Nuclear experiments at KoBRA and Y2L in Korea

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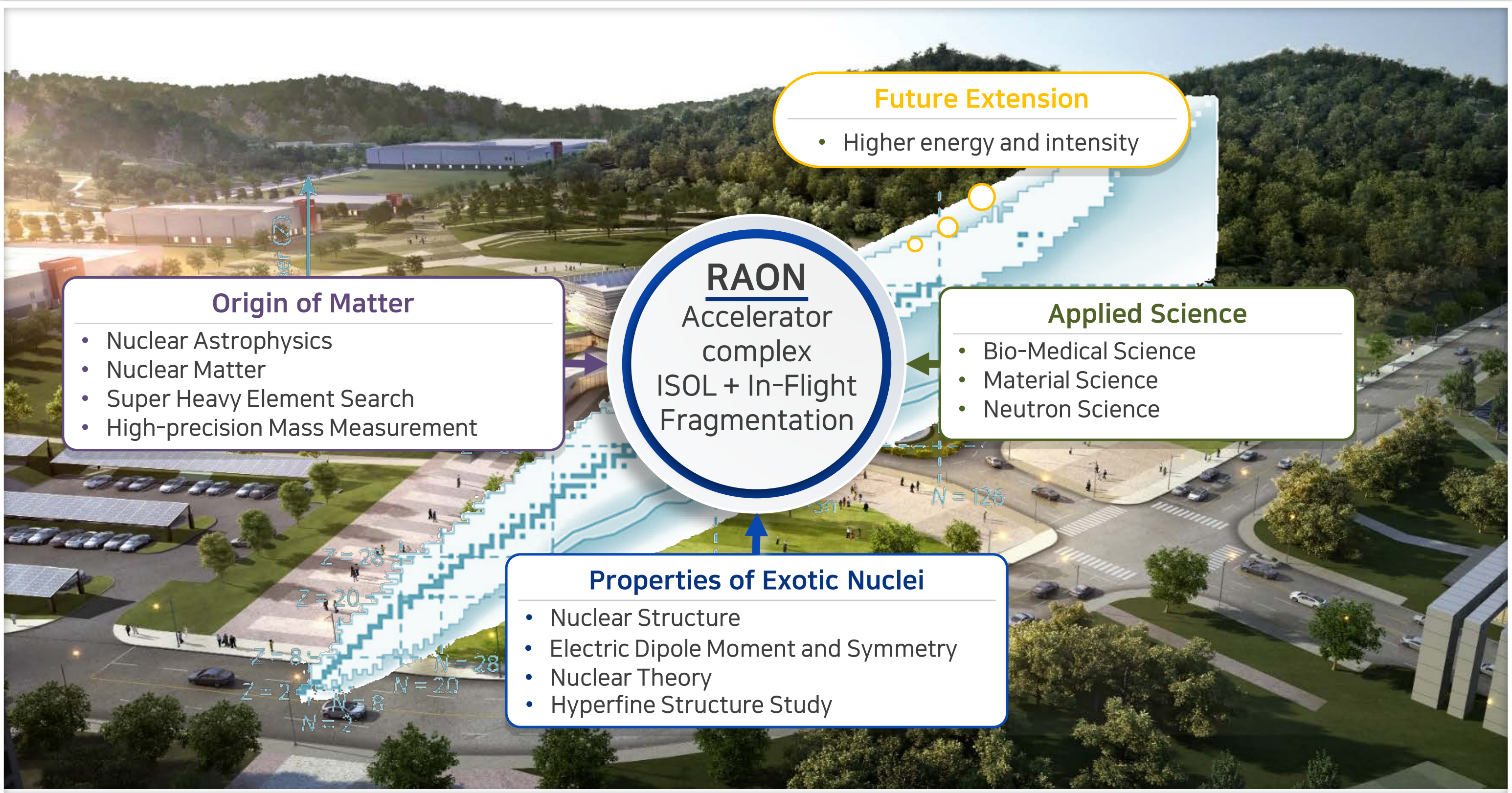
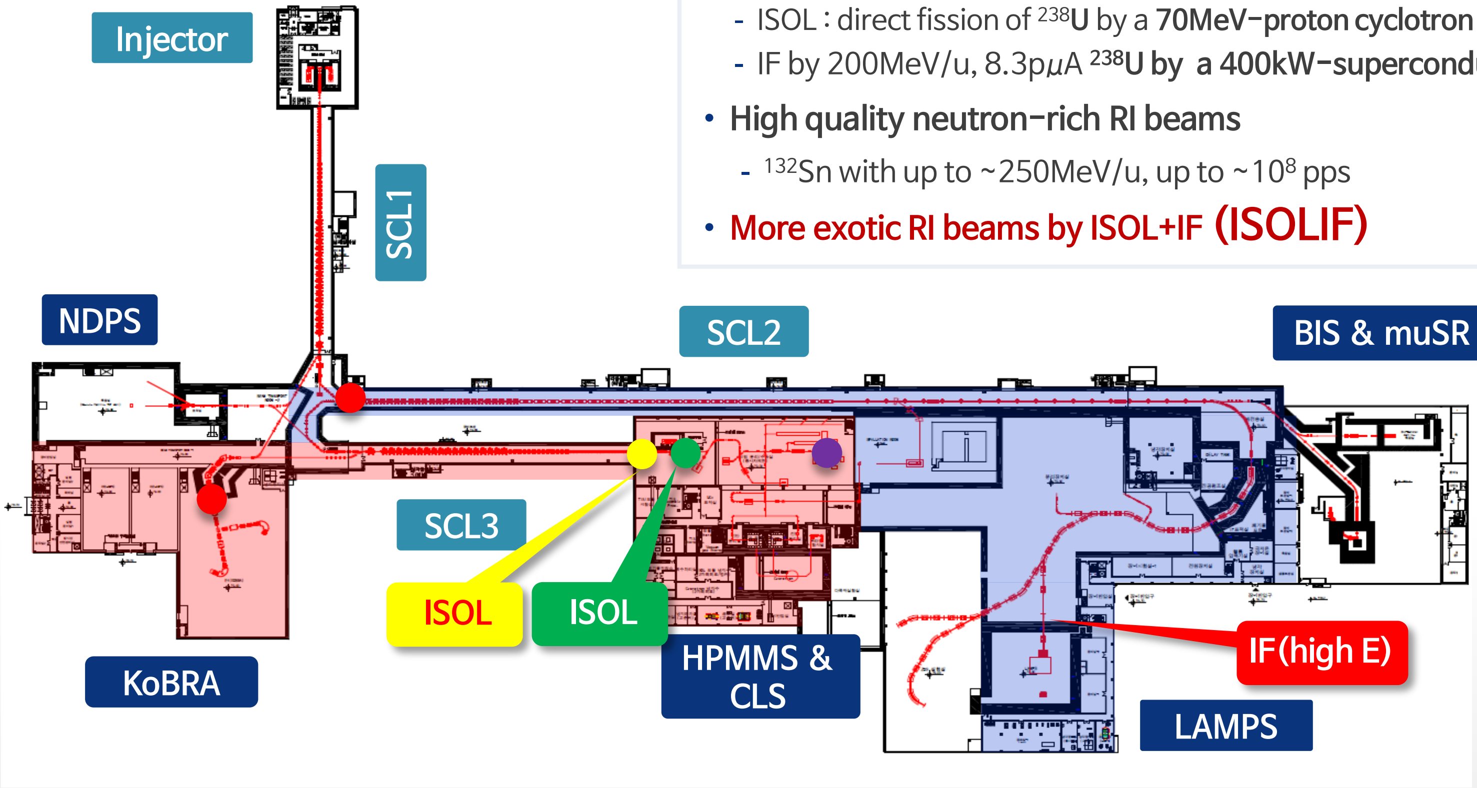
The next generation RI accelerator RAON

- **Goal: To build a rare isotope accelerator complex RAON for RI sciences in Korea**
  * RAON - Rare isotope Accelerator complex for ON-line experiments
- **Period: 2011.12 ~ 2021.12 (10.1 years)**



