Early-stage developments about studying Ta-180m decay at cryogenic temperature

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CENTER FOR UNDERGROUND PHYSICS

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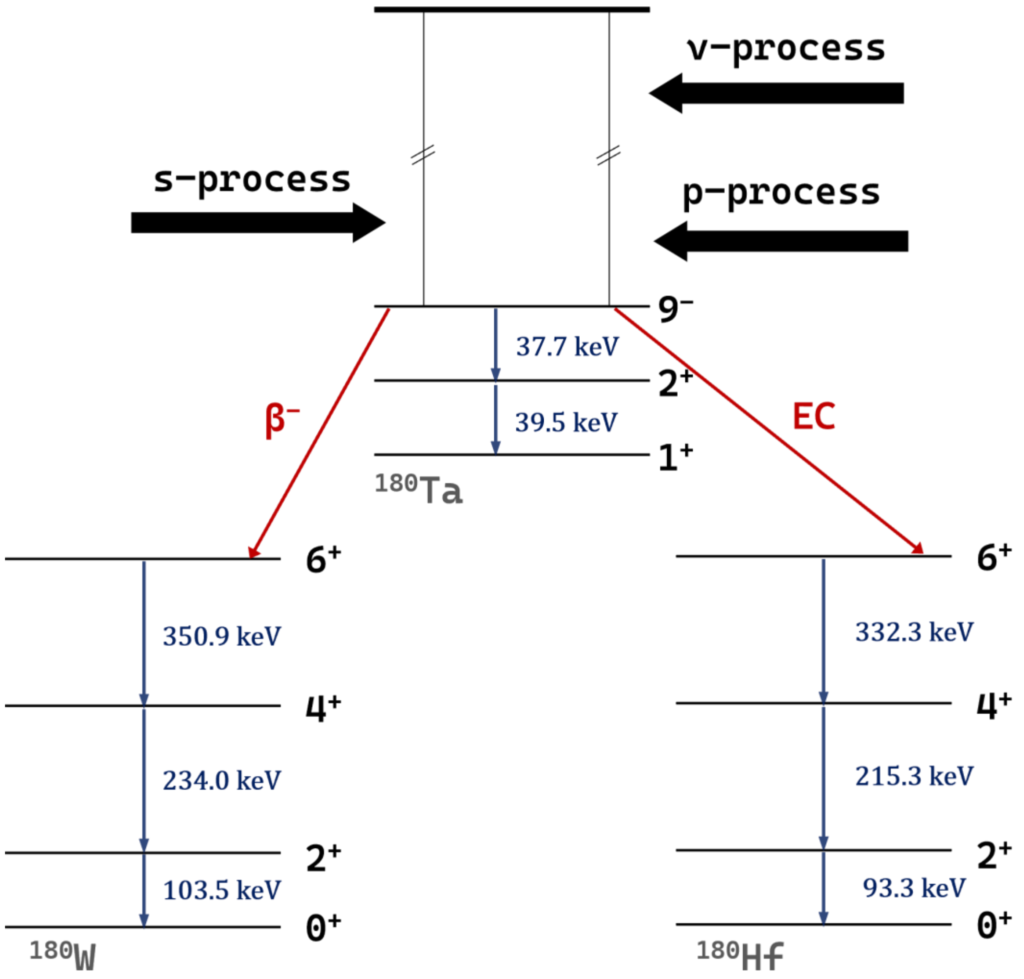
Diverse Physics Investigations Using the Tantalum

- Origin of Ta in the Universe
  - The rare existence of ^{180m}Ta provides insight into nucleosynthesis mechanisms
  - Understand of possible production channels of Tantalum :
    - ν-process, s-process, p-process, Thermal excitation in the early universe

- Longest-Lived Metastable Nuclear State
  - **^{180m}Ta:** The only naturally occurring isomer never observed to decay
  - An extreme case for studying spin traps and nuclear selection rules
  - Theoretical decay modes: β^-, EC, γ-transition, internal conversion, etc
  - Ground-state ^{180}Ta is unstable



