The AMoRE

(Advanced Mo-based Rare process Experiment) :

Search for

Neutrinoless Double Beta Decay in ^{100}Mo

HyangKyu Park

On the behalf of AMoRE collaboration

Center for Underground Physics,

ibs (Institute for Basic Science), Korea

International Workshop on "Double Beta Decay and Underground Science"

RCNP, Osaka, Nov 8 - 10, 2016

AMoRE Collaboration

8 Countries
18 Institutions
~90 Collaborators

We are accepting collaboration.

AMoRE Experimental Strategy

For sizeable background case;

$$T_{1/2}^{0n}(\exp) = (\log 2) N_a \frac{a}{A} e \sqrt{\frac{MT}{b\mathrm{D}E}}$$

- Isotopic Abundance
- Detection Efficiency
- Detector Mass
- Time
- Atomic mass
- Background level (count/keV kg year)
- Energy Resolution

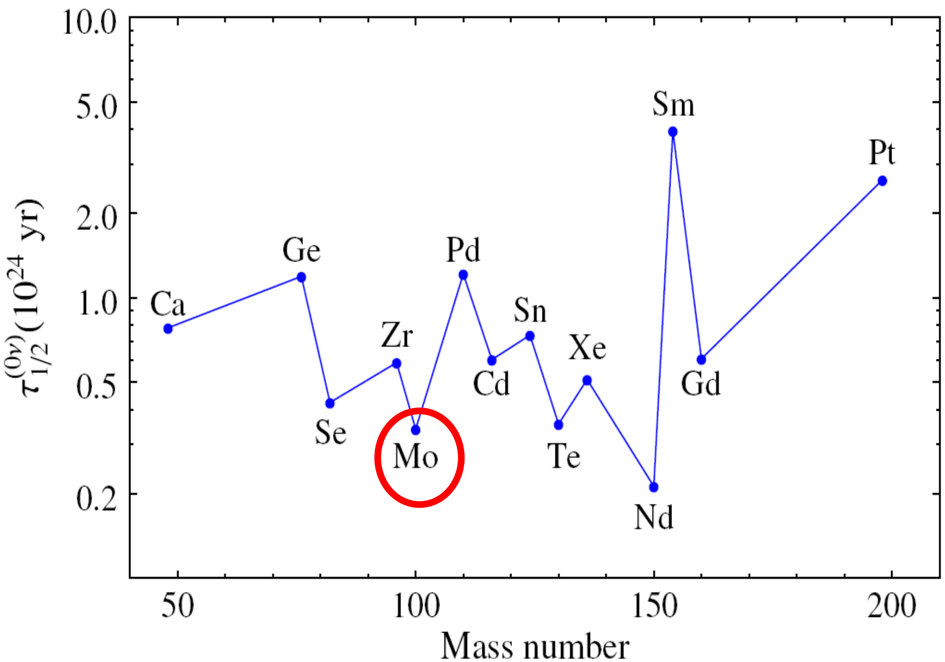
For "zero" background case;
No. of background events ~ O(1)

$$T_{1/2}^{0n}(\exp) = (\log 2) N_a \frac{a}{A} e \frac{MT}{n_{CL}}$$

The AMoRE is aiming to zero background.

Why we use ^{100}Mo for 0νββ search ?

- High Q-value (ββ) of 3034.40 (12) keV.
- High natural abundance of 9.7%.
- Relatively short half life (0νββ) expected from theoretical calculation.



Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

Candidate	Q (MeV)	Abund. (%)
^{48}Ca	4.271	0.19
^{76}Ge	2.040	7.8
^{82}Se	2.995	8.7
^{100}Mo	3.034	9.7
^{116}Cd	2.802	7.5
^{124}Sn	2.228	5.8
^{130}Te	2.533	34.1
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