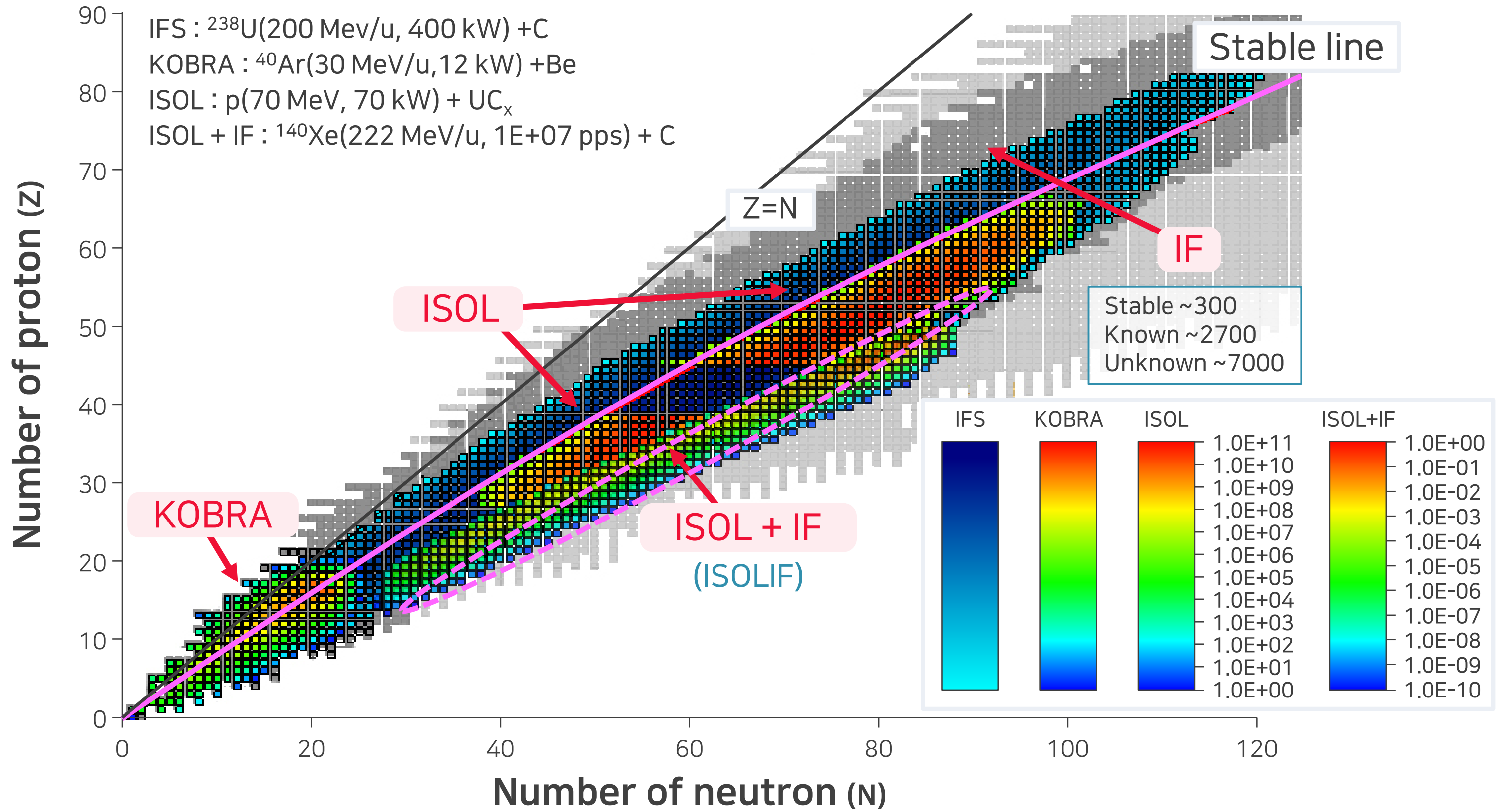
The RAON Facility

- High intensity RI beams by ISOL & IF
  - ISOL : direct fission of ^{238}**U** by a **70MeV-proton cyclotron** ~ 10^{14} f/s
  - IF by 200MeV/u, 8.3pμA ^{238}**U by a 400kW-superconducting LINAC**
- High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to ~10^{8} pps
- More exotic RI beams by ISOL+IF **(ISOLIF)**



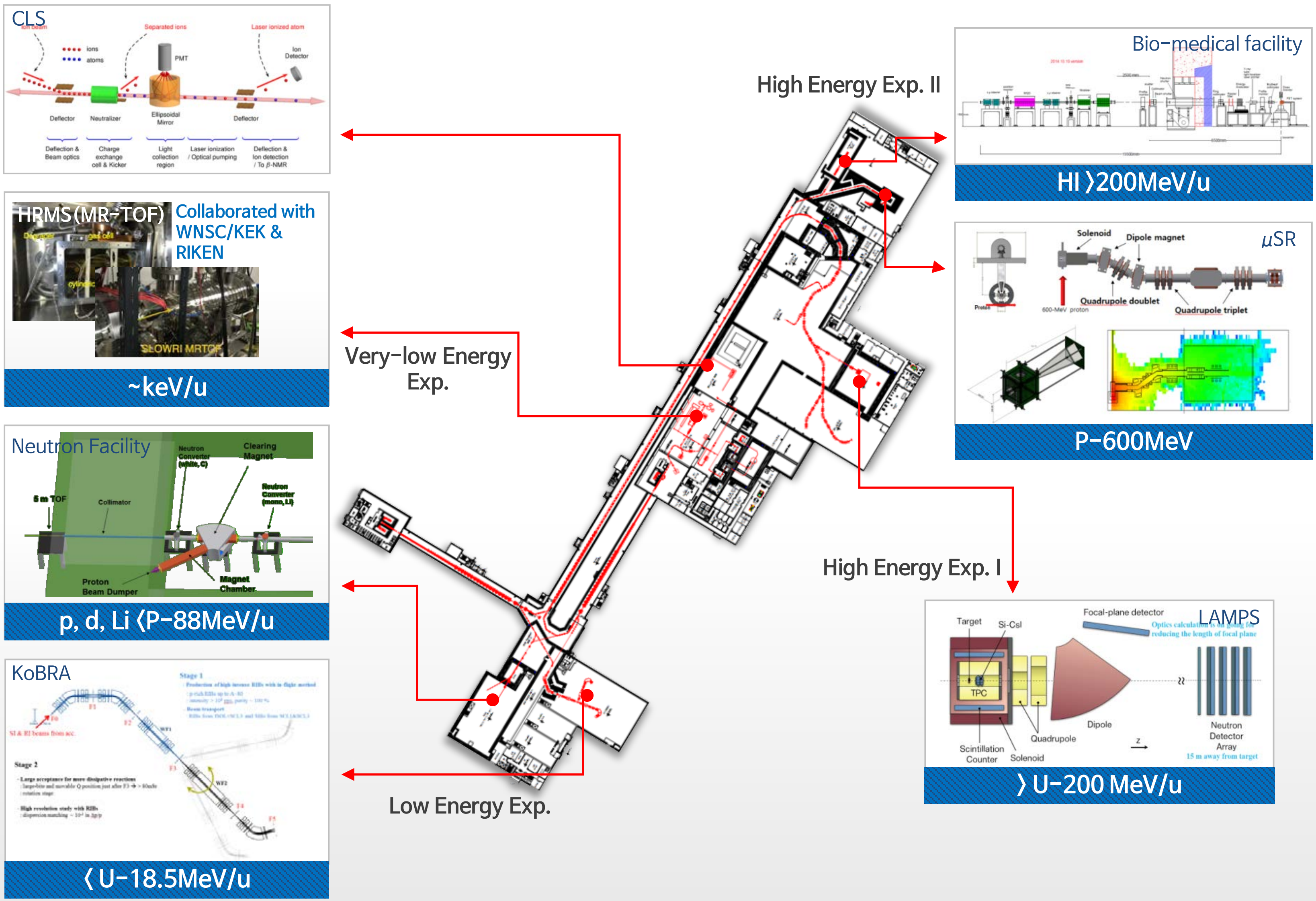
SCL1 has been decided to be pended
SCL3 is going to be taking a role of SCL1 in the early operation

Expected RIBs at RAON in nuclear landscape
Frontiers of RI nuclear physics



- RAON will provide access to unexplored regions of the nuclear chart !
- RAON will be a powerful RIBs' supplier to users globally
  → More exotic, more intense, and more varied RIBs for r-process and structure studies

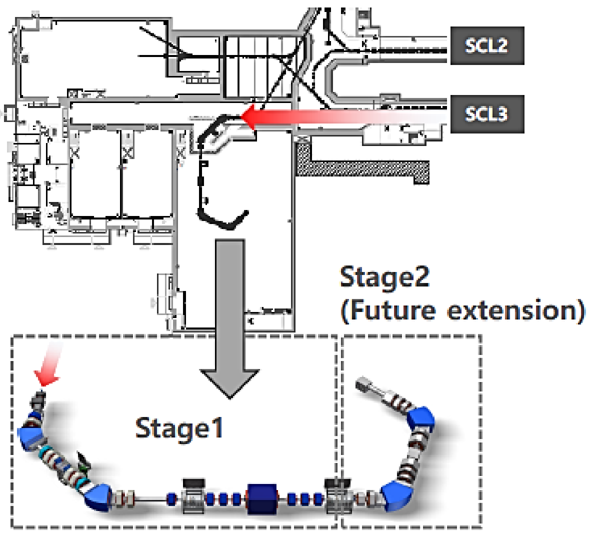
RAON Experimental Systems (7 Exp. Lab)

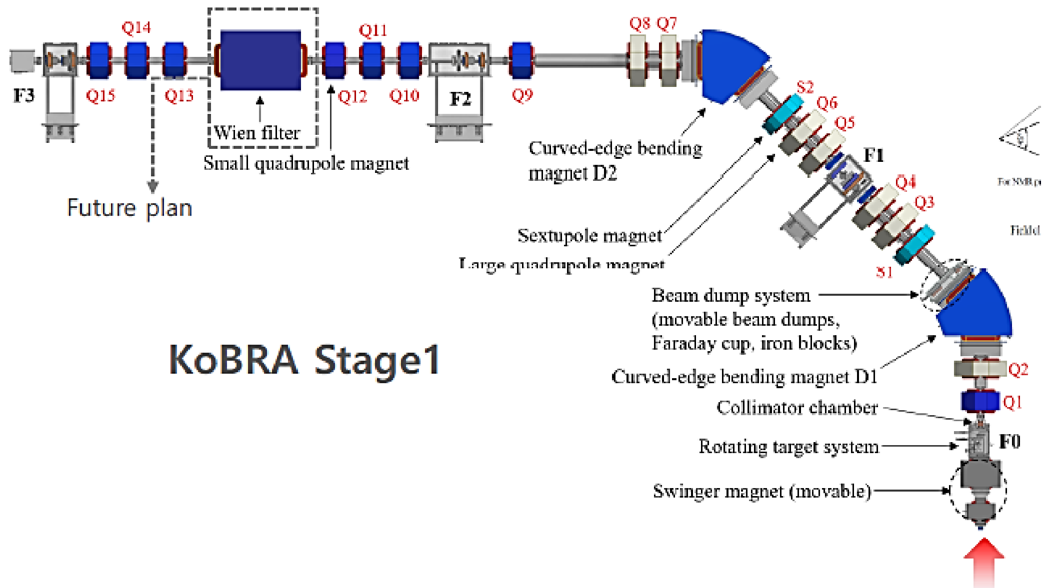


KoBRA

Facility – KoBRA (Korea Broad acceptance Recoil Spectrometer & apparatus)