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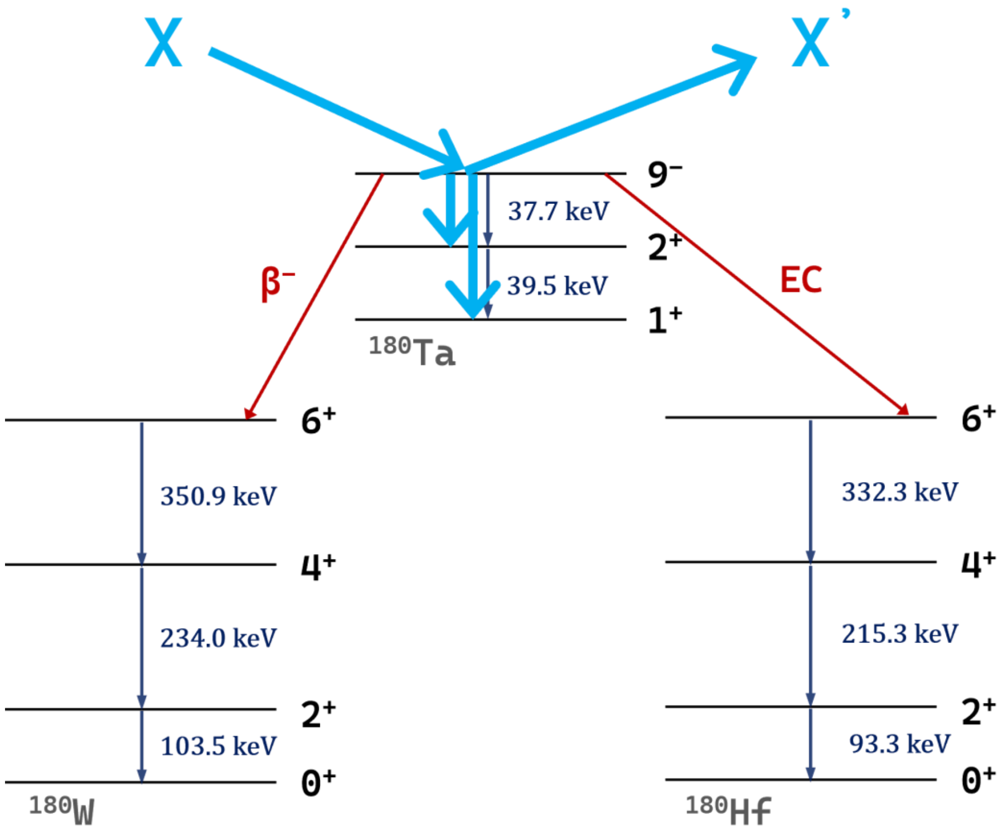
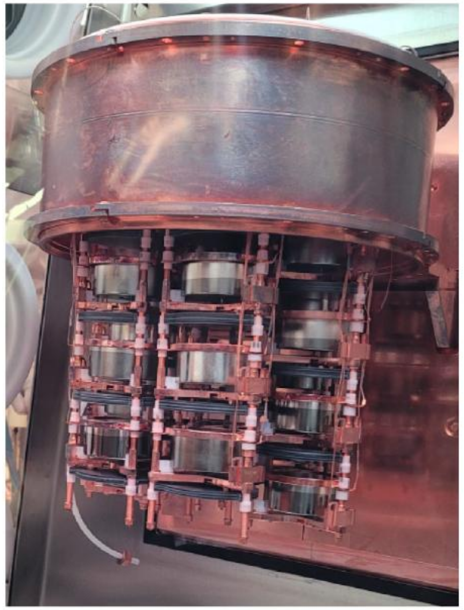
- Search for Dark Matter with Tantalum (PHYSICAL REVIEW D 101, 055001 (2020))
  - Long-lived nuclear isomers like ^{180m}Ta can probe strongly interacting DM and inelastic DM by utilizing their stored excitation energy.



Ta-180 experiments

Most resent

MAJORANA DEMONSTRATOR ([1])



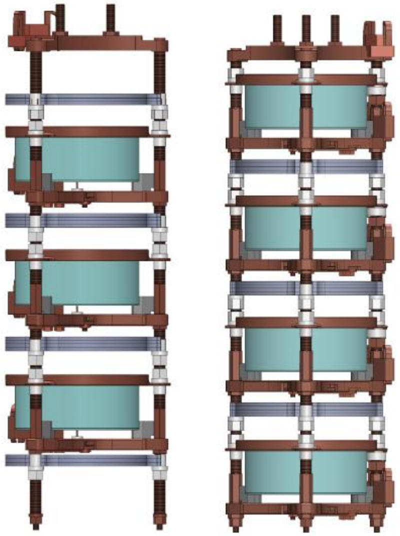


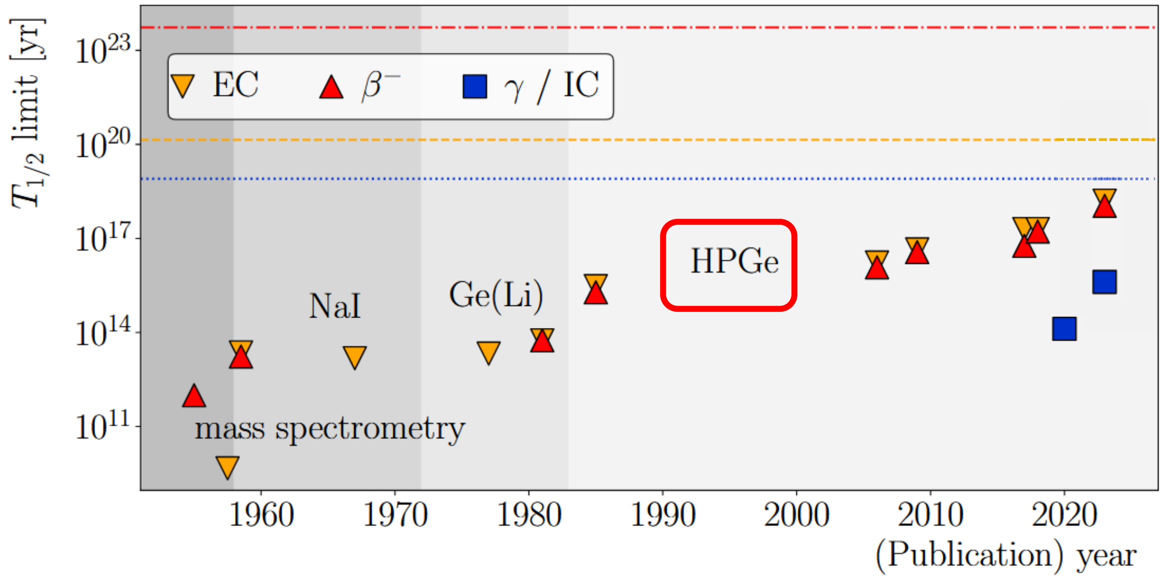
TABLE I. Measured decay half-life limits. Results are given at a 90% C.L. using the one-dimensional spectral fits (SF), a multiplicity-two analysis (2D) where applicable, and the strongest limit for the decay channel. The nomenclature introduced in Eq. (1) is used to describe each decay channel. For the 39.5-keV transition (*), the internal conversion factor is calculated using Ref. [17].