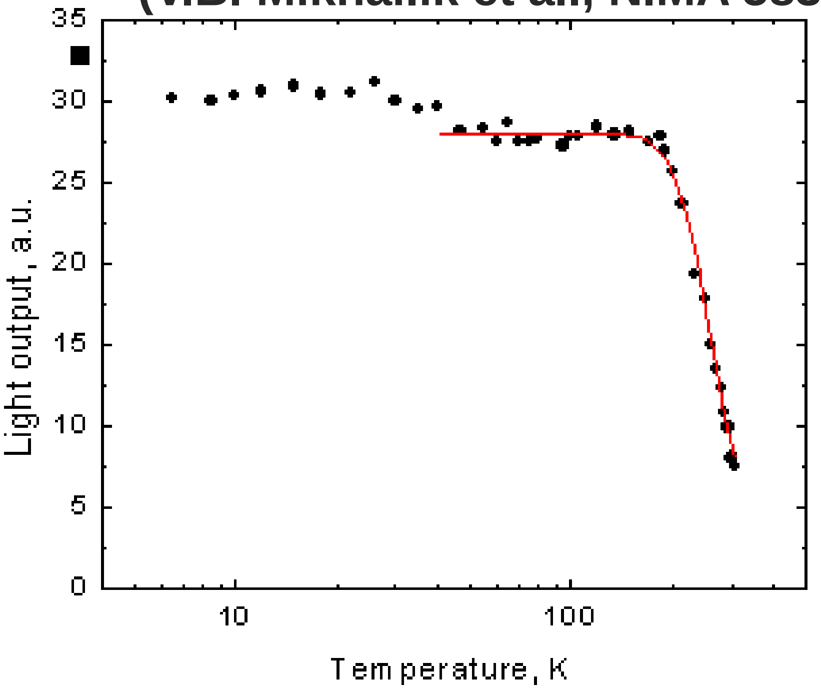
AMoRE Parameters

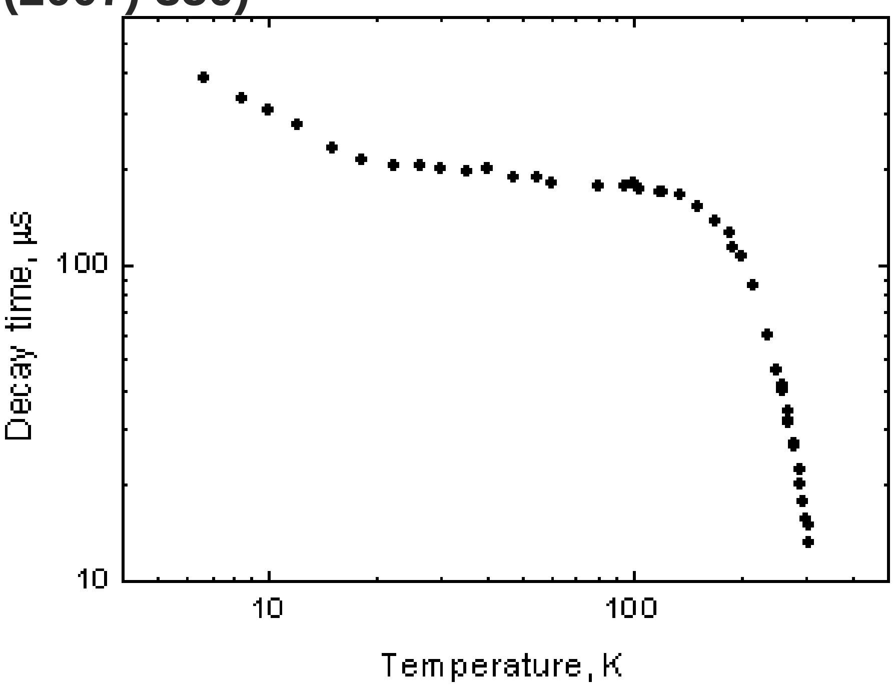
- **Crystals: $^{40}Ca^{100}MoO_4$**
  - ^{100}Mo enriched: > 95%
  - ^{48}Ca depleted: < 0.001% (N.A. of ^{48}Ca:0.187%)
- **Low temperature detector: 10 – 30 mK**
- **Energy resolution: 5 keV @ 3MeV**
- **The AMoRE Plan:**

	Pilot	Phase I	Phase II
Mass	1.5 kg	5 kg	200 kg
Bkg [keV ·kg· year]$^{-1}$	10^{-2}	10^{-3}	10^{-4}
$T_{1/2}$ Sensitivity [years]	~10^{24}	2.7x10^{25}	1.1 x 10^{27}
<$m_{\beta\beta}$ > Sensitivity [meV]	300-900	70-140	12-22
Location	Y2L (700 m depth)		New deeper Lab.
Schedule	2016~2017	2017 - 2019	2020 - 2025