- **KoBRA Stage1** (2021–2022) **will provide stable beams such as ^{16}O, ^{40}Ar**
  - To understand the origin of the chemical elements
  - Possible experiment: ^{16}O+^{9}Be, ^{16}O+^{12}C, ^{40}Ar+^{9}Be, ^{40}Ar+^{12}C reactions in the energy of 20–30 MeV/u
  - KoBRA experiments are related to RIKEN CRIB/RIBF





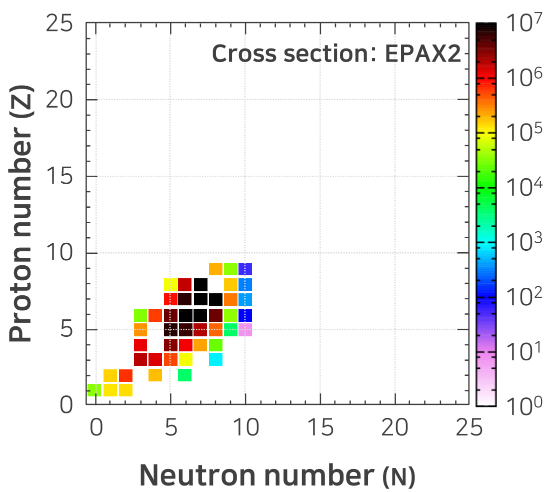
KoBRA Stage1

Anticipated early phase experiment: RIB production

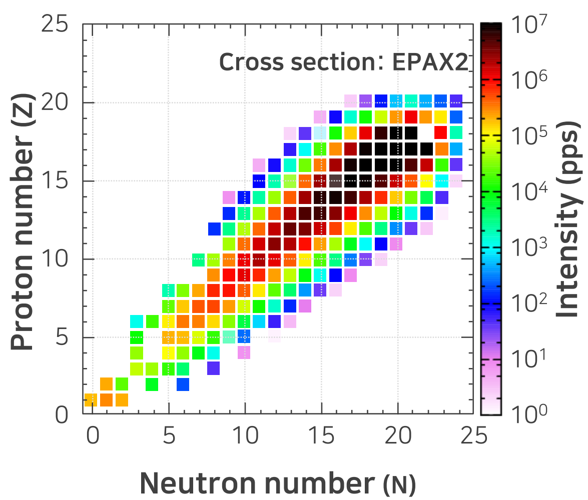
RI beam production via quasi-projectile-like fragmentation from ^{16}O or ^{40}Ar in the energy range of 20 – 30 MeV/u with a light mass target

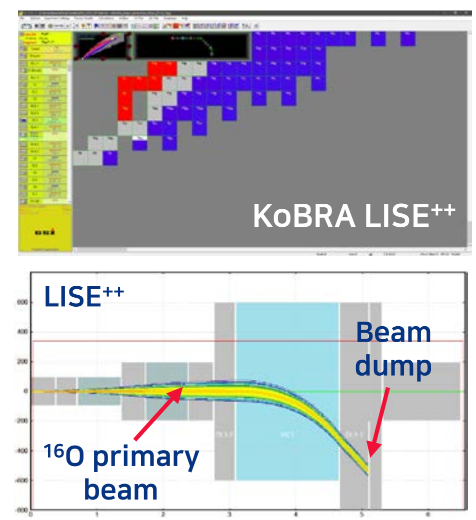
- We consider a measurement of the production cross section using commissioning beams, such as ^{16}O and ^{40}Ar, delivered from SCL3 with a ^{9}Be or ^{12}C production target, in the early part of 2021 due to the lack of production cross section data in the energy range of 20 - 30 MeV/u.
- We believe that such experiment can give us not only the commissioning results but also the some guide lines of available RI beams for the future experiments.

RI beam intensity for 100 pnA ^{16}O beam with 0.3 mm-thick ^{12}C target



RI beam intensity for 100 pnA ^{40}Ar beam with 0.3 mm-thick ^{12}C target





We distributed LISE++ file to domestic users. LISE++ is useful to easily understand spectrometer tuning for beginners and to presume the intensity of secondary beam.

Possible experiments using KoBRA

Facility – KoBRA (Korea Broad acceptance Recoil Spectrometer & apparatus)

- Candidate for early stage RIBs at KoBRA

^{18}F ($t_{1/2}$ = 109 min)

can be produced at **ISOL** facility

- High intensity a beam from the cyclotron and HfO_2 ISOL target
- Through the $^{16}O(\alpha,pn)^{18}F$ reaction
- $^{18}F(p,\alpha)^{15}O$ reaction (for the 330 keV resonance)

^{26g}Al ($t_{1/2} = 7.2\times10^5$ y)

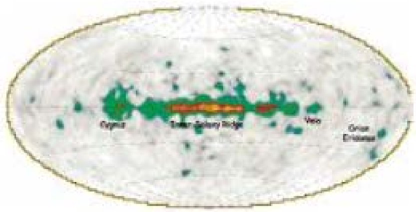
can be produced using **batch mode** sputter ion source

- Dry material sample
  - Dissolving in HCl
  - Compressed into a pellet
  - Cs sputter ion source
- $^{26g}Al(d,p)^{27}Al$ reaction (for 68- and 127 keV resonance)

^{29}P ($t_{1/2}$ = 4.142 s)

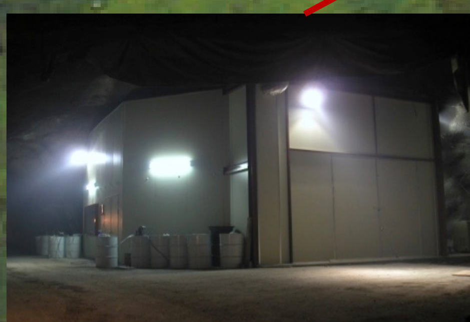
can be produced at **KoBRA**

- KoBRA, production mode
- ^{40}Ar primary beam on ^{9}Be target
- $^{29}P(d,p)^{30}P$ measurement for the $^{26}Al(p,\alpha)^{24}Mg$ reaction rate



Underground Physics Experiments at Y2L

YangYang (Y2L) Underground Laboratory



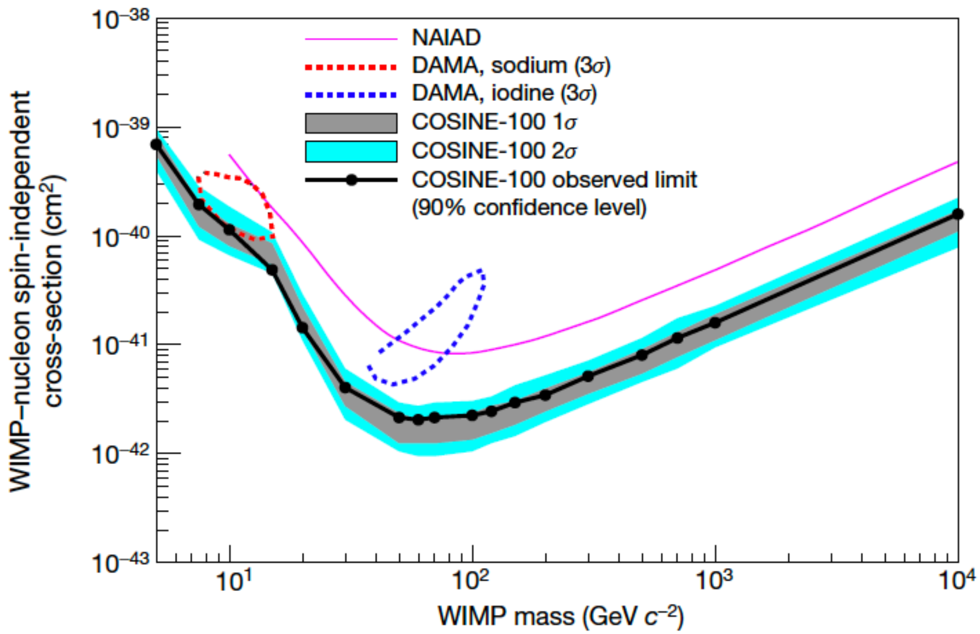
Center for Underground Physics IBS

- KIMS/COSINE (Dark Matter Search)
- AMoRE (Double Beta Decay Experiment)
- Minimum depth: 700 m/Access to the lab by car (~2km)

COSINE-100

Spin independent WIMP-nucleon cross section limit

Published in **Nature** Vol 564, 83, 2018
- First result constraining DAMA result with NaI crystals.



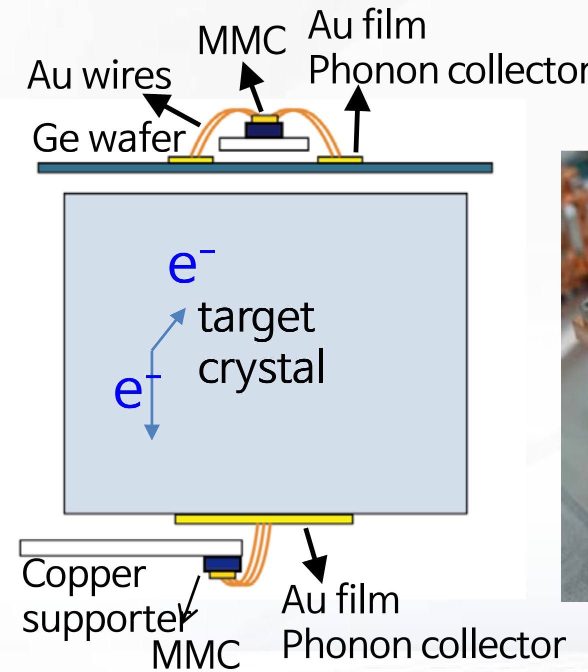
Result of spin-independent cross section