	EC		β^-		γ		IC		α	
Method	Energy (keV)	$T_{1/2}$ (10^{18} yr)	Energy (keV)	$T_{1/2}$ (10^{18} yr)	Energy (keV)	$T_{1/2}$ (10^{18} yr)	Energy (keV)	$T_{1/2}$ (10^{18} yr)	Energy (keV)	$T_{1/2}$ (10^{18} yr)
SF	93.3	1.23(30)	103.6	1.54(17)	37.7	0.63(8)	···	···	184.1	4.80(42)
	215.3	5.69(55)	234.0	5.76(75)	39.5	0.06(1)*	39.5	0.06(1)*	204.7	5.58(54)
	332.2	10.0(13)	350.9	9.31(114)	93.3	0.29(4)	93.3	0.29(4)	388.8	10.2(12)
					103.6	0.07(2)	103.6	0.07(2)		
2D	93.3 + 215.3	1.88(35)	103.6 + 234.0	2.65(49)	···	···	···	···	184.1 + 204.7	11.3(22)
	93.3 + 332.2	3.18(56)	103.6 + 350.9	4.18(78)	···	···	···	···		
	215.3 + 332.2	13.3(22)	234.0 + 350.9	15.4(27)	···	···	···	···		
Best: this work		13.3(22)		15.4(27)		0.63(8)		0.29(4)		11.3(22)
Previous works		1.6 [11]		1.1 [11]		0.0045 [11]		0.0045 [11]		···
Expected $T_{1/2}$ [12,13,18,19]		10^{20} yr		10^{23} yr		10^{31} yr		10^{18-19} yr		10^{28} yr

- HPGe detector
- A total of 17.39 kg of Ta disks, total ^{180m}Ta mass of 2.045 g
- New limit up to 1.5×10^{19} yr, improve previous results by 1–2 orders of magnitude and represent the most sensitive searches to date for β and EC

[1] PRL131,152501

Ta-180 experiments



History of tantalum decay measurements with lower limits on each channels. ([2])

- For γ/IC, the detection efficiency of HPGe detectors is a few percent when using a tantalum metal disk several mm thick. ([2], [3]) therefore, previous experiments employed large quantities of tantalum.

➢ Source = detector: Increasing detection efficiency

➢ Enrichment of ^{180}Ta using thermal diffusion column (From 0.0123% to 0.5 – 5 %)

