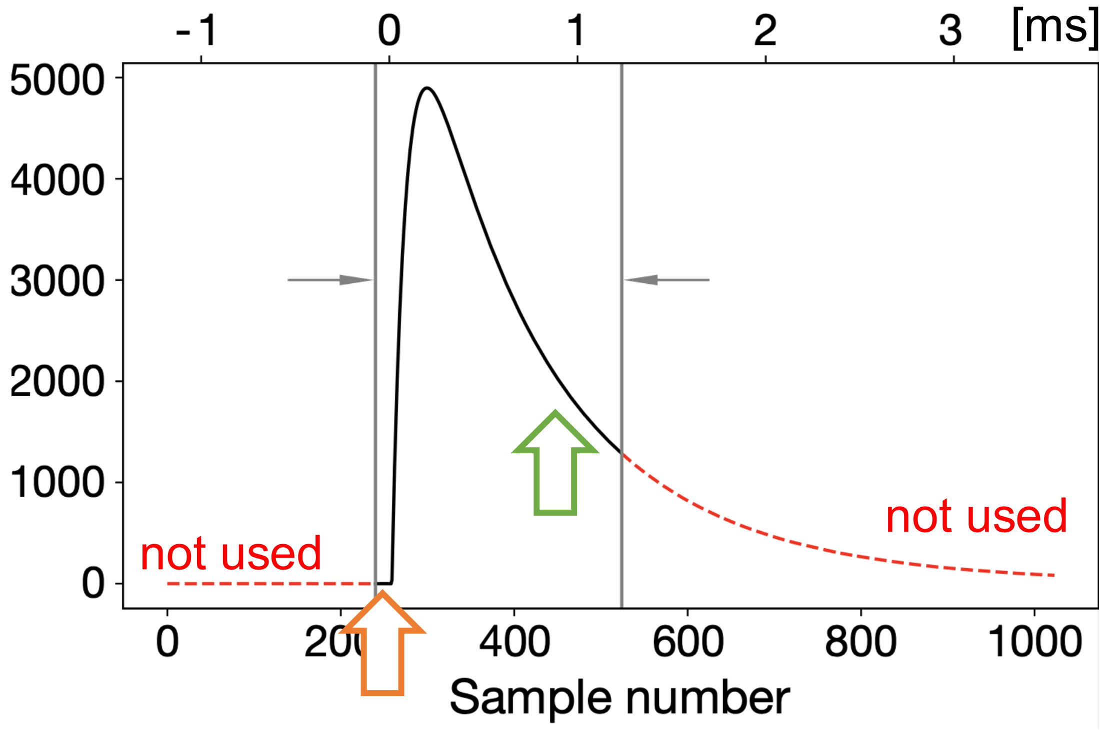
(-250 μs, 250 μs) cut

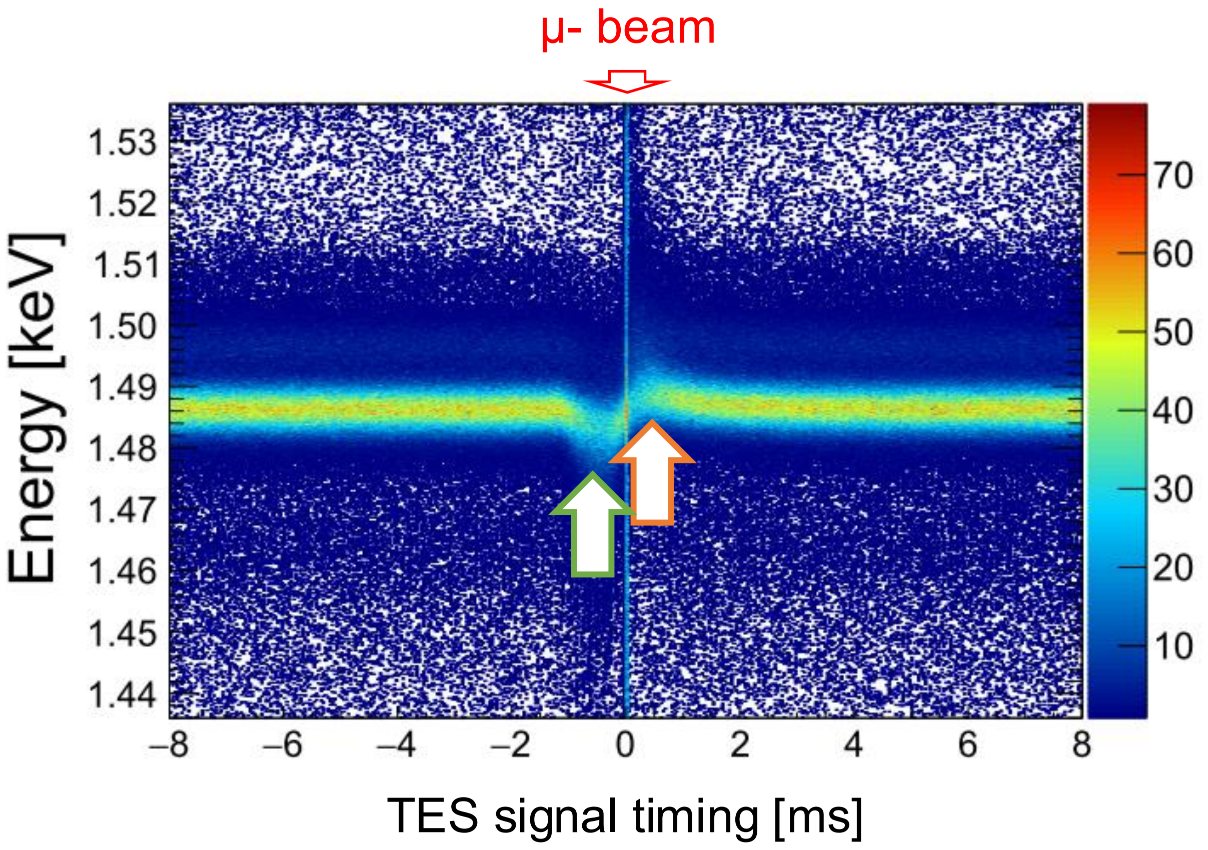




- Low & high energy tails
- FWHM= 8.3 eV at 1.5 keV
  - Voigt (peak) + Asymmetry Gaussian (tail)