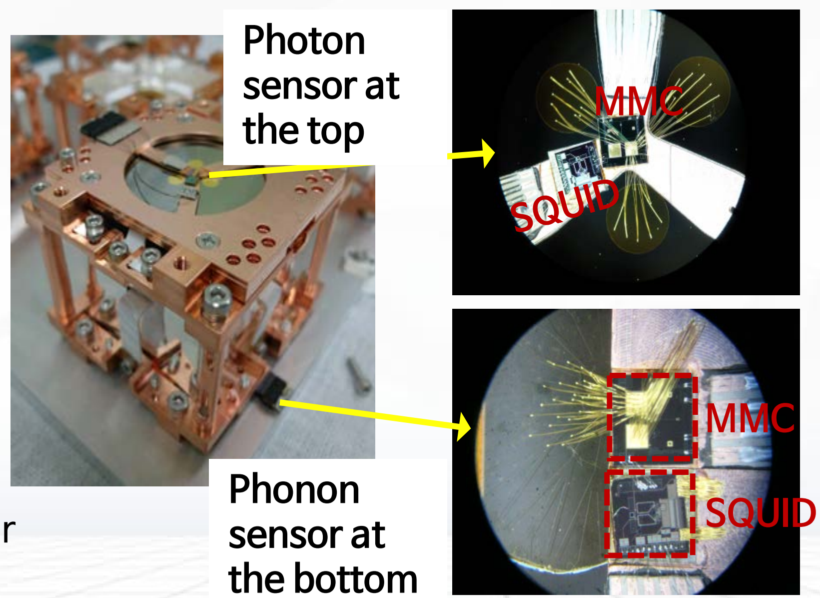
- COSINE-100 excludes DAMA/LIBRA-phase1's signal as spin-independent WIMP with Standard Halo Model in NaI(Tl)
- Consistent with null results from other direct detection experiments with different target media

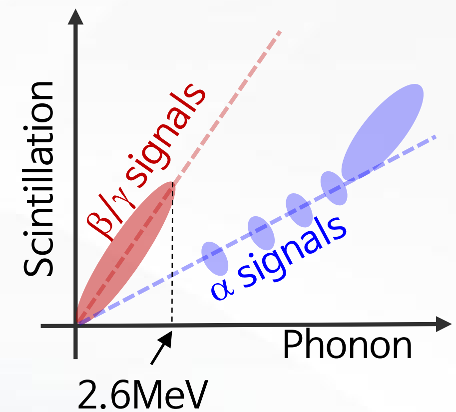
These results will generate tension for isospin violating models explaining DAMA along with null results from other experiments.

Principle of AMoRE detector

- Use Mo containing Scintillating Bolometer : $(^{40}Ca,X)^{100}MoO_4$ + MMC
- For Each crystal, phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal).





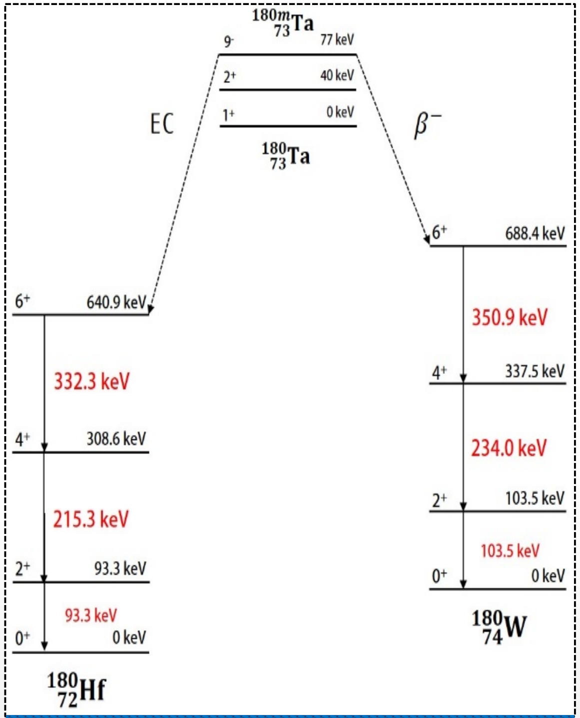


Decay of ^{180m}Ta using HPGe detectors at Y2L

Half-life of ^{180m}Ta

- **^{180m}Ta : one of the most interesting nuclei**
  - Natural tantalum : ^{181}Ta(99.988%), ^{180m}Ta(0.012%)
  - The heaviest long-lived odd-odd nucleus
  - Naturally occurring metastable isotope
  - Nucleosynthesis of ^{180m}Ta is still unsolved problem : because its process is bypassed by the main production for heavy nuclei such as r- or s- processes.

- **Half-life of ^{180m}Ta**
  - The half-life of the ground state of ^{180}Ta is 8.1 hours, but the half-life of ^{180m}Ta was never measured to date.
  - The latest half-life lower limit of ^{180m}Ta :
    - EC > 2.0×10^{17} years
    - β- decay > 5.8×10^{16} years [B.Lehnert, Phys Rev C **95** 044306 (2017)]
  - The purpose of this experiment is to get improved limit values for the half-life of ^{180m}Ta decay.

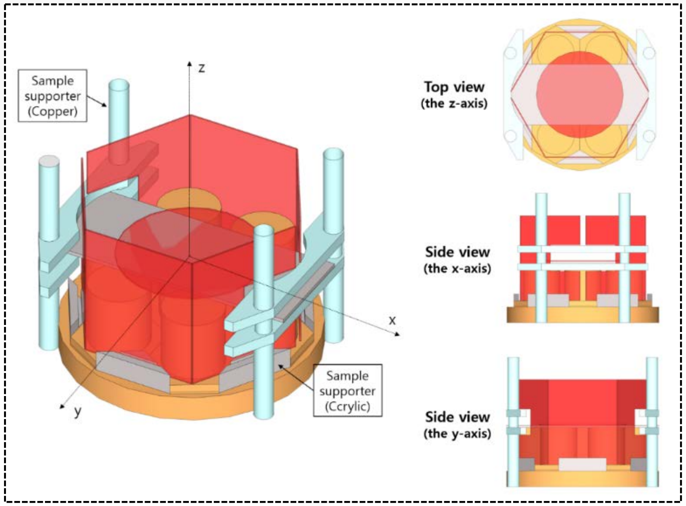


Decay scheme of ^{180m}Ta

Experimental setup

Experimental setup

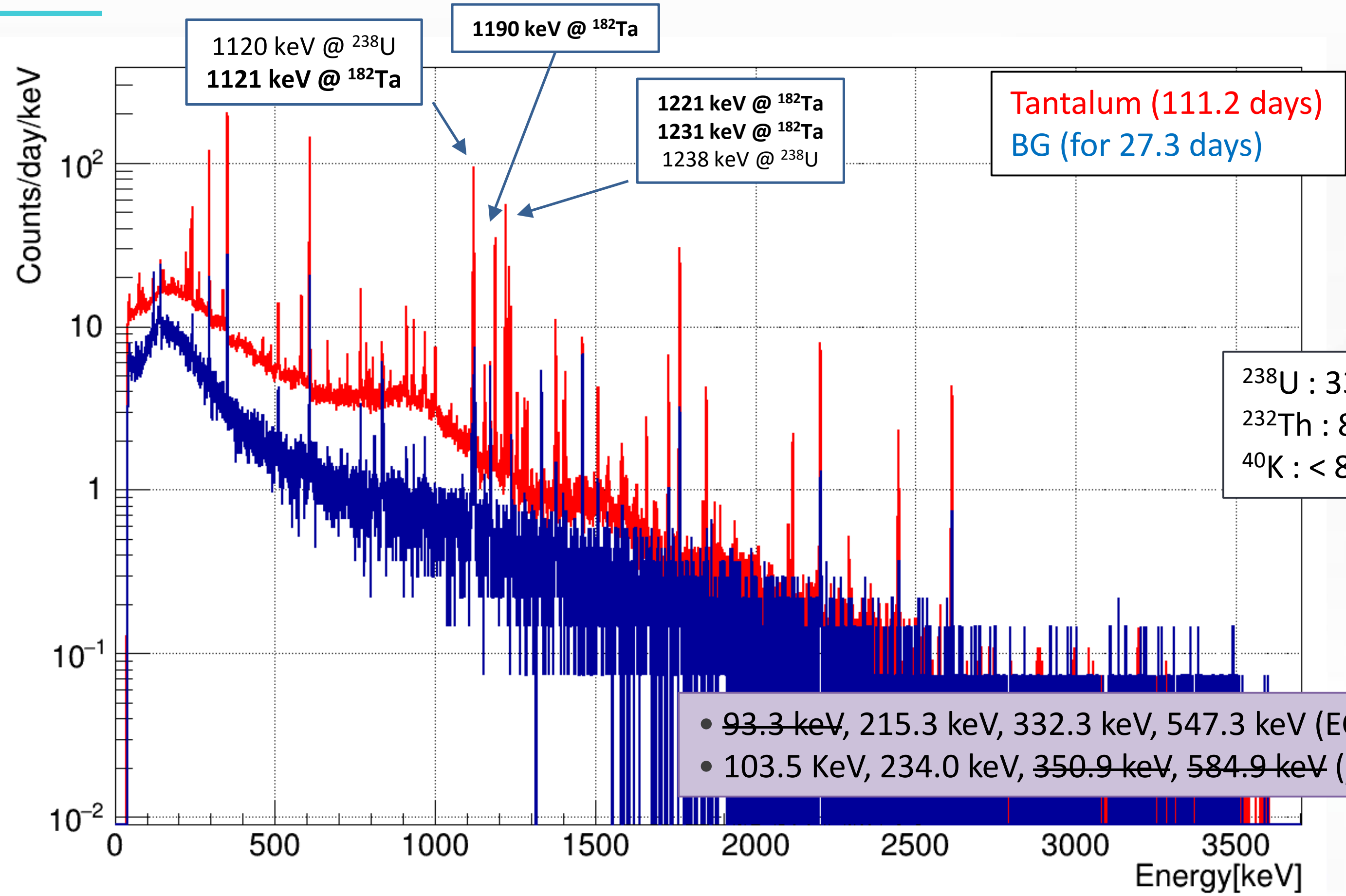
- **Sample (natural tantalum)**
  - A simulation study was conducted to determinate the sample configuration. (JKPS paper will be published in July)
  - The final sample configuration is composed of one central disk and six side panels (6.9 kg).
  - The tantalum sample was kept at underground with N_2 gas flushing for 2 months to reduce the ^{182}Ta level.