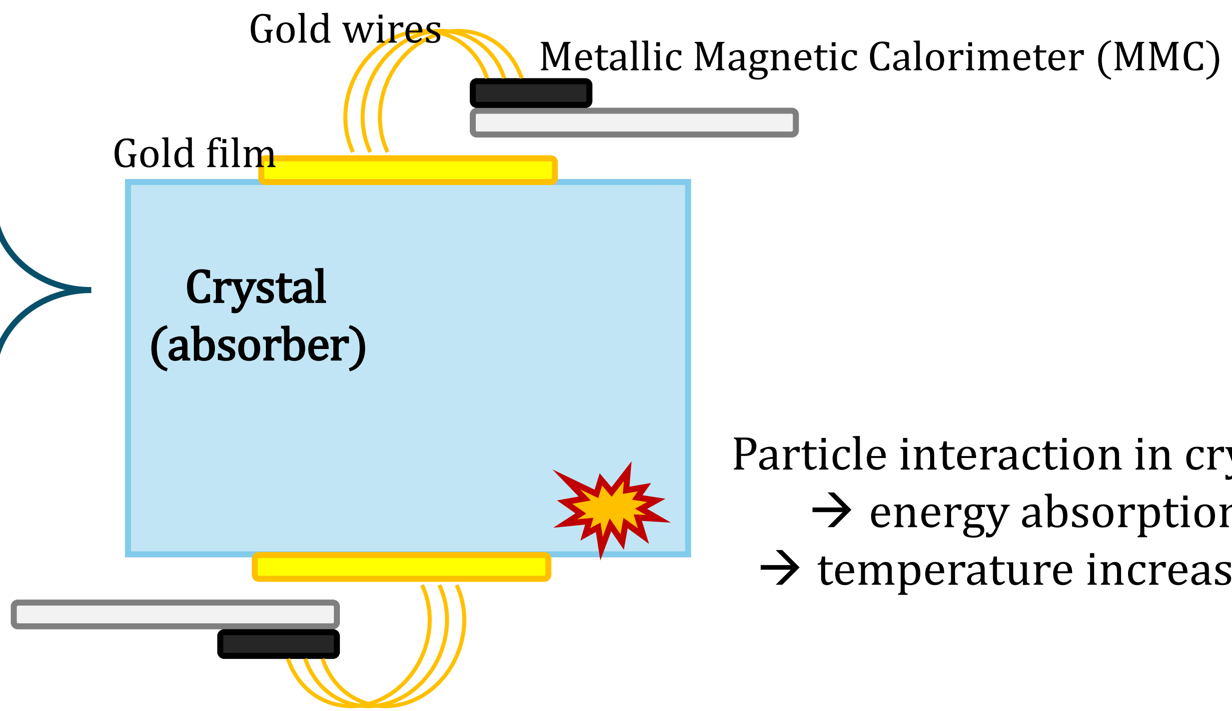
[2] arXiv:2305.17238v3

[3] G. Kim, Ph.D. thesis, Ewha Womans Univ., 2019.

^{180m}Ta decay searching at Low temperature

Candidates

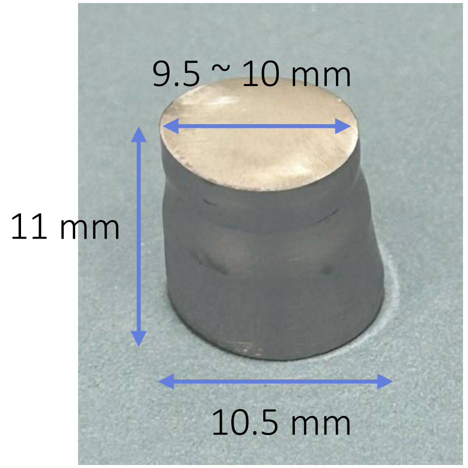
- Ta single crystal: Superconductor
- ~~LiTaO$_3$: Pyroelectric material~~
- KTaO$_3$: potassium background
- Ta$_2$O$_5$: high melting point
- NaTaO$_3$, etc.



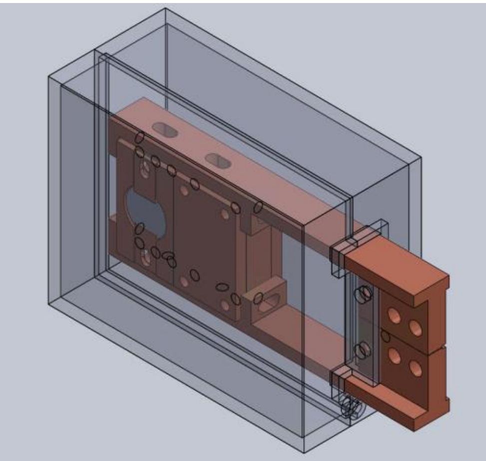
Particle interaction in crystal
→ energy absorption
→ temperature increasing

Quasiparticle recombination → Dual phonon channels

Experimental Set up



- Tantalum single crystal
  - 99.99 % impurity
  - Mass: ~ 15.8 g
- Acid cleaning was performed using a BOE solution.
- Using Bress screws and METCLAS 2714 shield to avoid field trap in superconductor.
- Source: ^{232}Th (511, 583, 911, 968, 2615 keV γ-ray)
- Operation temperature: ~26 mK