Beam timing and wave form of TES

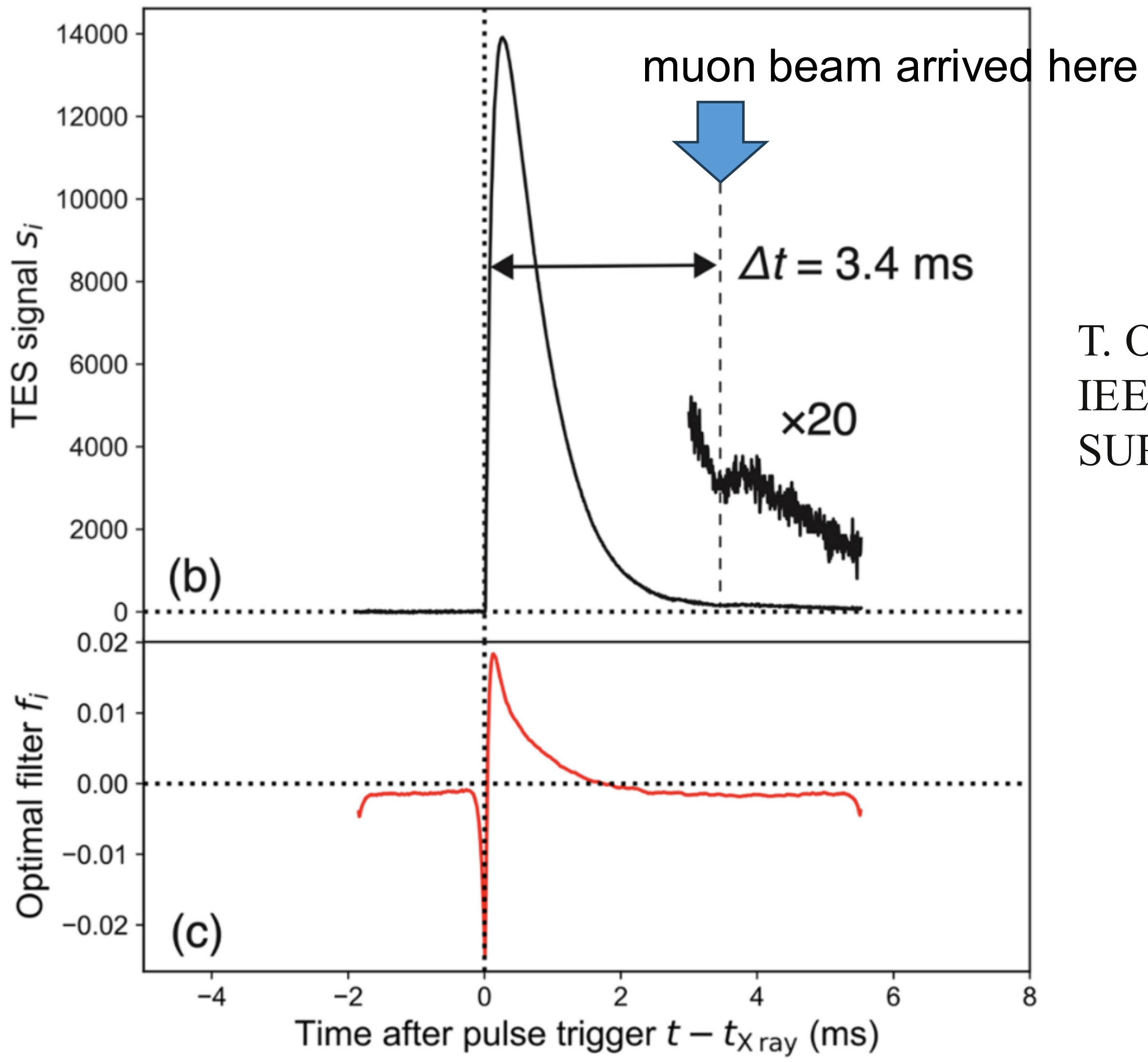




- Charged particles distort signal wave form of TES

→ Distort energy spectra

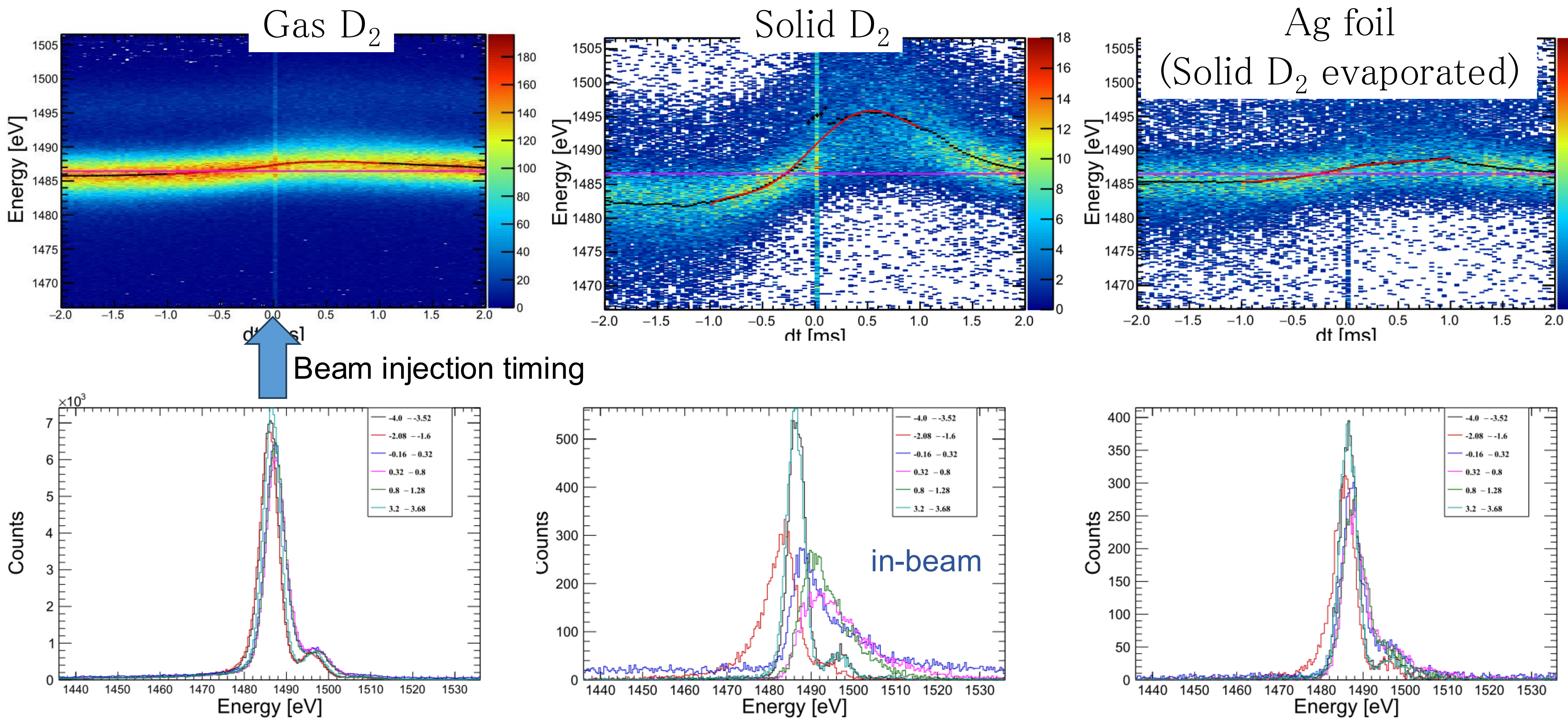
Example of hump structure in TES wave form



T. Okumura et al.,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 31, NO. 5, AUGUST 2021

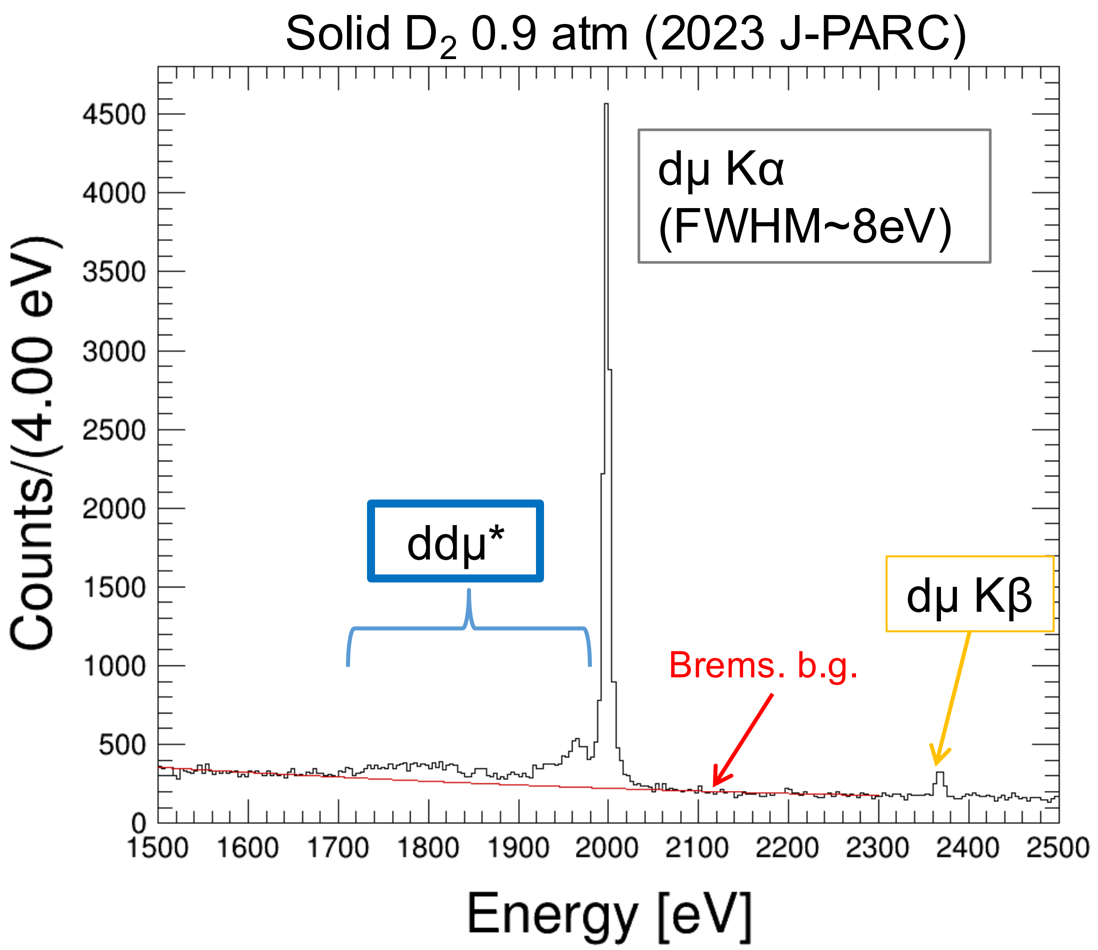
TES response: Gas, Solid target comparison

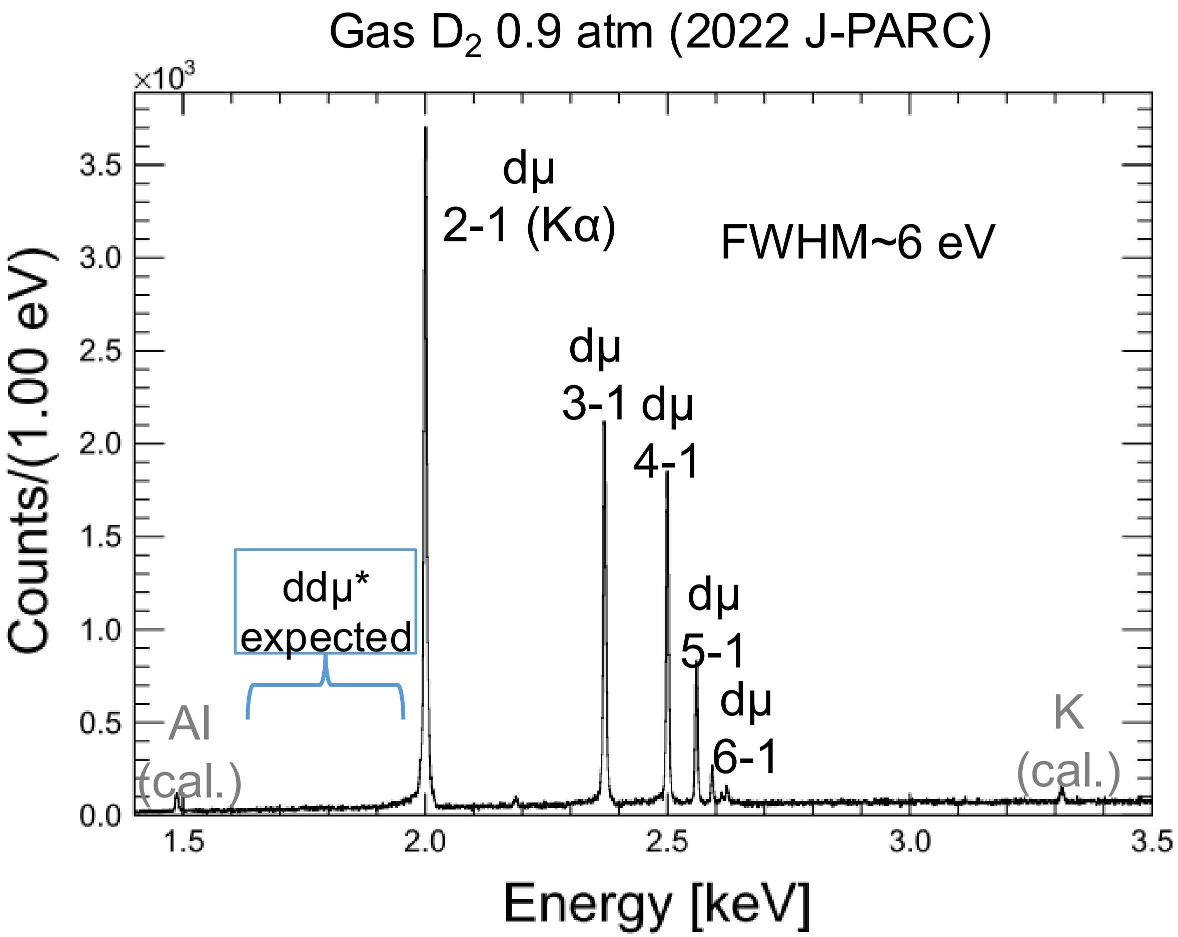
Al Kα peak



Solid D_2 exp. is the worst distorted.

Solid D_2 vs Gas D_2

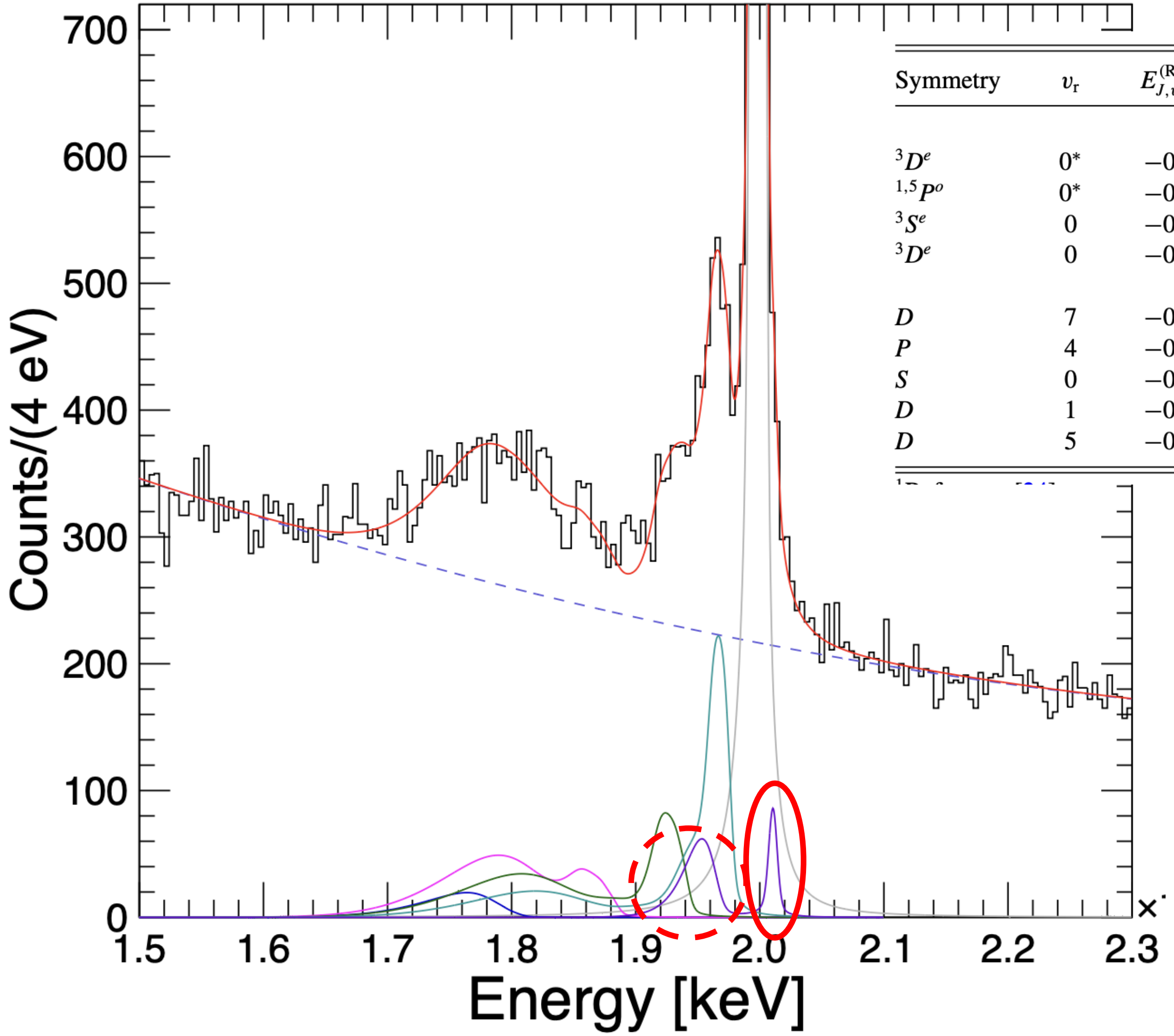




- Gas D_2 data is clean but no ddμ* signals
- Solid D_2 data has much more b.g. events

Higher resolution could be achieved with CW beam?