- **Run information**
  - Measurement period : 111.2 day

Data analysis: Single-hit

Data analysis : Single-hit



^{238}U : 33.0(66) mBq/kg
^{232}Th : 8.0(16) mBq/kg
^{40}K : < 8.1 mBq/kg

- ~~93.3 keV~~, 215.3 keV, 332.3 keV, 547.3 keV (EC)
- 103.5 KeV, 234.0 keV, ~~350.9 keV~~, ~~584.9 keV~~ (β- decay)

Data analysis: Single-hit result

Data analysis : Single-hit result

Mode	Energy (keV)	Counts rate (CPD)	Partial $T_{1/2}$ (year)	Lehnert
EC	215.3	2.19(44)	**> 1.45 x 10^{17}**	> 2.0 x 10^{17}
	332.3	< 1.13		
	547.6	< 0.39		
β- decay	103.5	< 0.76	**> 1.11 x 10^{17}**	> 5.8 x 10^{16}
	234.0	< 0.79		

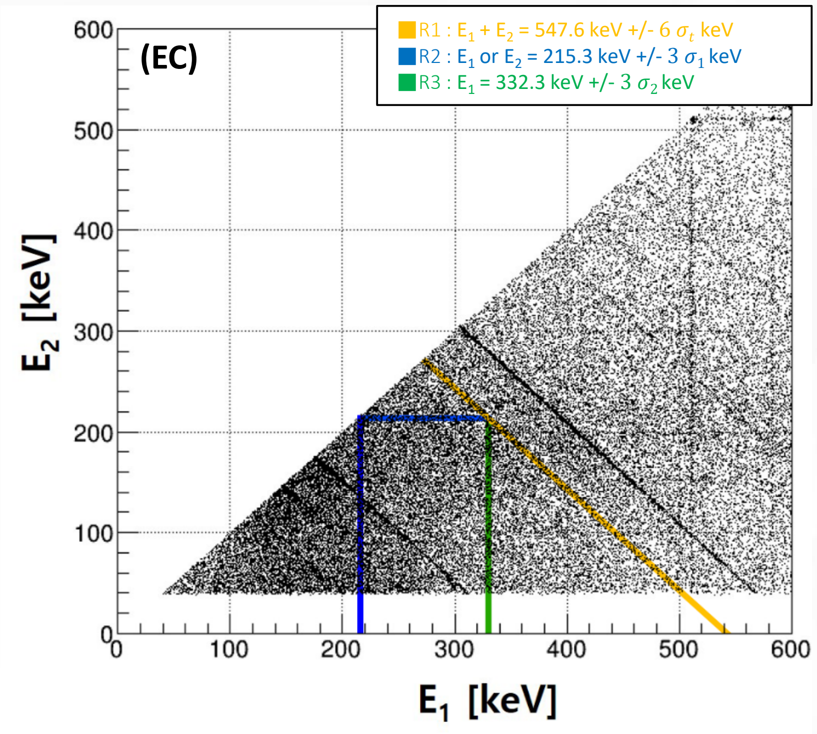
a = specific activity
N_A = Avogadro's number
NA = Natural abundance
$A_{r,Ta}$ = Atomic mass of tantalum

$$a = \frac{\ln 2 \times N_A \times \mathrm{NA}}{T_{1/2} \times A_{r,Ta}}$$

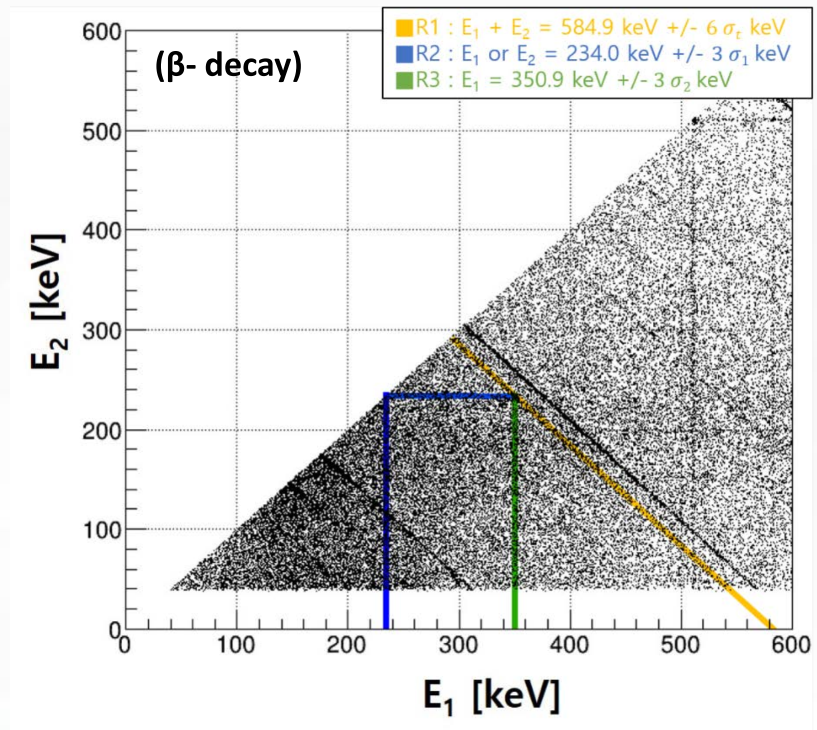
- 93.3 keV peak for EC could not be used for analysis because of 92.8 keV peak from ^{234}Th.
- 350.9 keV peak for **β- decay** could not be used for analysis because of **351.9 keV peak from ^{214}Pb**.
- 584.9 keV peak for β- decay could not be used for analysis because of **583.2 keV peak from ^{209}Tl**.

Data analysis: Double-hit histogram

Data analysis : Double-hit histogram



σ_1 = 0.681
σ_2 = 0.724
σ_t = 1.405

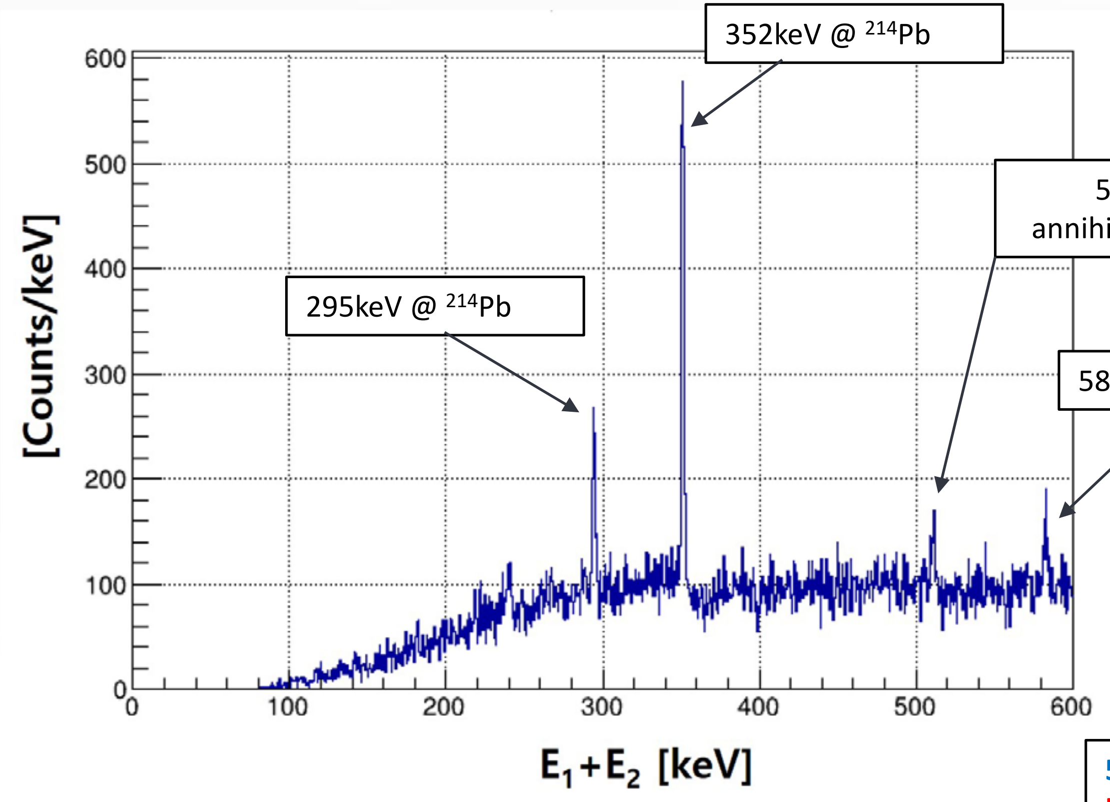


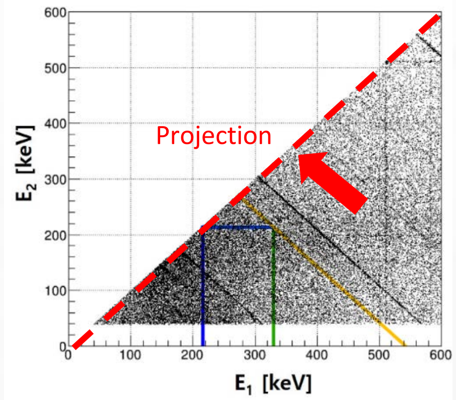
σ_1 = 0.688
σ_2 = 0.730
σ_t = 1.419

[2-Dim plot for 2 gamma coincidence (E_1, E_2)] * $E_1 > E_2$

Data analysis: (1) 1-Dim plot for R1

Data analysis : (1) 1-Dim plot for R1





548 keV @ EC -> 215 keV & 332 keV
584 keV @ β- decay -> 234 keV & 350 keV

Data analysis: Double-hit result

Data analysis : Double-hit result

Mode	Region	Counts rate (CPD)	Partial $T_{1/2}$ (year)	Lehnert
EC	R1	< 0.182	**> 3.67 x 10^{17}**	> 2.0 x 10^{17}
	R2	< 0.422		
	R3	< 0.428		
β- decay	R2	< 1.530	**> 3.17 x 10^{17}**	> 5.8 x 10^{16}
	R3	< 0.409		

a = specific activity
N_A = Avogadro's number
NA = Natural abundance
$A_{r,Ta}$ = Atomic mass of tantalum