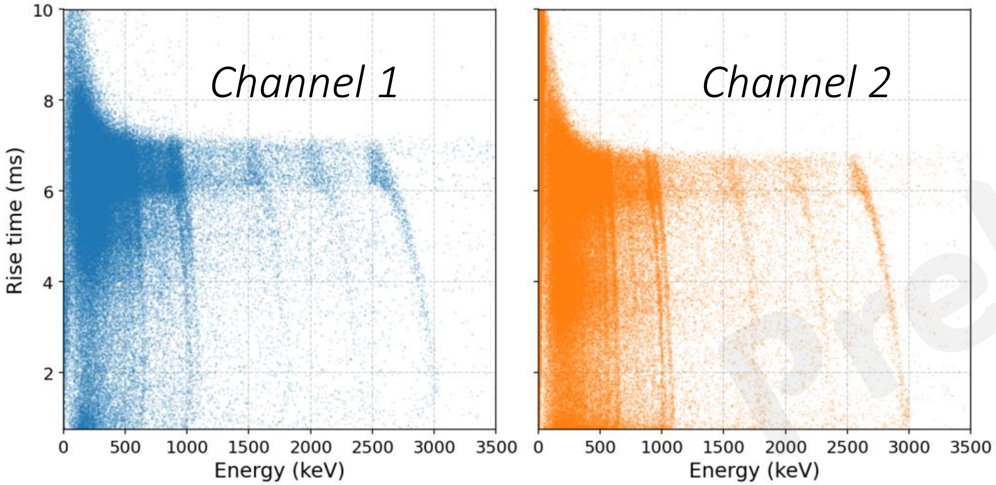


(Left) dual phonon detector design with aluminum shielding

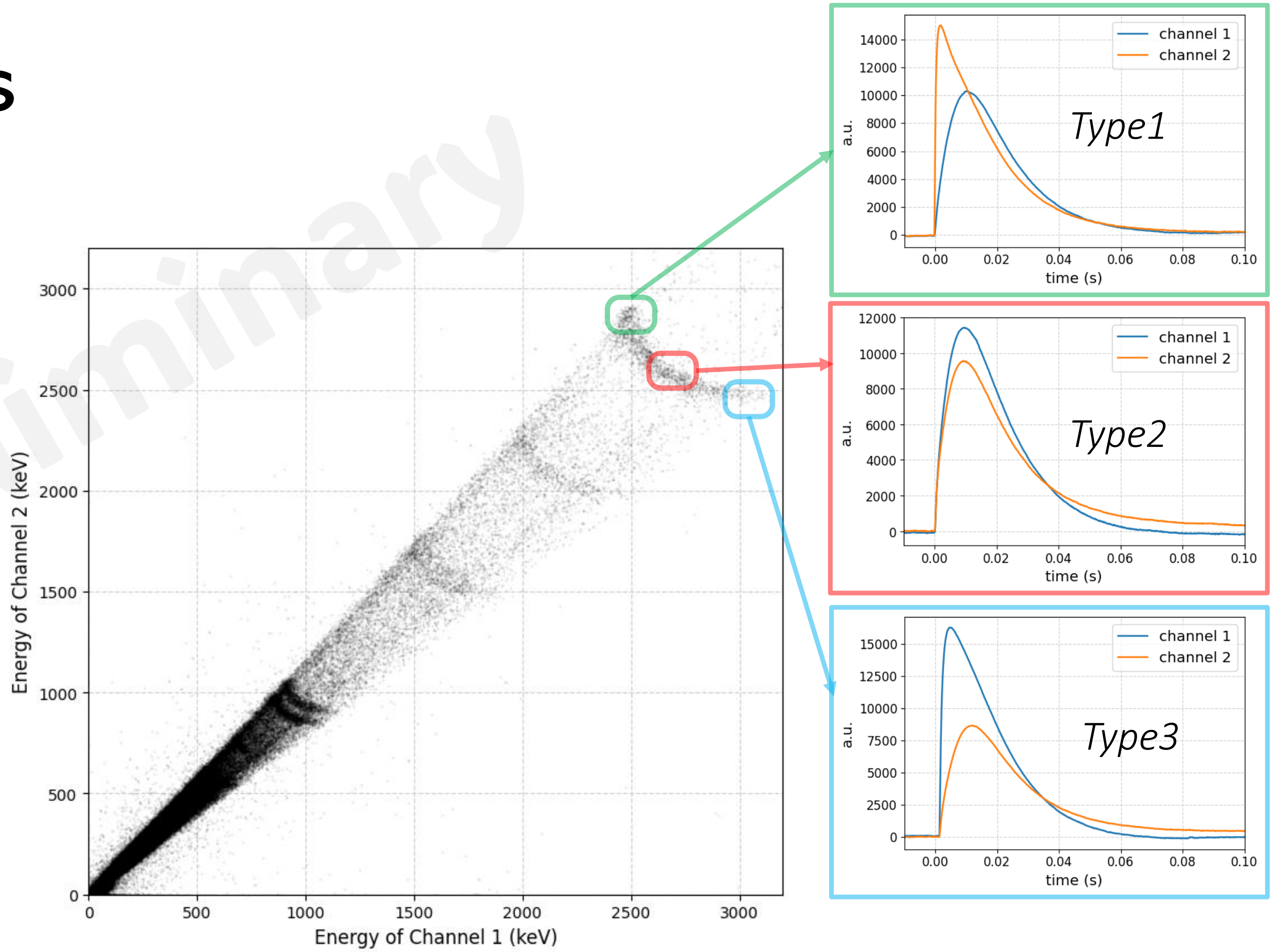
(Right) Gold wire bonding between MMC and gold film on the Ta crystal

Install the 2nd Tantalum experiment in the R&D dilution refrigerator.