Resonance to bound transition

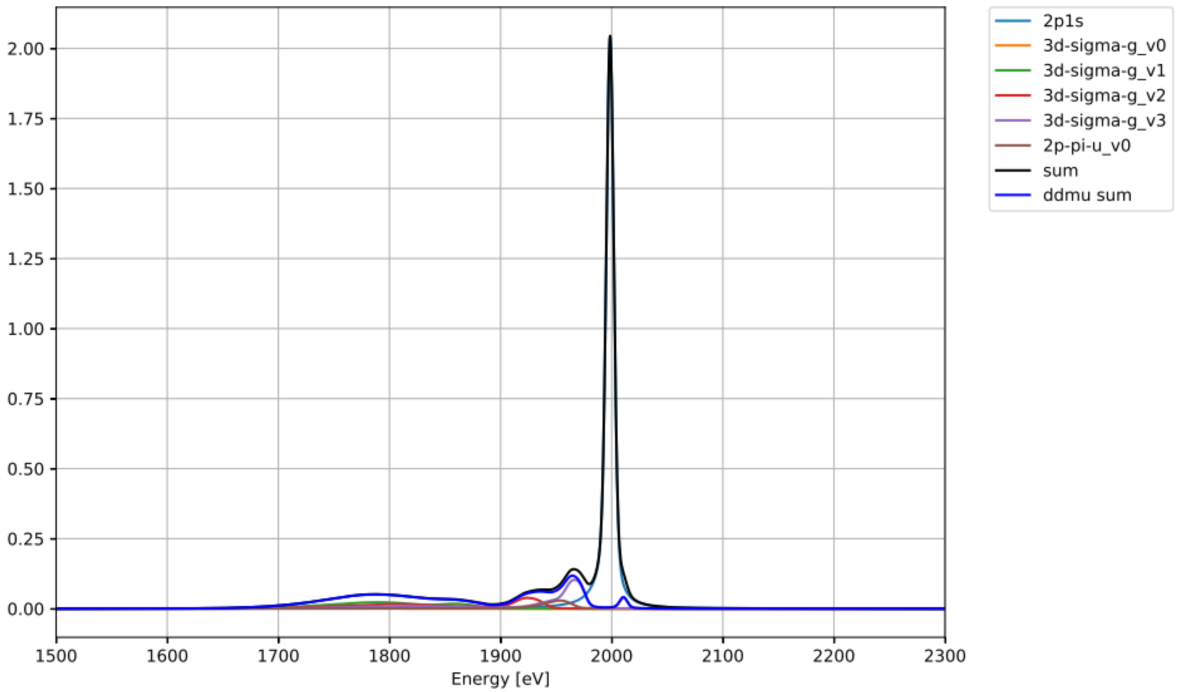


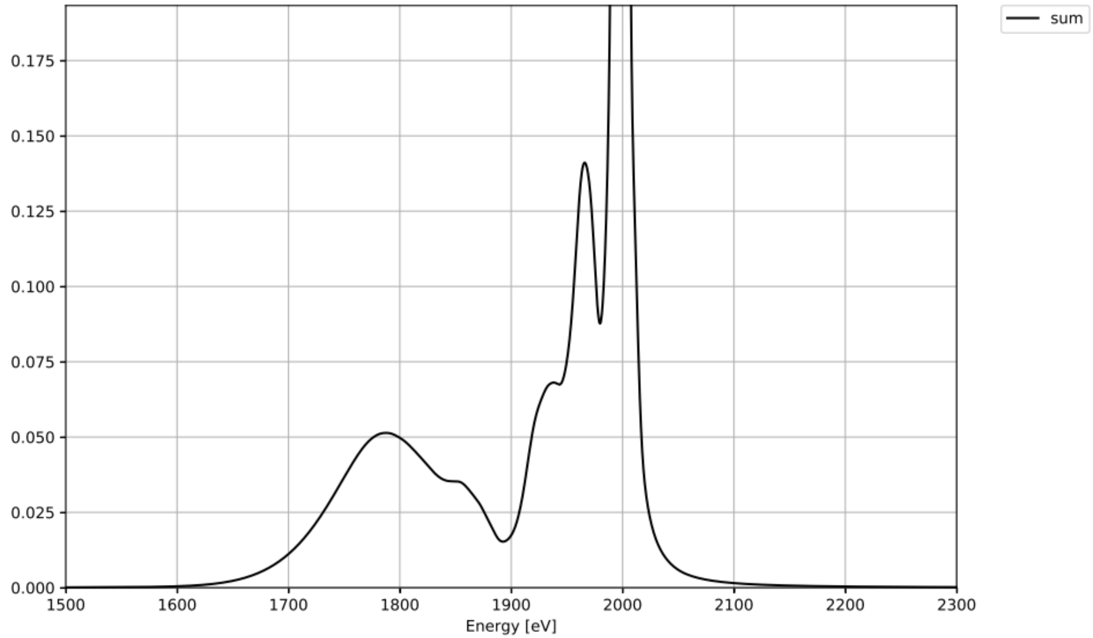
Symmetry	v_r	$E^{(R)}_{J,v_r}$ (m.a.u.)	ε_{J,v_r} (eV)	Γ_{RC} (ps^{-1})	Γ_{Coul} (ps^{-1})	J_f	v_b	E_γ (eV)	Γ_{RB} (ps^{-1})	Υ_{RB}
				ddμ^*						
$^3D^e$	0*	−0.120 109	9.9880	5.9[−2]	2.4[−3]	1	1	1989.35	5.62[−2]	0.49
$^{1,5}P^o$	0*	−0.122 359	22.6458	8.2[−2]	3.5[−3]	0	1	2010.56	3.51[−2]	0.30
$^3S^e$	0	−0.122 094	21.1551	5.8[−2]	(< 1[−3])	1	1	1978.18	5.66[−3]	0.09
$^3D^e$	0	−0.121 559	18.1432	6.0[−2]	(< 8[−4])	1	1	1981.19	3.44[−3]	0.05
				dtμ^*						
D	7	−0.121 883	7.957	7.6[−2]	8.9[−4]	1	1	2026.72	2.68[−2]	0.35
P	4	−0.123 874	19.159	9.5[−2]	1.2[−3]	0	1	2049.10	2.50[−2]	0.26
S	0	−0.159 195	217.887	7.1[−2]	2.9[−5][1]	1	1	1816.19	3.01[−3]	0.04
D	1	−0.156 357	202.083	7.4[−2]	(< 1[−3])	1	1	1832.16	2.79[−3]	0.04
D	5	−0.122 998	14.272	6.1[−2]	(< 1[−2])	1	1	2019.85	1.39[−3]	0.02

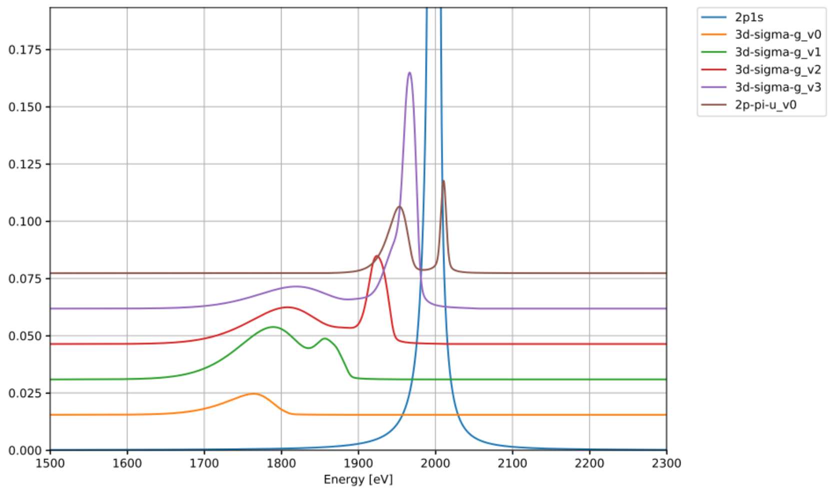
T. Yamashita *et al.*, PRA **111**, 012811 (2025)

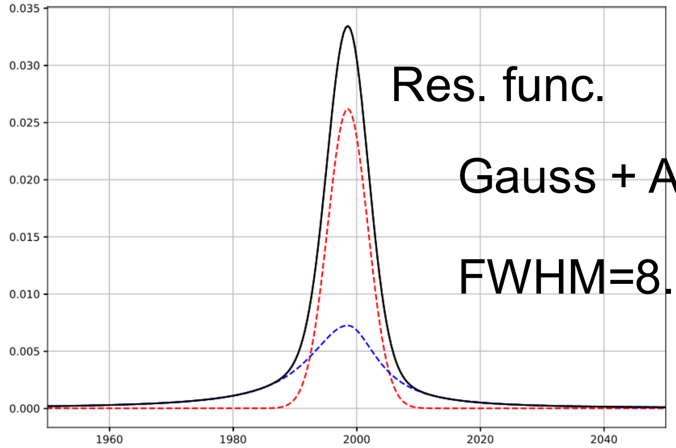
- Resonance to bound transition (ddμ*→ddμ)
  - Some states has some branches of RB transition with emitting monochrome X-rays
  - Accelerate μCF cycle
- Already taken into account in the analysis
  - by fixing ratio to RC branch
- Not “direct” observation

Result of the solid D_2 experiment w/o Brems. b.g.









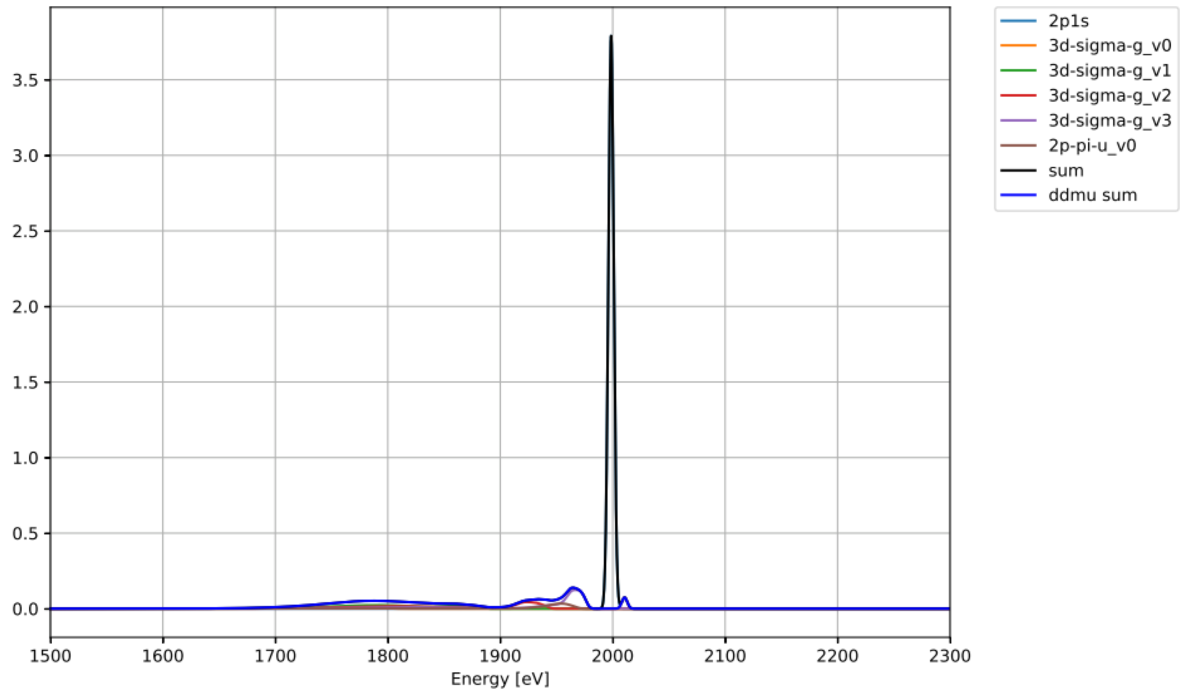
Res. func.