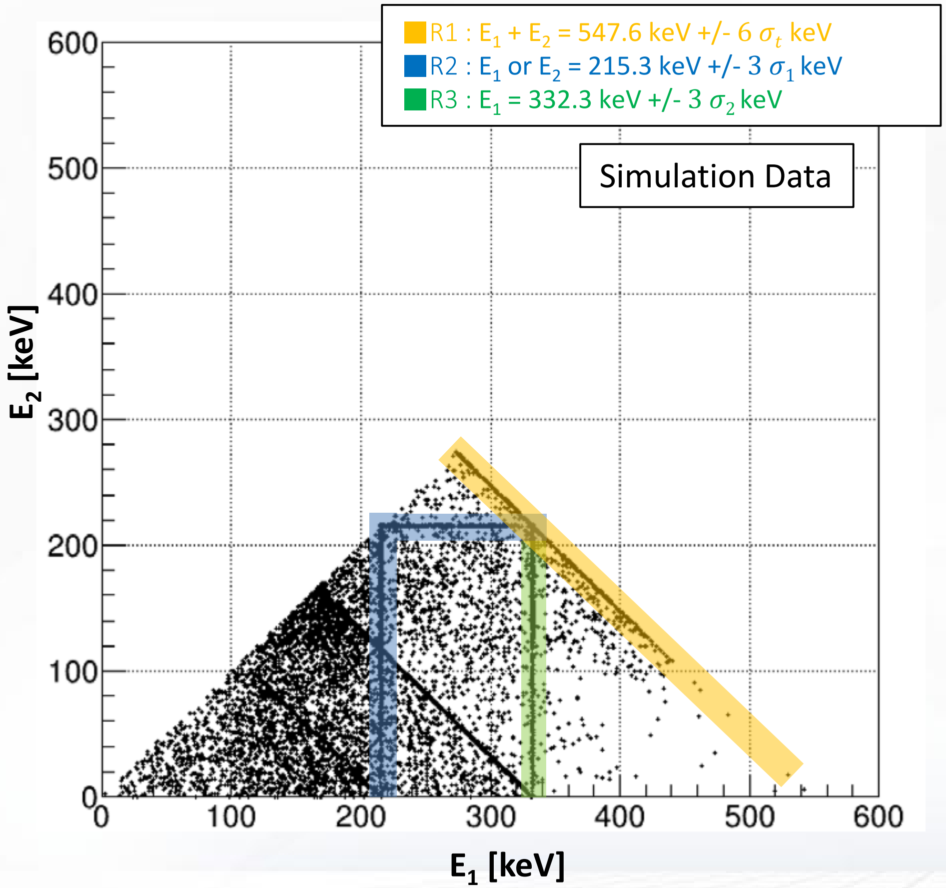
$$a = \frac{\ln 2 \times N_A \times \mathrm{NA}}{T_{1/2} \times A_{r,Ta}}$$

- R1 region for β- decay could not be used for analysis because of **583.2 keV** **peak from ^{209}Tl**.

Analysis method: Double-hit (EC)

Analysis Method : Double-hit (EC)

[gamma energies from EC]
215.3 keV, 332.3 keV

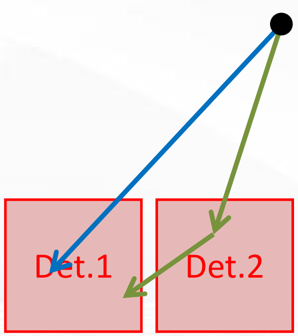


- coordinates of histogram (E1, E2)
  - Deposited energies of 2 gamma
  - E1 > E2

- Regions of histogram

  [R1]

  - E1 + E2 = 547.6 keV (215.3+332.3 keV)
  - 215.3 keV and 332.3 keV from EC
  - No energy loss
  - line? : Cross-talk



Result

Result

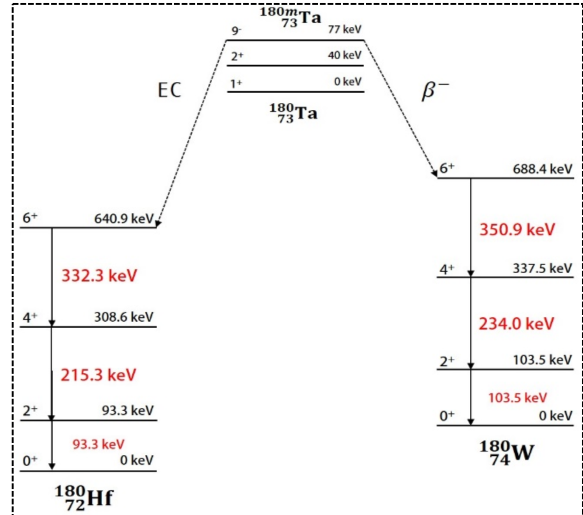
Mode	Partial $T_{1/2}$ (year)		Lehnert
	Single-hit	Double-hit	
EC	**> 1.45 x 10^{17}**	**> 3.67 x 10^{17}**	> 2.0 x 10^{17}
β- decay	**> 1.11 x 10^{17}**	**> 3.17 x 10^{17}**	> 5.8 x 10^{16}

- We could not find peaks of interest from ^{180m}Ta decay and only get the limit values.
- We obtained improved half-life for β- decay mode compared to Lehnert's result.
- A longer measurement time is required because more statistics are needed to find peaks. We have devised a plan for the second run to improve our first result of the tantalum measurement.

Decay of ^{180m}Ta using HPGe detectors at Y2L

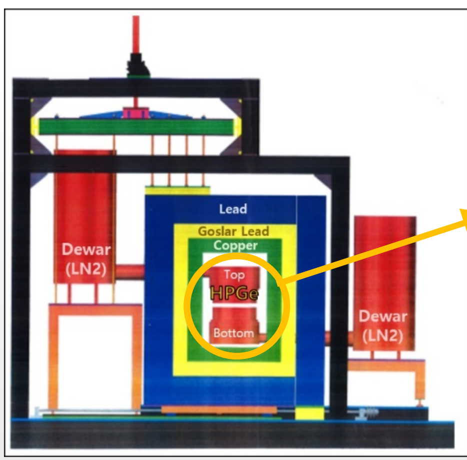
Half-life of ^{180m}Ta

- ^{180m}Ta: one of the most interesting nuclei
  - Natural tantalum: ^{181}Ta (99.988%), ^{180m}Ta (0.012%)
  - Nucleosynthesis of ^{180m}Ta is still unsolved problem
- Theoretical estimations
  - EC: 1.4×10^{20} yr $\beta-$ decay: 5.4×10^{23} yr
- Best experimental limits to date
  - EC: 〉 2.0×10^{17} yr $\beta-$ decay: 〉 5.8×10^{16} yr



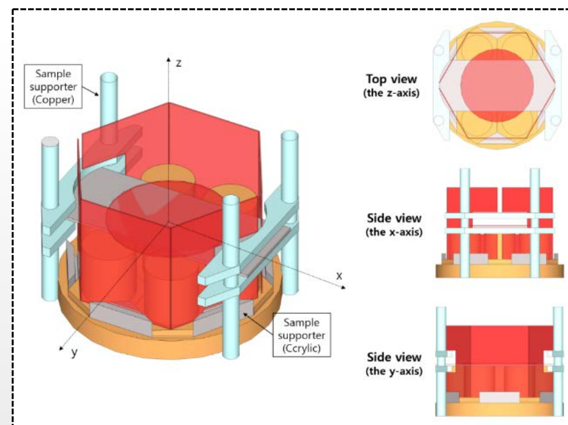
Decay scheme of ^{180m}Ta

CAGe: Array of 14 HPGe detectors



CAGe system

CAGe



Tantalum sample for measurement

[Experiment Ⅱ]

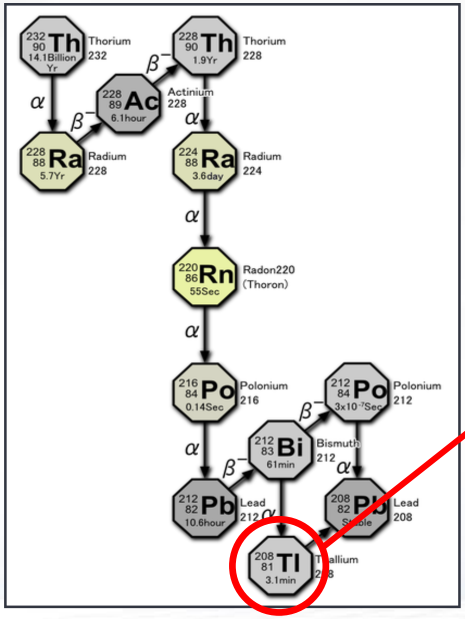
Measurement for gamma transitions of the $^{208}Pb^*$ (CC1)

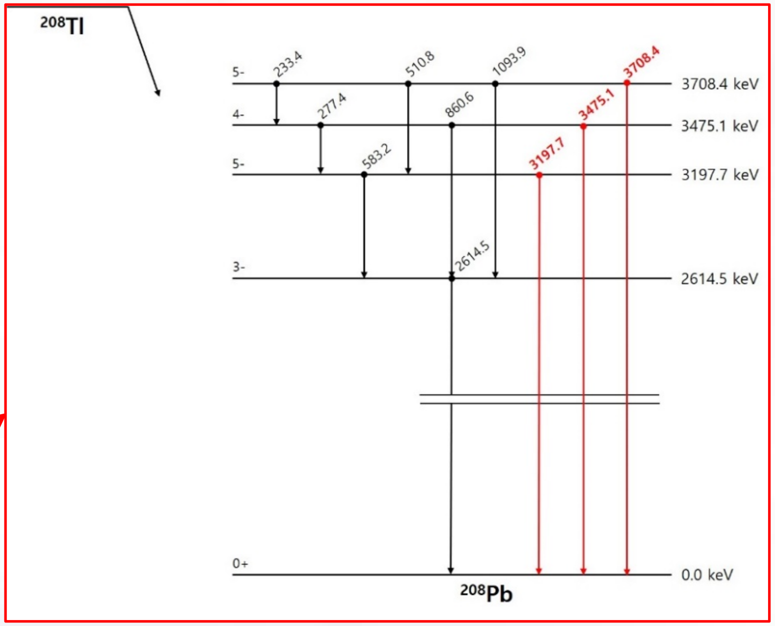
Measurement for gamma transitions of the $^{208}Pb^*$

Experimental concept

Energy (keV)	3198	3475	3708
BR (%)	< 0.007*	< 0.003*	< 0.004*

- ThO_2 powder measurement using an HPGe detector to identify unknown branching ratios of gamma transitions.
- Transitions of interest : 3197.7 keV, 3475.1 keV, and 3708.4 keV gamma transitions in excited states of ^{208}Pb, after the ^{208}Tl decay.