Dual phonon detectors

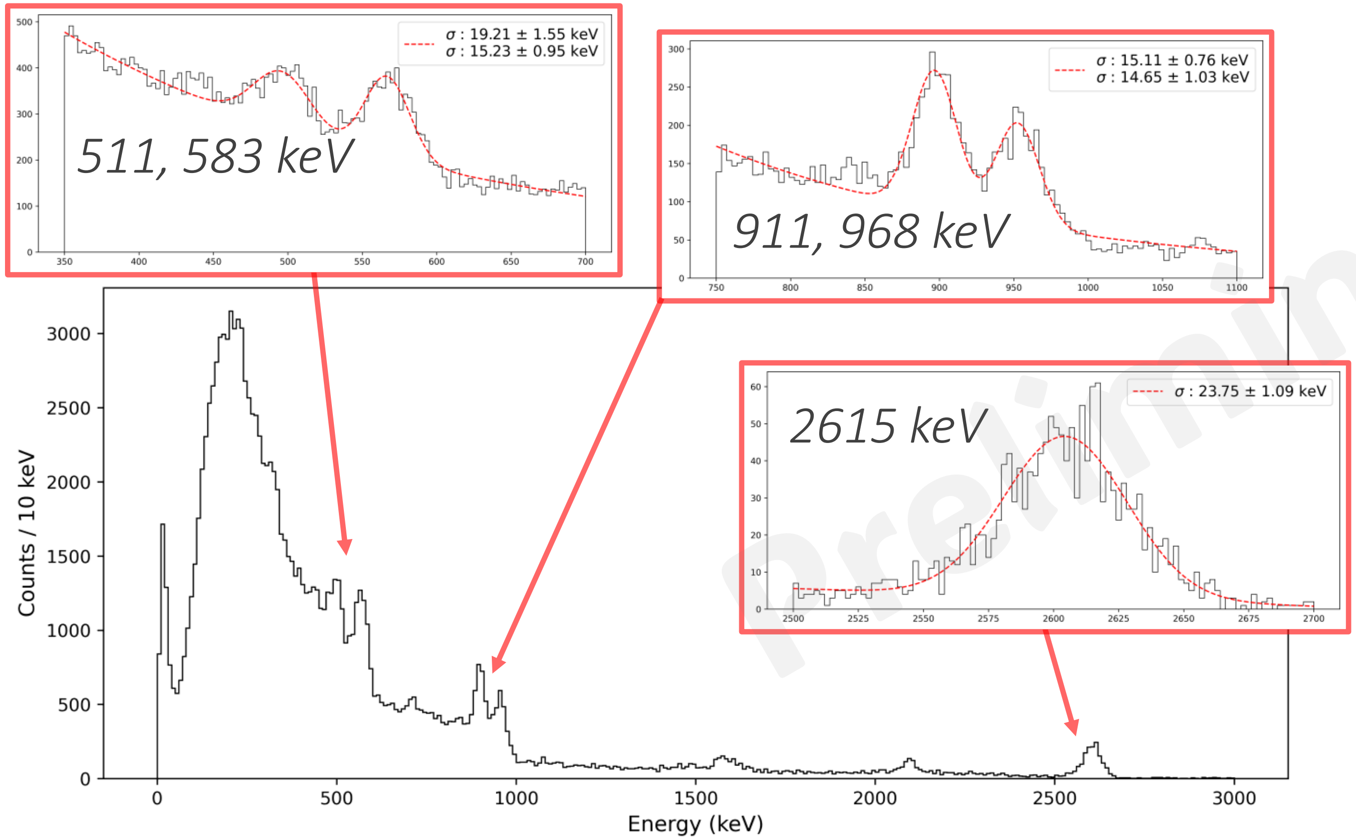


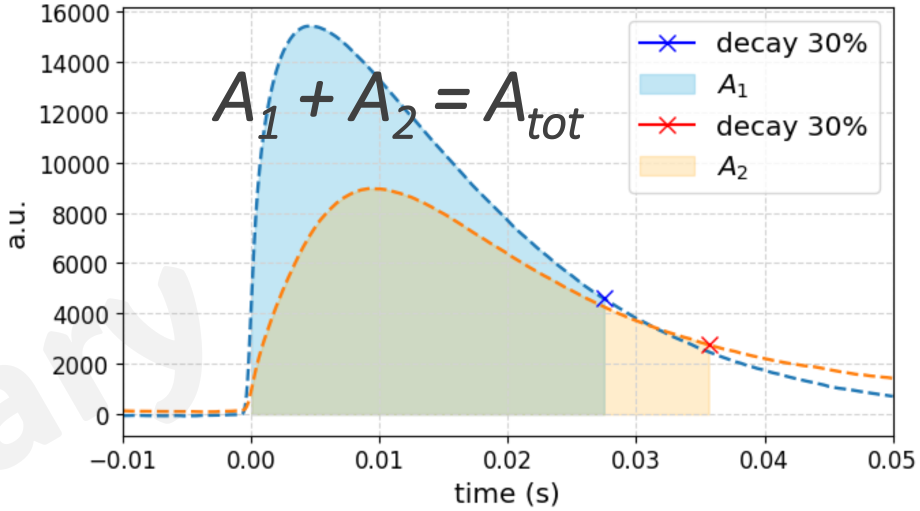
- Preliminary result for dual phonon detectors of Ta single crystal.
- Pulses from the two detectors show the different shape by the quasiparticle recombination effect.
- The amplitude is highly sensitive to signal shape parameters such as rise time and pulse width.