Temperature dependence $CaMoO_4$ crystal

- **From RT to 7K, light yield is increased by factor of 6.**
  (V.B. Mikhailik et al., NIMA 583 (2007) 350)





- **CMO absolute light yield:**
  ~4,900 ph/MeV@Room Temp. **(H.J. Kim et al., IEEE TNS 57 (2010) 1475)**
  ~30,000 ph/MeV@Low Temp.

-> Highest light yield among Mo contained crystals.

^{100}Mo enriched & ^{48}Ca depleted materials

- **^{100}Mo isotope production:**
  - **ECP (Electrochemical plant), Russia**
  - **$^{100}MoO_3$ powder:**
    - **^{100}Mo Enrichment: ~ 95%**
    - **Impurities:**

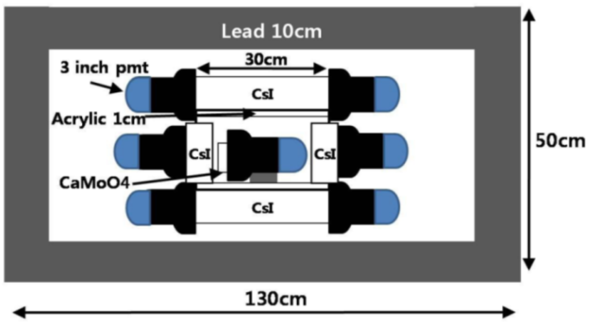
ICP-MS at CUP	U: ~ 0.2 ppb	Th: < ~0.05 ppb
HPGe at Y2L	^{226}Ra: 8.3 mBq/kg	^{228}Ac < ~1.0 mBq/kg

- **^{40}Ca with depletion of ^{48}Ca isotope production:**
  - **ELEKTROCHIMPRIBOR, Lesnoy, Russia**
  - **$^{40}CaCO_3$ powder:**
    - **- ^{48}Ca < 0.001%**
    - **- Impurities: U ≤ 0.1 ppb, Th ≤ 0.1 ppb, Sr = 1 ppm, Ba = 1 ppm**
      ^{226}Ra = 51 mBq/kg ^{228}Ac(^{228}Th) = 1 mBq/kg

Internal backgrounds of $^{40}Ca^{100}MoO_4$ crystals

4π CsI(Tl) active setup with Pb shielding at Y2L

4π gamma veto system



β–α decay in ^{238}U (164 μs)
^{214}Bi (Q-value : 3.27-MeV) → ^{214}Po (Q-value : 7.83-MeV)

α–α decay in ^{232}Th (145 ms)
^{220}Rn (Q-value : 6.41-MeV) → ^{216}Po (Q-value : 6.91-MeV)

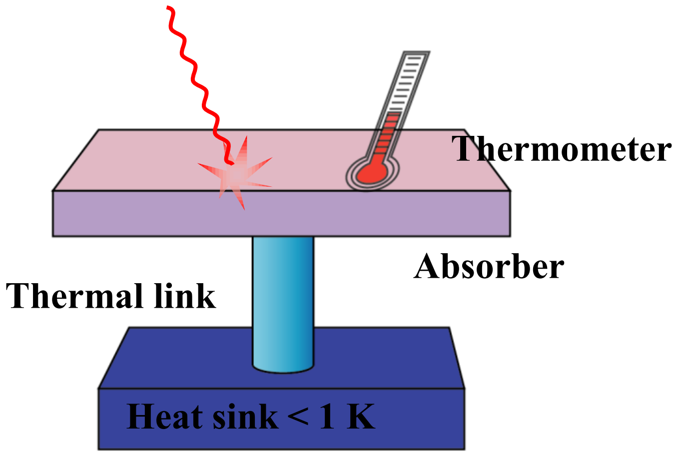
α–α decay in ^{235}U (1.78 ms)
^{219}Rn (Q-value : 6.23-MeV) → ^{215}Po (Q-value : 7.38-MeV