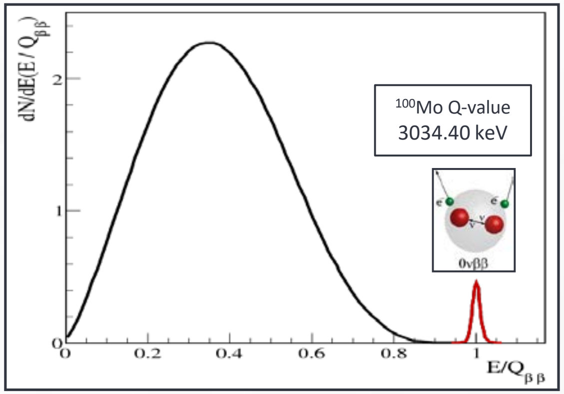
Motivation

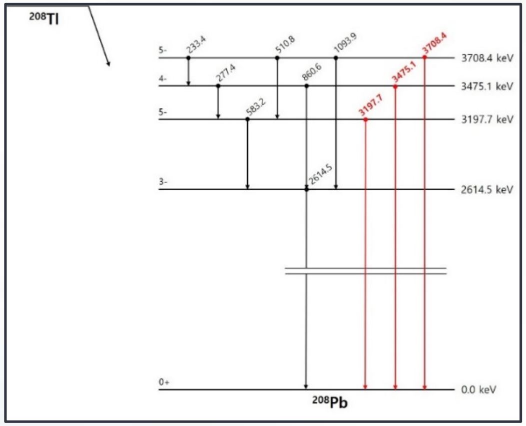
Motivation : Background study for 0νββ experiments

- **0νββ**
  - Most Q values of **0νββ** decay are less than 3.1 MeV.
  - Ex : ^{100}Mo (Q=3034 keV) is an ideal candidate for the 0νββ search because most background events from gamma emissions are below 2700 keV.
  - ^{208}Tl decay Q value = 4999 keV -> a main background for the 0νββ decay experiment.
- **Gamma transitions with E > 3 MeV from the ^{208}Tl decay**

Energy (keV)	3198	3475	3708
BR (%)	< 0.007*	< 0.003*	< 0.004*

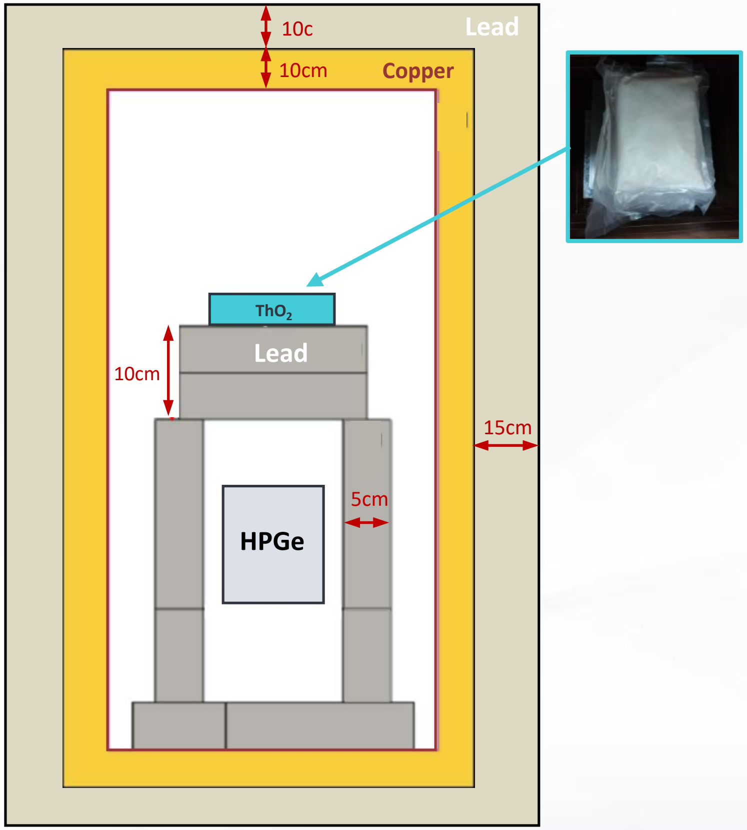
  - Gamma intensities with E > 3 MeV are not known.
  - The current limits are **not** negligible for zero background experiment.



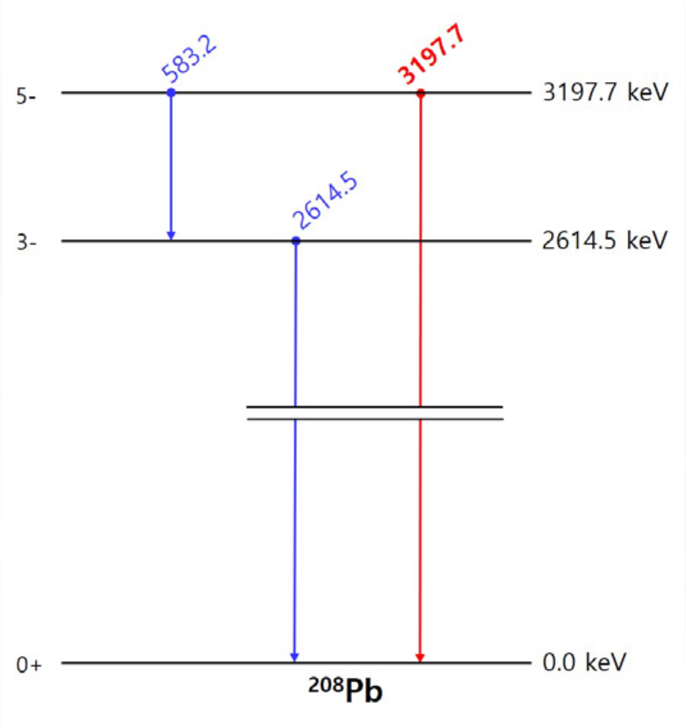


* NNDC database, S. I. Vasil'ev et al., Instruments and Experimental Techniques 49, 34 (2006).

Experimental setup



▲[HPGe detector structure & sample set up]