Amplitude of the two channels and 2.615MeV events

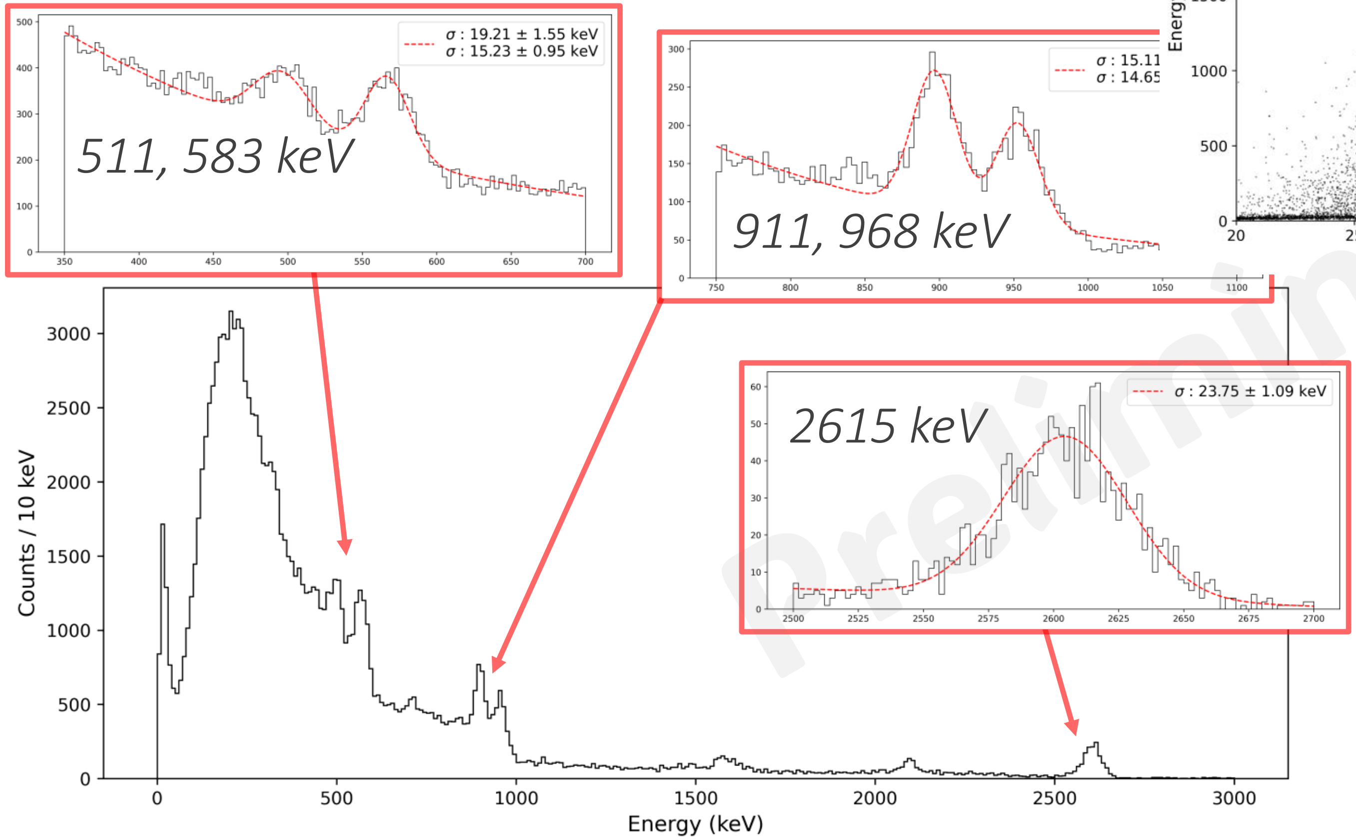
Dual phonon detectors



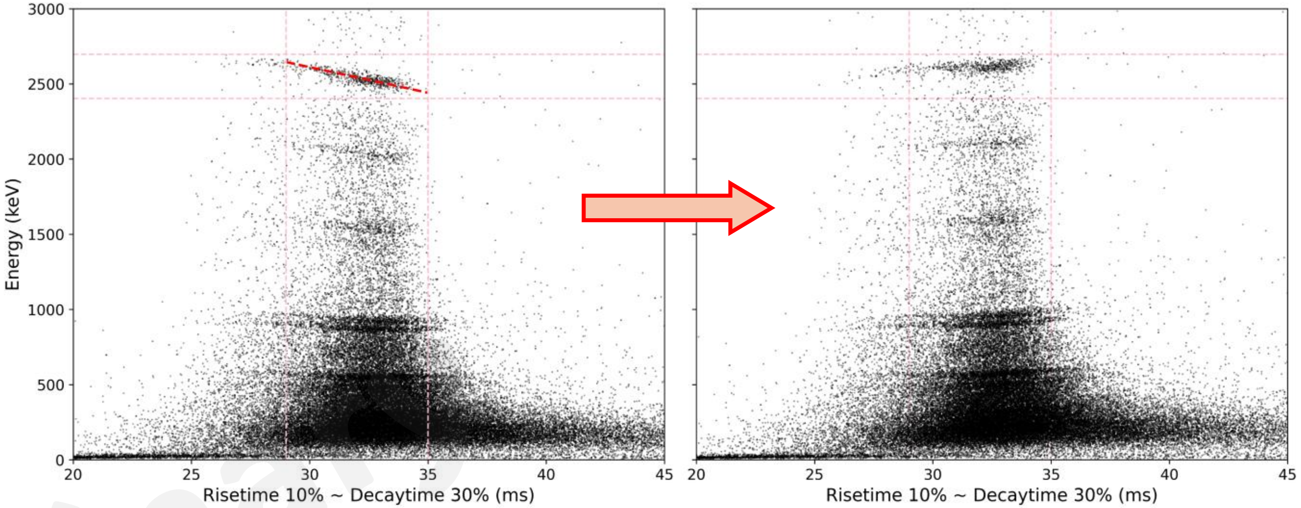


- The summed amplitude spectrum from the two channels shows greater improvement compared to the energy spectrum of each individual channel.

Dual phonon detectors



Ch1 of type3 events



- Despite summing the signals from two channels, the amplitude still shows a correlation with the pulse shape.
- Simply, correction about amplitude dependence with pulse shape parameter, energy resolution was improved.