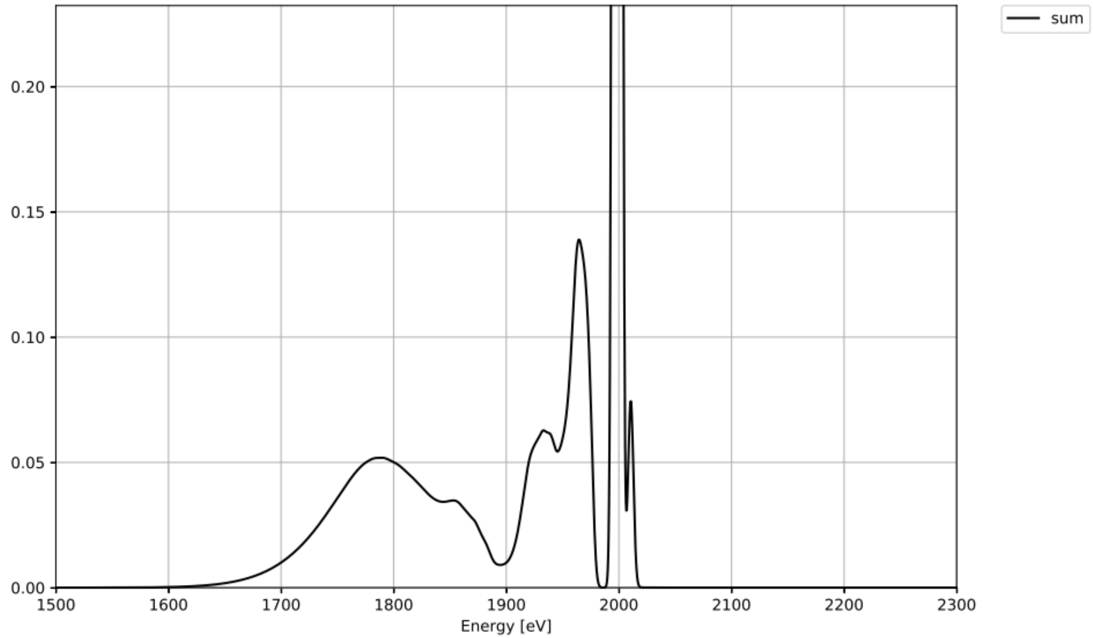
Gauss + AsymLorentz

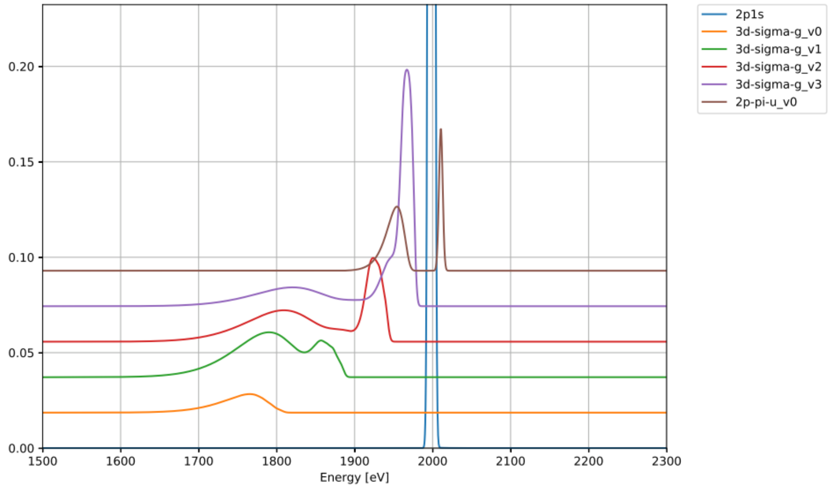
FWHM=8.2 eV (w/ tail)

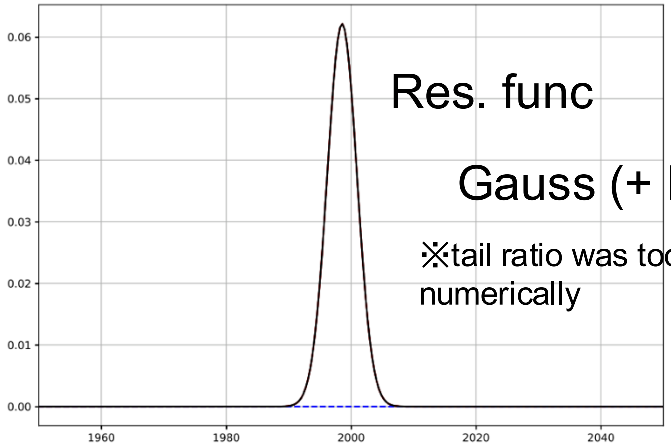
Assuming off-beam resolution

FWHM=5.6 eV, w/o tail







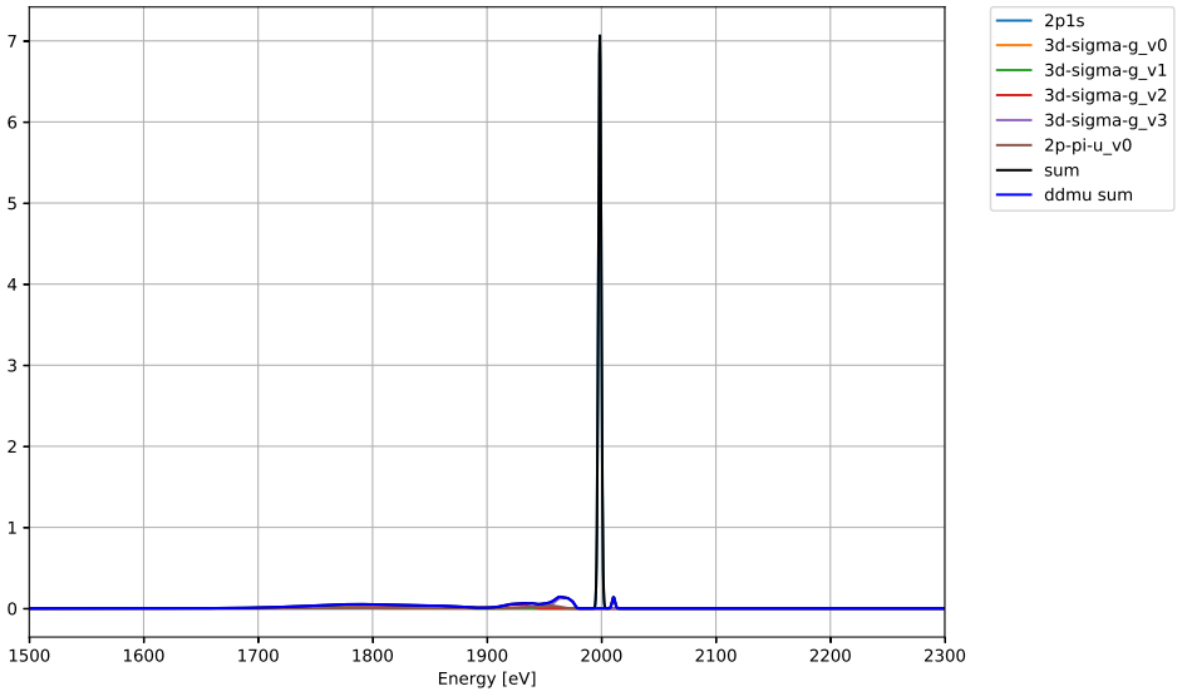


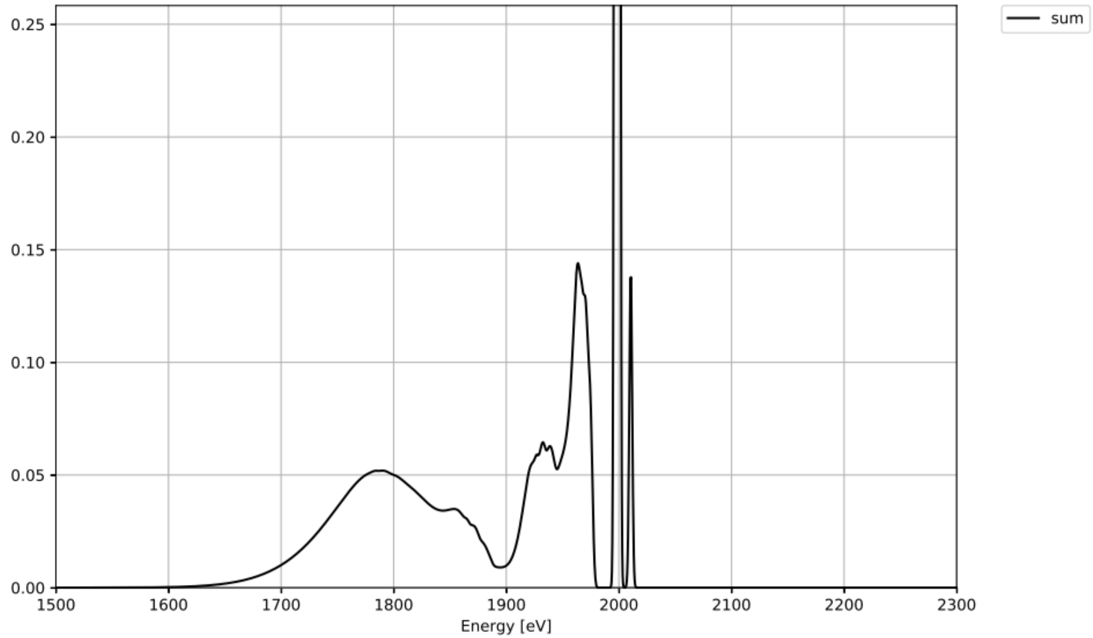
Res. func

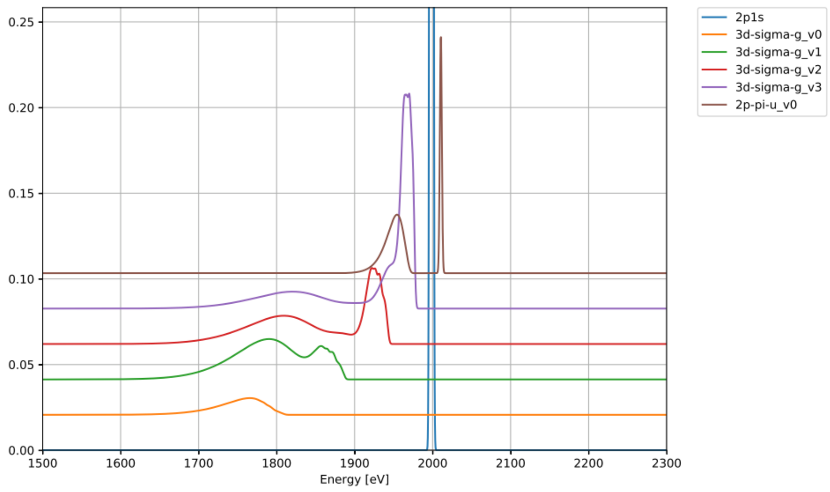
Gauss (+ ExpGauss)