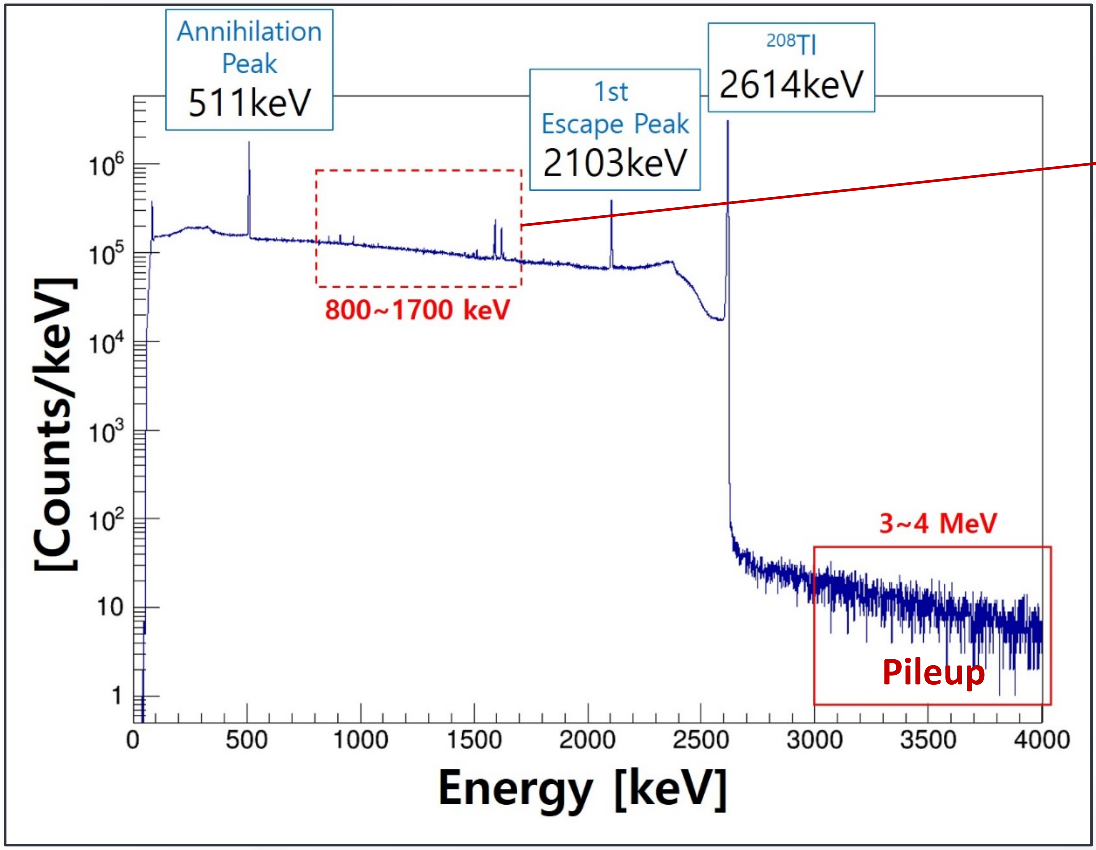


[ex] 3198 keV peak

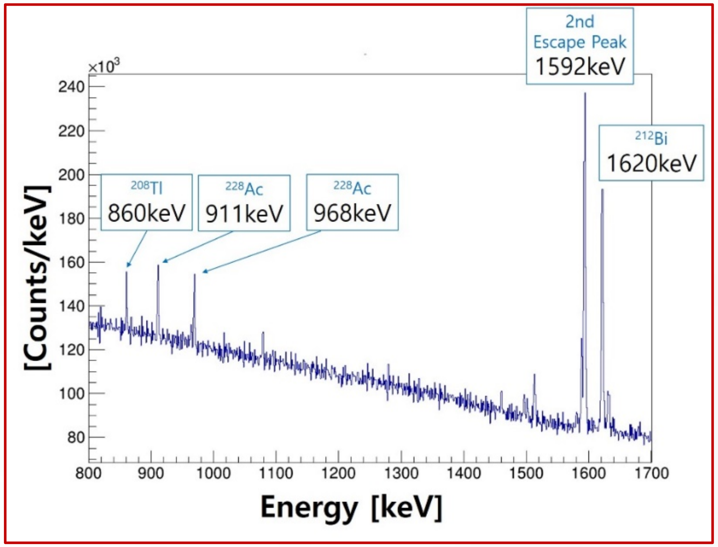
(1) Coincidence with 583 keV and 2614 keV gamma rays

(2) 3198 keV gamma transition

Data analysis : Energy histogram (39.5 days)



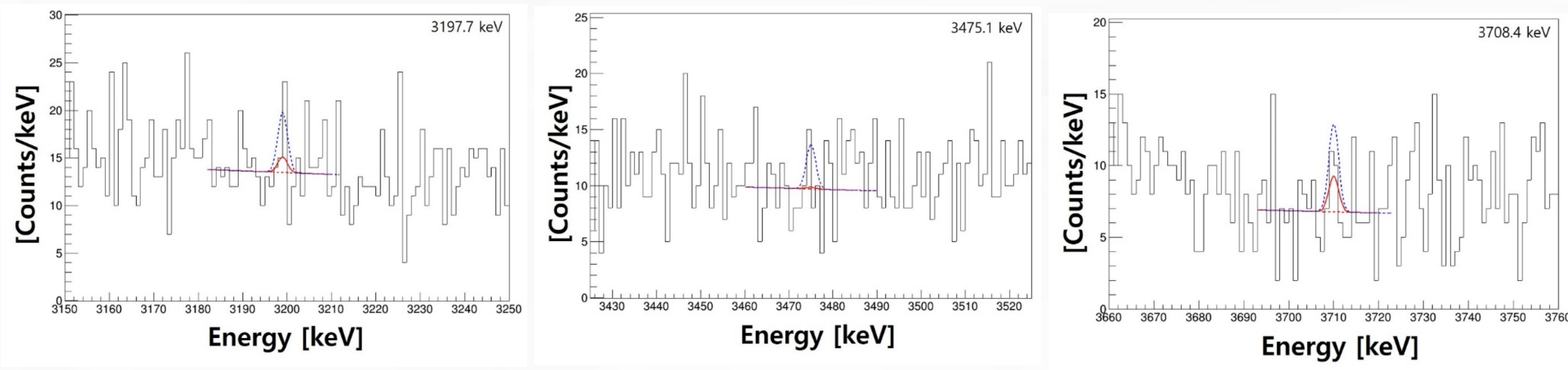
▲ [Energy histogram / 1keV bin]



- Peaks with E < 600 keV were not founded except 511 keV caused by 10cm lead.
- Pileup events make background at E > 3 MeV regions

Data analysis : Peak fitting

– Best-fit curve
– Limit estimation curve (90% C.L.)

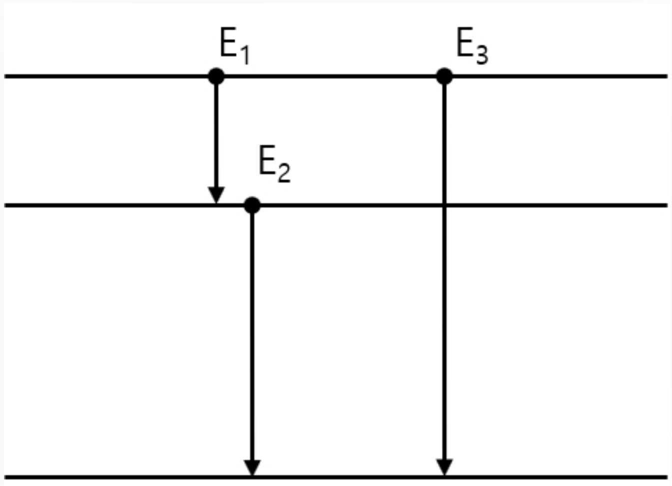


Energy (keV)	Count rate (CPD)
3198	< 0.38
3475	< 0.31
3708	< 0.33

Result: Equation

Result : Equation

$N_{3'}$ = E_3 peak counts
N_{decay} = Total number of decay
I_i = transition intensity(BR)
E_i = detection efficiency for i keV peak



$E_1 + E_2$ = coincidence

Energy (keV)	Efficiency
3198	5.95(60)E-06
3475	5.85(59)E-06
3708	5.40(54)E-06

- BR(I) calculation

$$N_{3'} = N_{decay} \times (\underbrace{\boxed{I_3 \times \varepsilon_3}}_{\text{E3 transition}} + \underbrace{\boxed{\cancel{I_1 \times \varepsilon_1 \times I_2 \times \varepsilon_2}}}_{\text{E1+E2 coincidence}})$$

$$\rightarrow \quad I_3 = \frac{1}{\varepsilon_3} \times \left(\frac{N_{3'}}{\boxed{N_{decay}}}\right)$$

- **Calculation for ^{208}Tl decay**

$$\boxed{N_{^{208}Tl}} = \frac{N_{2615}}{\varepsilon_{2615} \times I_{2615}}$$

$$\rightarrow \quad I_3 = \frac{N_{3'} \times \varepsilon_{2615} \times I_{2615}}{\varepsilon_3 \times N_{2615}}$$

Result

Result

Energy (keV)	BR (%)		
	NNDC	**This work**	Theoretical estimation
3198	< 7E-03	**< 1.6E-04**	< 6.43E-07
3475	< 3E-03	**< 1.3E-04**	< 6.52E-10
3708	< 4E-03	**< 1.5E-04**	< 1.25E-12

Improved measurement of gamma branching ratios for ^{208}Pb with $E_\gamma > 3$ MeV

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In the nuclear fusion reaction study, the branching ratios of gamma transitions are important inputs for the the coupled-channel equations. Pb is a widely used heavy target for the fusion reaction of halo nuclei study. The properties of ^{208}Pb such as excitation energies, spins, and parities of the ground and excited states are well known. However, the gamma ray transitions of $E_\gamma > 3$ MeV from the excited states to the ground state in ^{208}Pb have never been observed. We conducted a measurement to search these gamma transitions, specifically, peaks at 3197.7 keV, 3475.1 keV, and 3708.4 keV, which are emitted from the 2nd, the 3rd, and the 4th excited states in ^{208}Pb, respectively. A 2kg ThO_2 powder was measured with a 100% efficiency HPGe detector for 39.5 days in an underground laboratory in Yangyang, Korea. We obtained more precise upper-limit values than the previous results by controlling the background events better. The new values for the 3197.7 keV, 3475.1 keV, and 3708.4 keV gamma branching ratios through this experiment are < 0.00016%, < 0.00013%, and < 0.00015%, respectively. These upper-limits are at least a factor of 20 better than the previously reported measurements.

- Current intensities are from the NNDC database. (S. I. Vasil'ev *et al*)
- Our result are at least 20 times lower than current results.
- With this improved upper-limit numbers, the zero-background experiments are not effected from the gamma transitions with E > 3 MeV from the ^{208}Tl decay.

Conclusion

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- Two rare decay experiments using HPGe detectors were conducted in Y2L.

- Decay of ^{180m}Ta

  - We measured 6.9 kg tantalum sample using CAGe to identify the half-life of ^{180m}Ta

  - We obtained improved half-lives for each decay mode (EC, beta-) as following.

Energy (keV)	Partial $T_{1/2}$ (year)	
	Lehnert	**This work**
EC	> 2.0 x 10^{17}	**> 3.67 x 10^{17}**
Beta-	> 5.8 x 10^{16}	**> 3.17 x 10^{17}**

  - The result of this experiment will be submitted to PRC.

Conclusion

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- Two rare decay experiments using HPGe detectors were conducted in Y2L.

- **Rare transitions in excited states of ^{208}Pb**

  - We measured 2kg ThO_2 powder using a single HPGe detector to identify branching ratios for 3198 keV, 3475 keV, and 3708 keV gamma transitions from excited states in ^{208}Pb, after the ^{208}Tl decay.

- We obtained new upper-limit numbers for the three branching ratios, and our result are at least 20 time lower than current results.

- With this improved upper-limit numbers, the zero-background experiments are not effected from the gamma transitions with E > 3 MeV from the ^{208}Tl decay.

Energy (keV)	BR (%)	
	NNDC	This work
3198	< 7E-03	**< 1.6E-04**
3475	< 3E-03	**< 1.3E-04**
3708	< 4E-03	**< 1.5E-04**

Thank you very much
for everything!

We had a great time!!