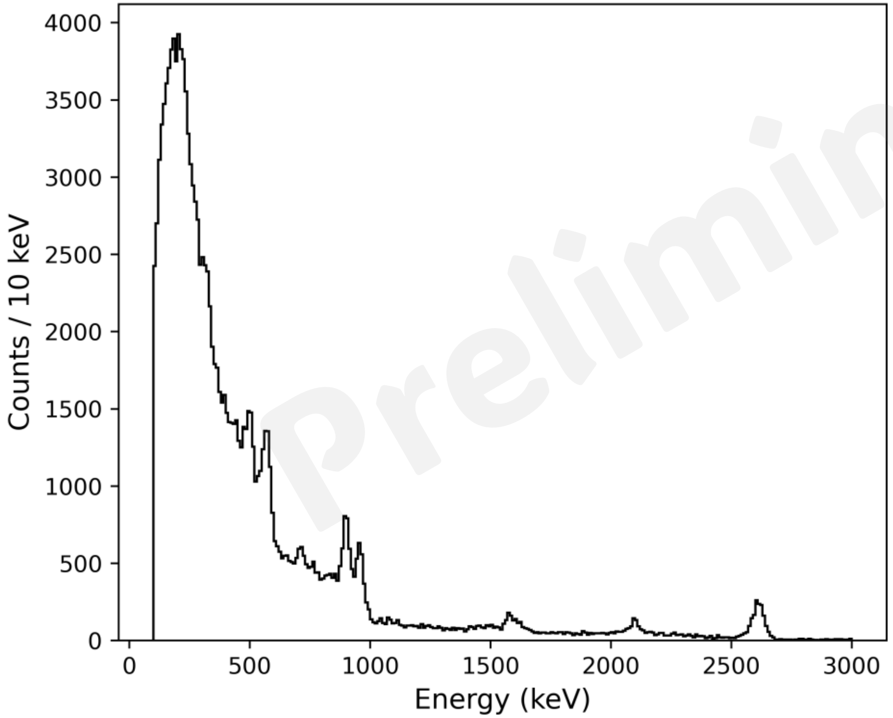
FURTHER

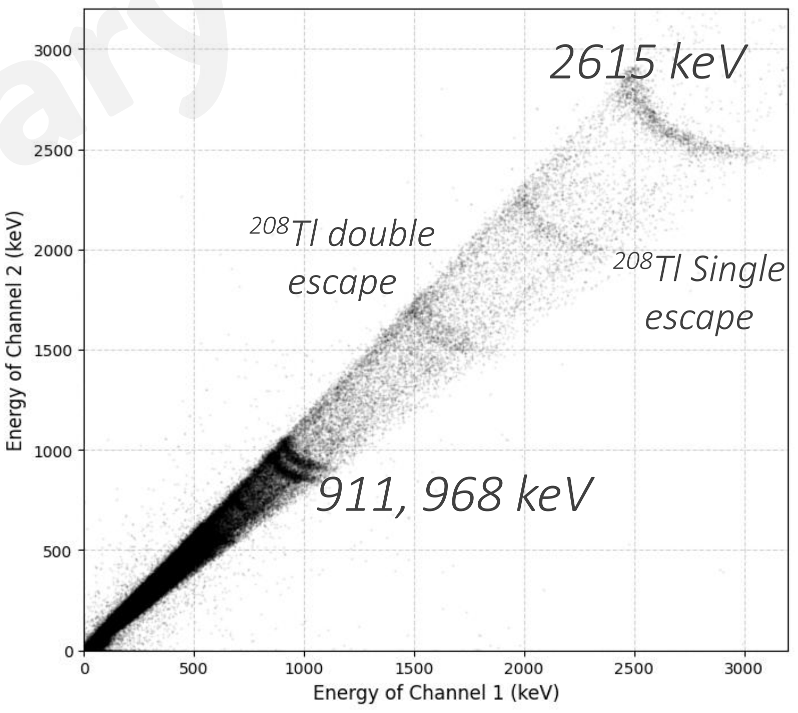
- Enrichment of 180Ta
  - ^{180m}Ta is the rarest isotope (Natural abundance: 0.0123%)
  - Using thermal diffusion column -> 0.5% ~ 5% Enrichment (proposal)

- Optimization detector design
  - Geometry of absorber: considering the attenuation length (quasiparticle recombination) of Tantalum single crystal
  - Absorber thickness for enough detection efficiency (γ, IC): simulation
  - Energy resolution, threshold (Region Of Interest, ROI: 37.7, 39.5, 77.2 keV)

- A tantalum single crystal with 5N purity will be used in the next phase of the study.

Summary





- The R&D experiment investigating the decay of Ta-180 using a tantalum single crystal at cryogenic temperatures is currently ongoing.
- At the same time, we are also exploring alternative candidate absorber materials.

Back Up

Back Up

Amount needed

crystal	Enrich	Ta180	N_180	half-life	# of events	Bkg	DE	BG	sigma	Significance
g	%	g		year	/year	dru	keV	/year		
100	0.26	0.1994	6.6482E+20	1.00E+19	46.01	10	5	1825	42.7	1.08
100	0.5	0.3835	1.2785E+21	1.00E+19	88.47	10	5	1825	42.7	2.07
200	0.5	0.7671	2.557E+21	1.00E+19	176.94	2	5	730	27.0	6.55
732	0.012	0.0674	2.2461E+20	1.00E+18	155.43	2	5	2671.8	51.7	3.01

To discover 1×10^{19} year half-life, about 1 g with 0.5% enriched Ta-180 with 2 dru background is necessary.