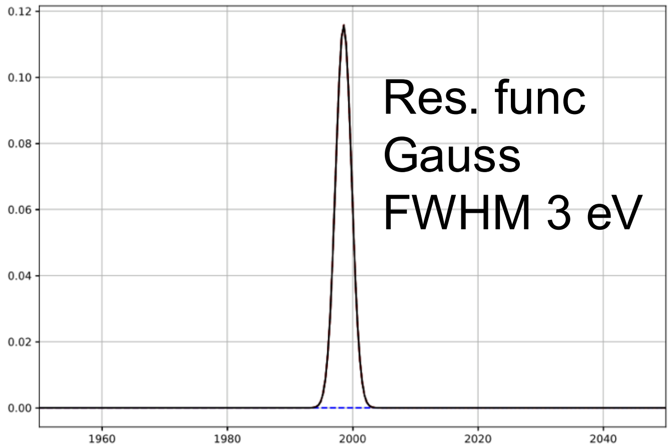
※tail ratio was too low to implement numerically

Assuming better resolution (New TES, FWHM=3.0 eV)

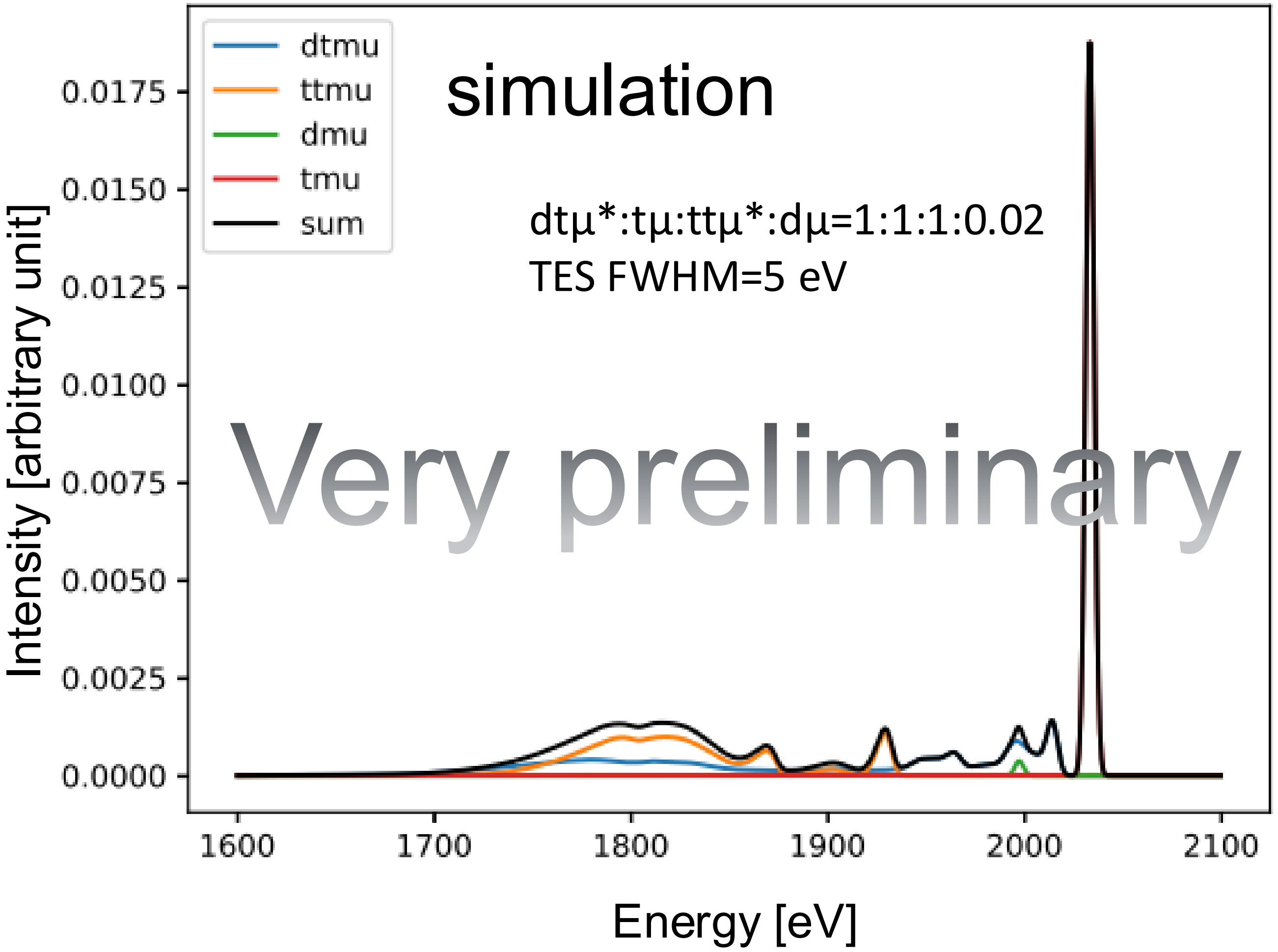


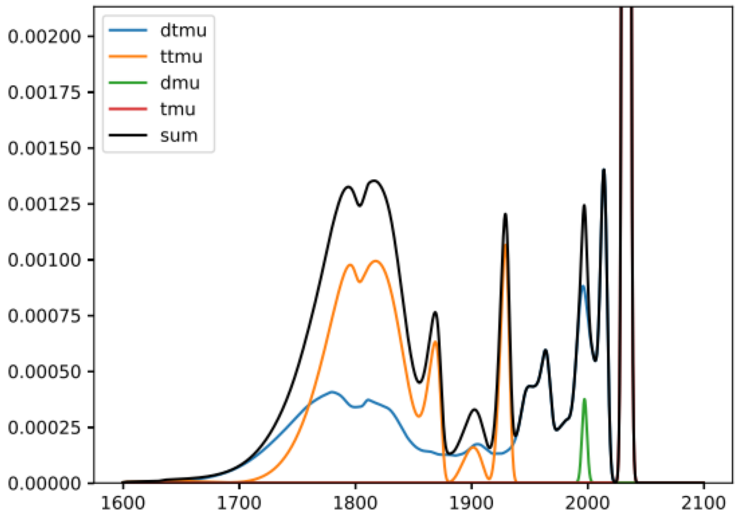






Future TES experiment with a tritium target





- 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

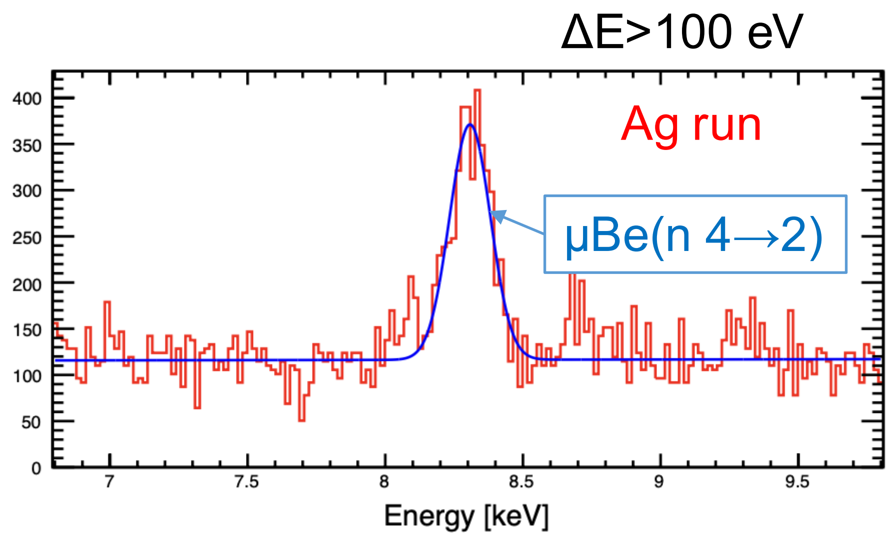
Pulse beam or CW beam

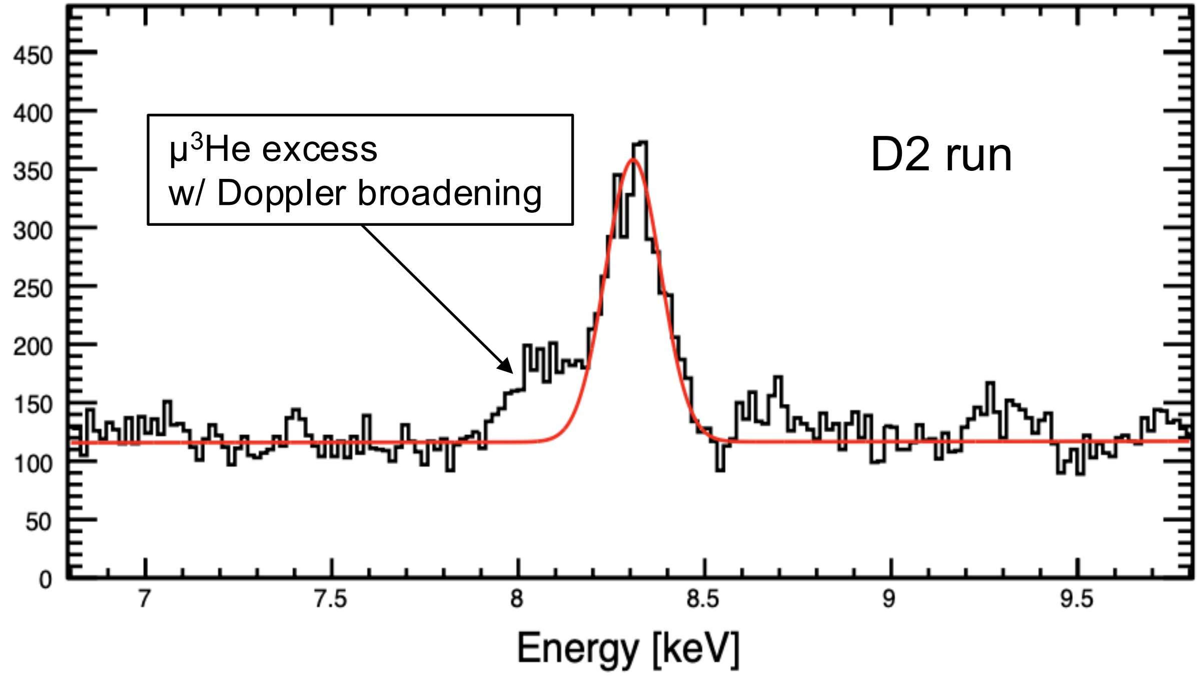
- In experiments using tritium, beta rays are continuously emitted due to tritium decay, so pulsed beams have traditionally been considered advantageous. However, based on the results of the previous J-PARC experiment, even when this disadvantage is taken into account, the temporally intense background 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

SDD (μ^3He X-ray 8.13 keV) in solid D_2 experiment





- SDD placed in forward
- $dd\mu \rightarrow \mu^3\mathrm{He} + n$
- Excess of μ^3He X-ray 8.13 keV can be seen
  - Be window (vacuum window) was not good choice
- Low energy TES & SDD setup is possible

Summary

- TES calibration with X-ray tube (Al, Cl, K)
- Pulse beam affects energy spectrum (shift & broadening) especially in solid target exp.
- ddμ* spectroscopy with CW beam would be fruitful
  - need more quotatives estimation
- dtμ* case? need simulation
- 8 keV X-ray can be measured by SDD

Backup

HEATES collaboration

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

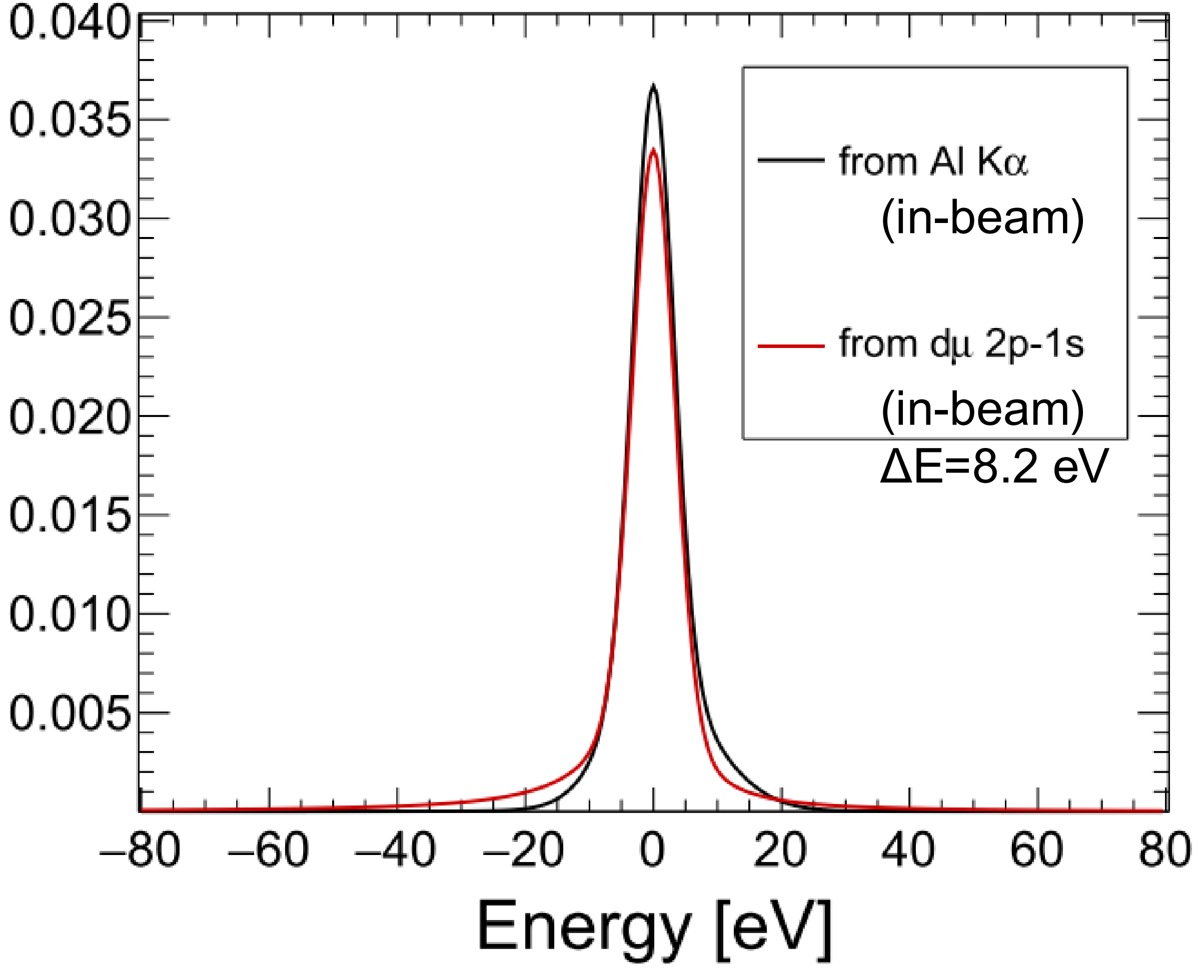
Scientists from many fields!
(Astro + (Nuclear & Hadron) + (Atomic & Muon)) physicists + TES experts

Challenge: Operate TES under severe condition

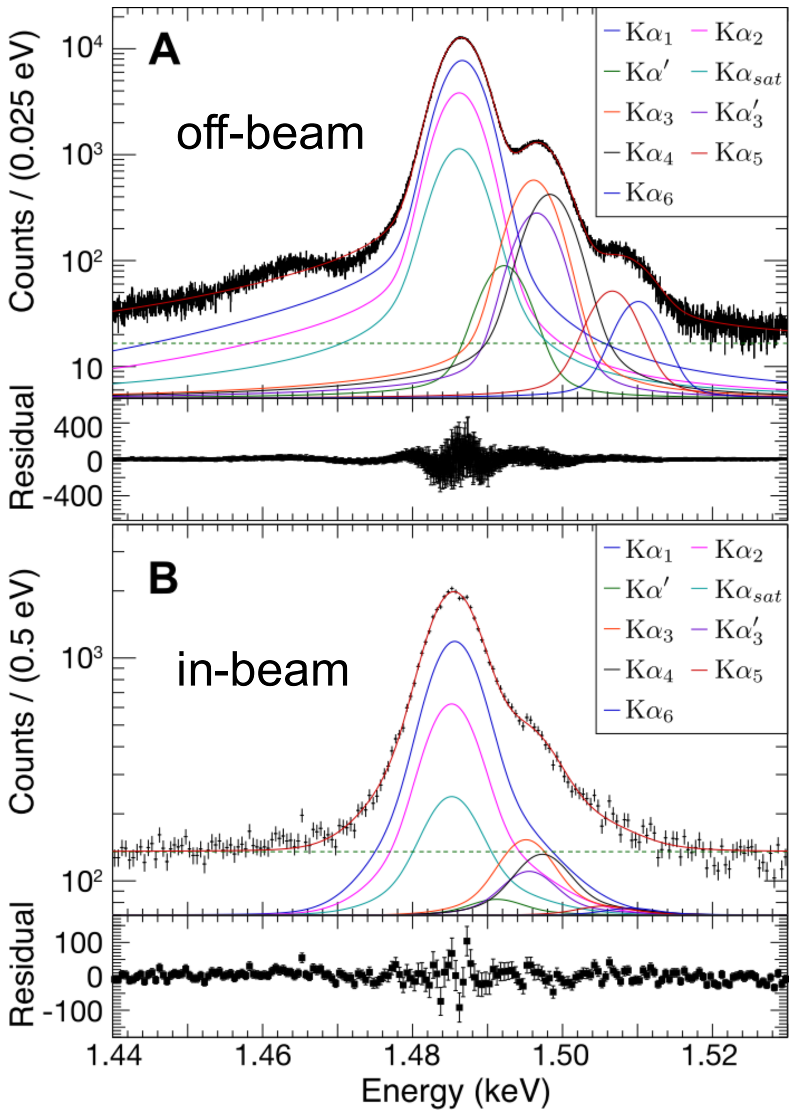
History

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	

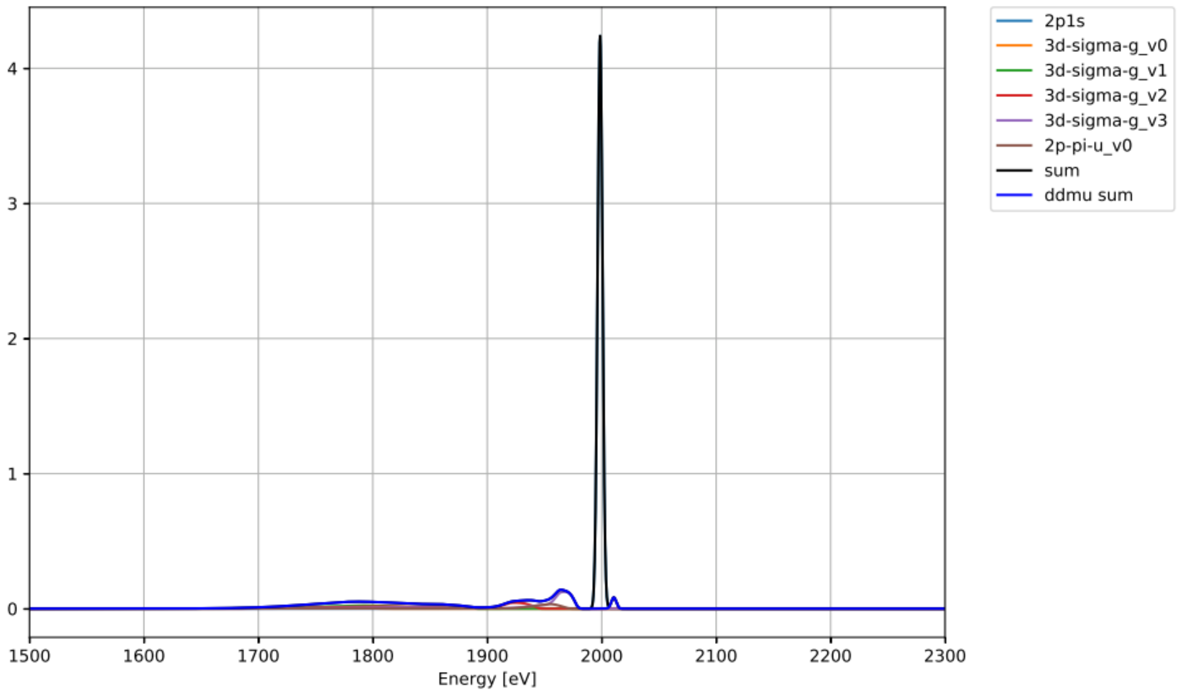
Response function of TES in solid D_2 exp.

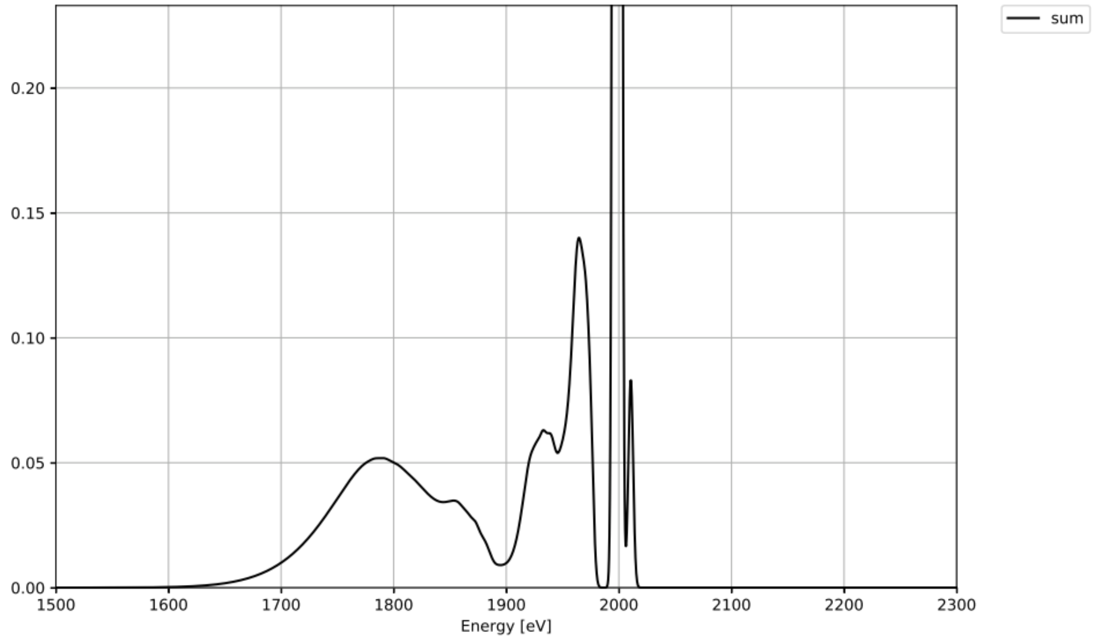


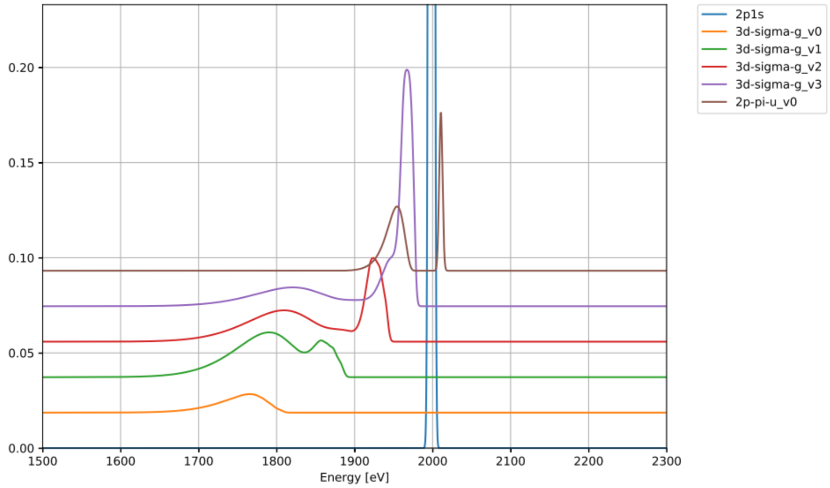
Al cal. line

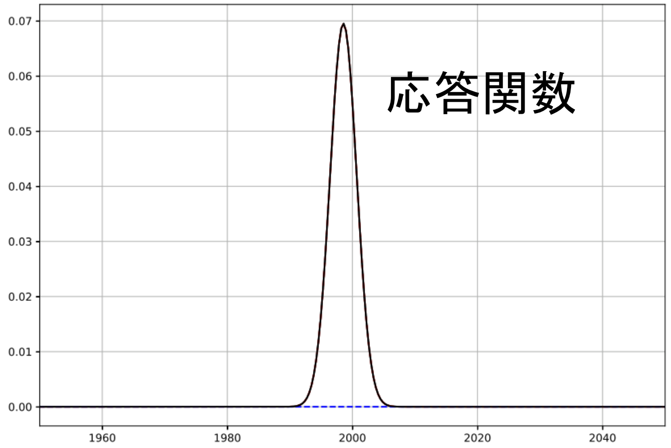


FWHM=5.0 eV, tailなしのGaussian応答関数を仮定

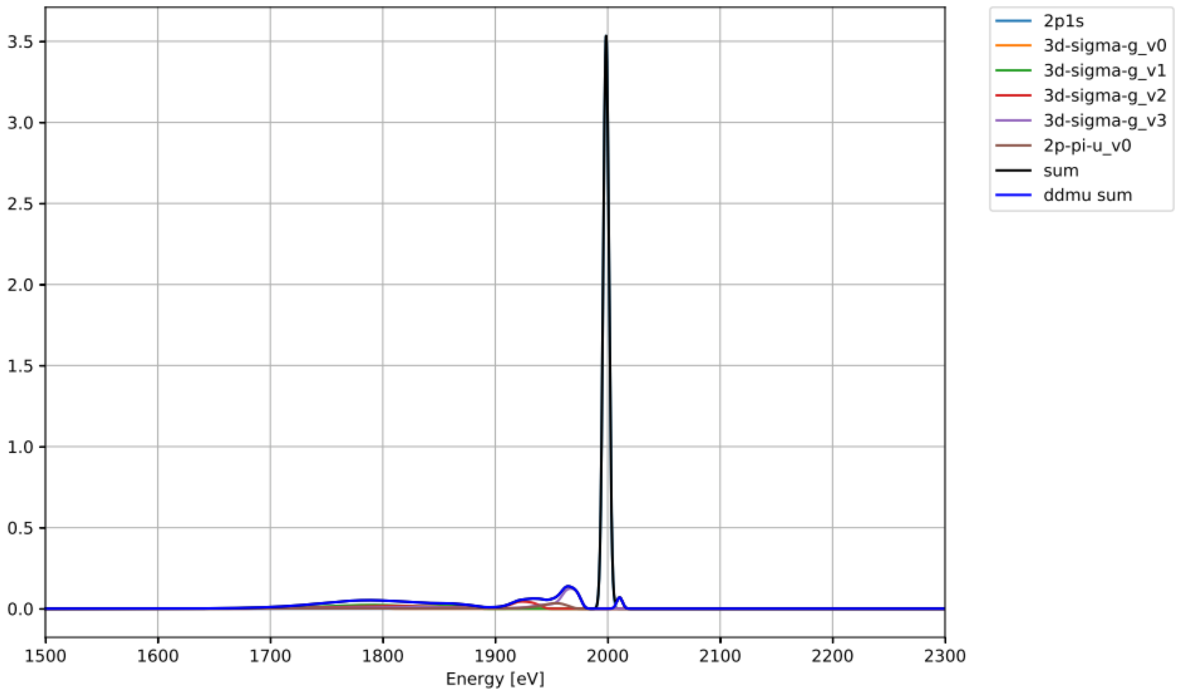


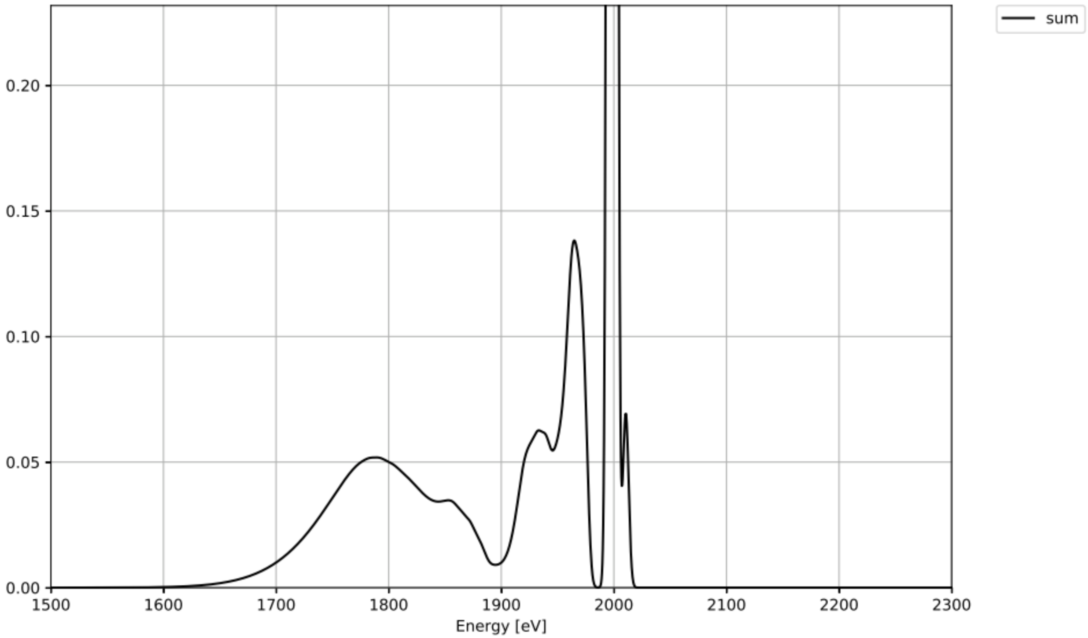


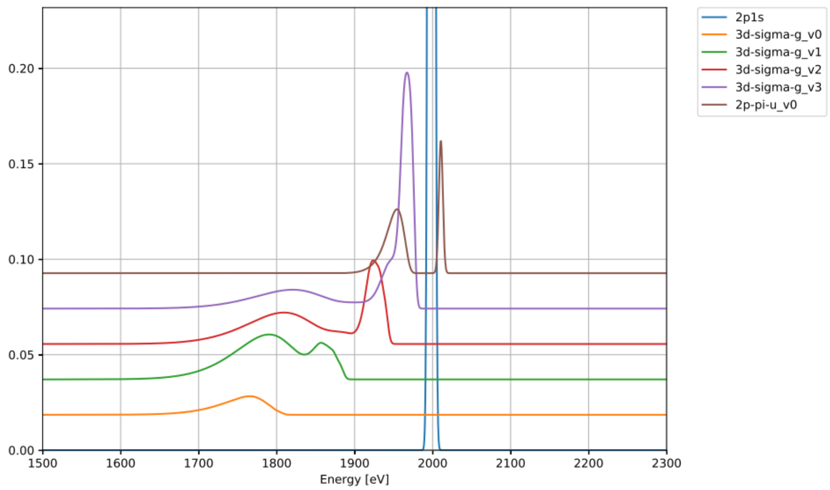


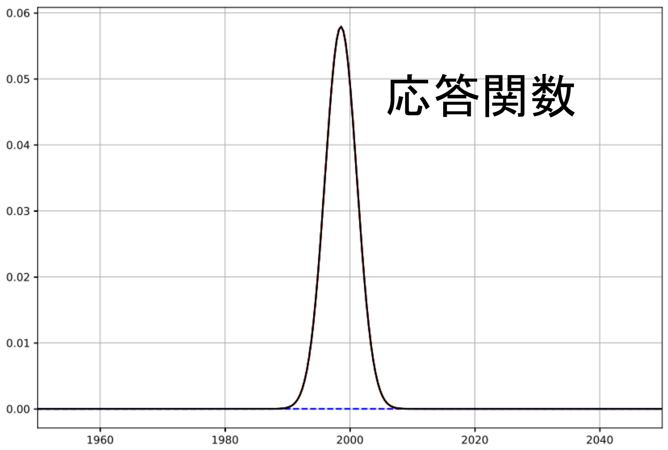


FWHM=6.0 eV, tailなしのGaussian応答関数を仮定



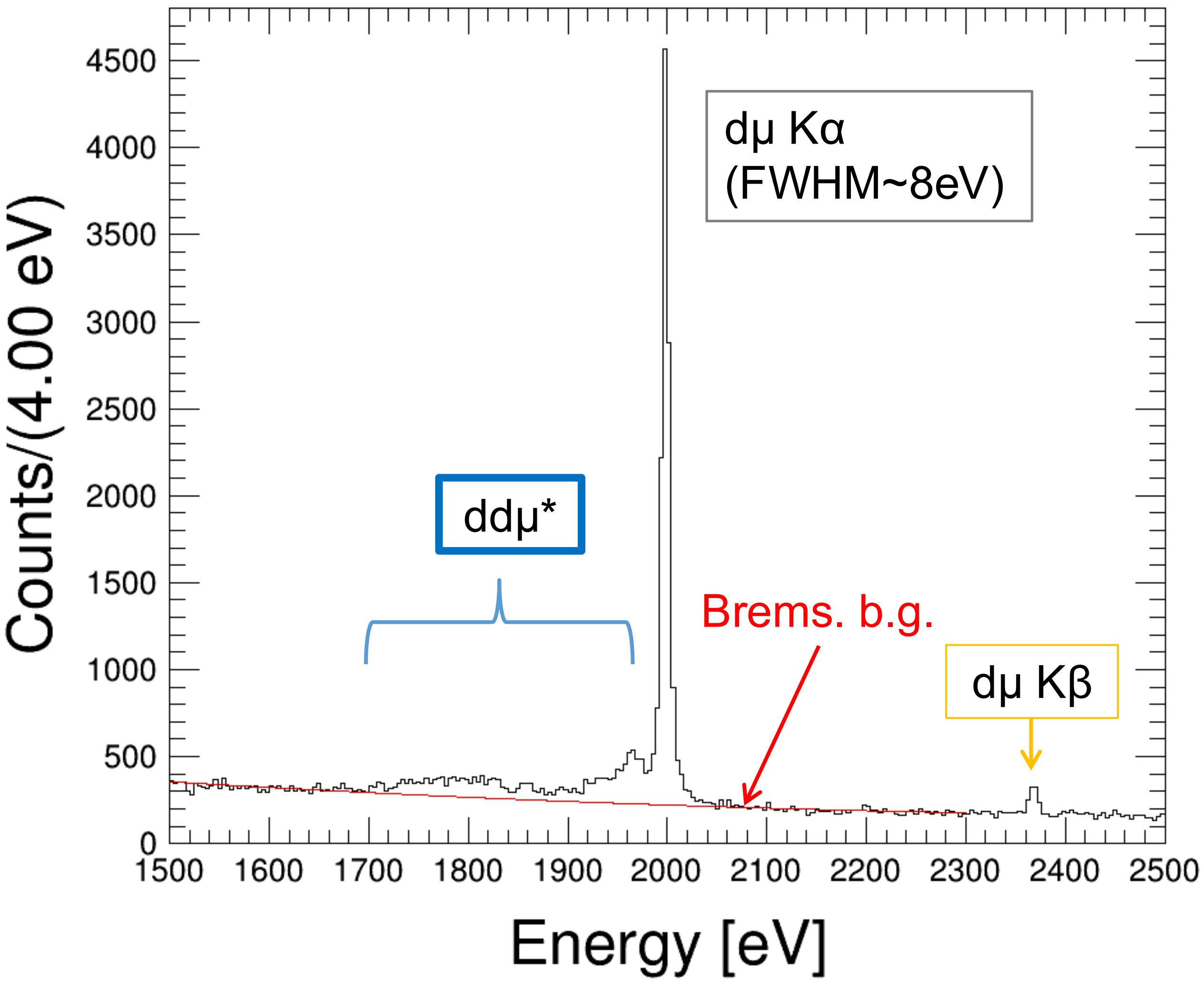






ddμ* dissociative X-ray

In-beam spectrum (-1.0 μs, 1.5 μs)



ddμ* X-rays were observed!

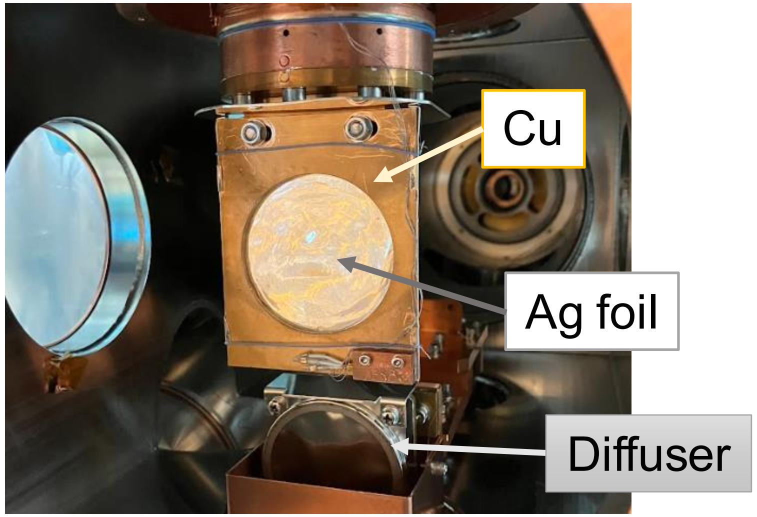
dμ Kα:ddμ* = 6:4

⇨ 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^-

Solid deuterium target system

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

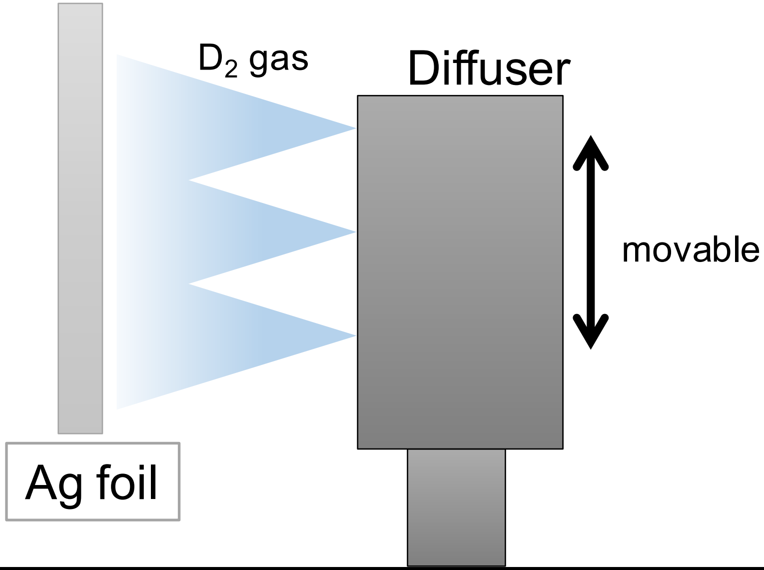


Al thermal shield
(before attaching window)

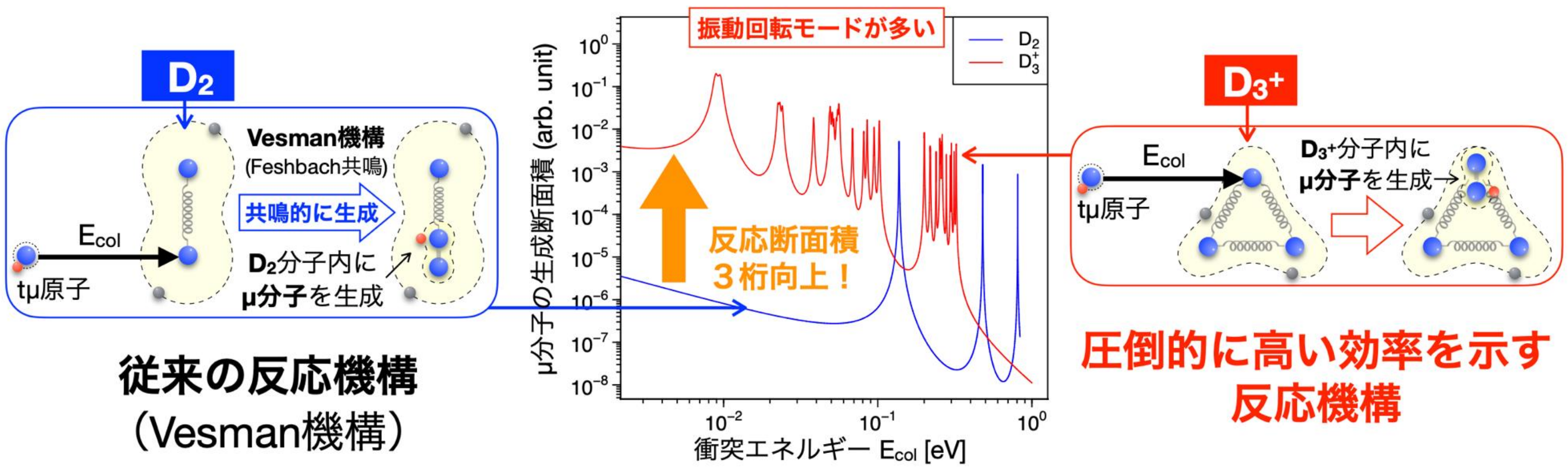
Solid deuterium target system

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

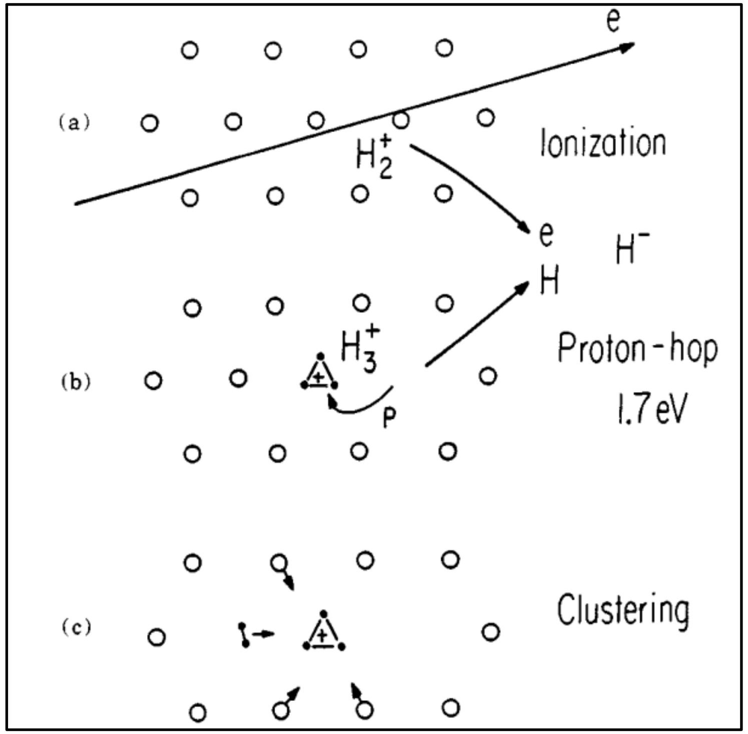
✓ Stable operation during the measurement.



Proposed measurement: Radiochemical effect



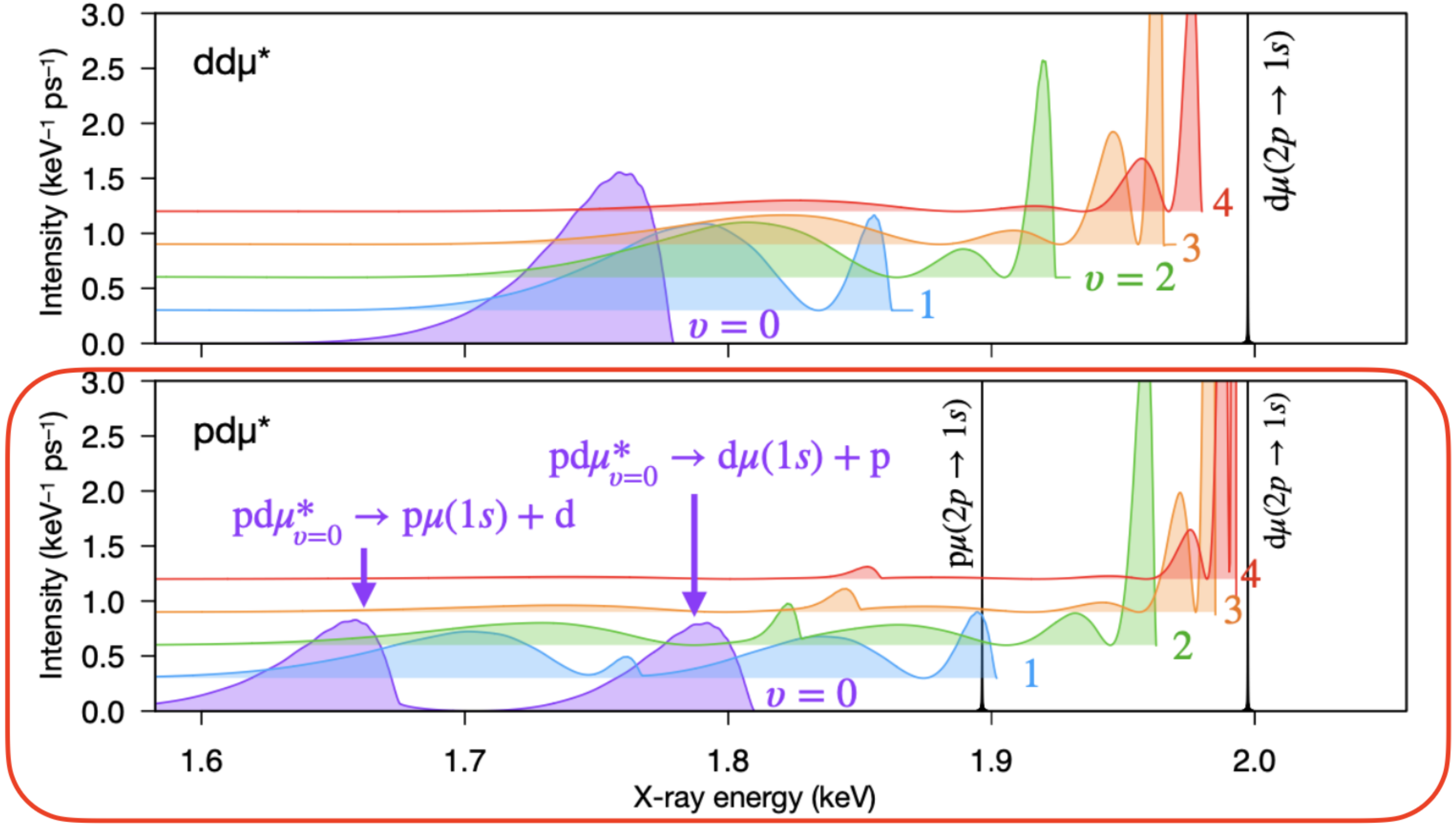
J. Phys. Chem. A 2000, 104, 3775-3779



- 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

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