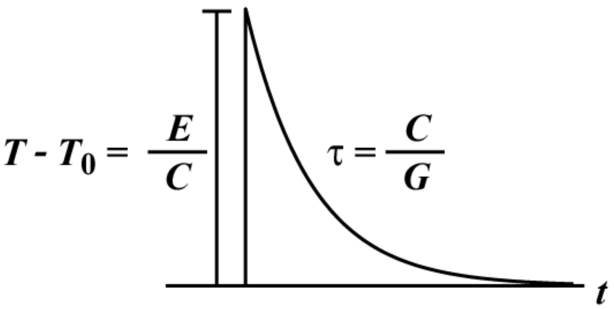
	U-238 chain (μB/kg)	U-235 chain (μB/kg)	Th-232 chain (μB/kg)
Crystals	Po-214	Po-215	Po-216
SS68	60±8	200±14	30±7
NSB29	200±14	700±26	80±9
S35	4400±66	1200±35	500±22
SB28	80±9	N/A	70±8
SE1	40±12	60±8	50±15

Note: 100 μBq/kg for ^{238}U, 50 μBq/kg for ^{232}Th decay chain for AMoRE-I

Low temperature detectors (Calorimeters)

Energy absorption → Temperature





Choice of thermometers

- **Thermistors (NTD Ge, doped Si)**
- **TES (Transition Edge Sensor)**
- **MMC (Metallic Magnetic Calorimeter)**
- **etc.**

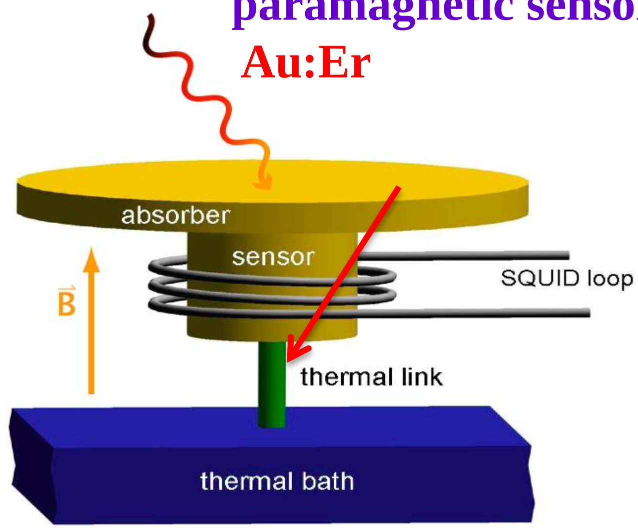
MMC (Metallic Magnetic Calorimeter)

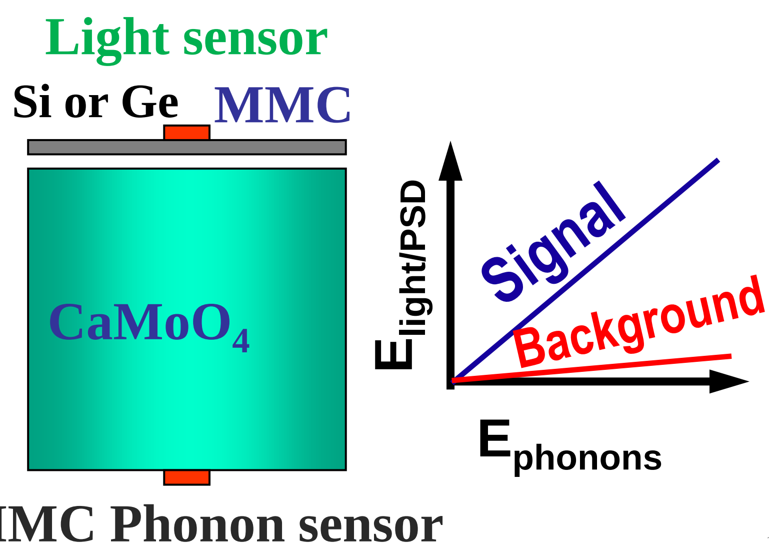
Principle of operation

1. Energy absorption in CMO crystal.
2. Phonon & Photon generation.
3. Temperature increase (gold film).
4. Magnetization of MMC decrease.
5. SQUID pickup the change.

Advantage of MMC

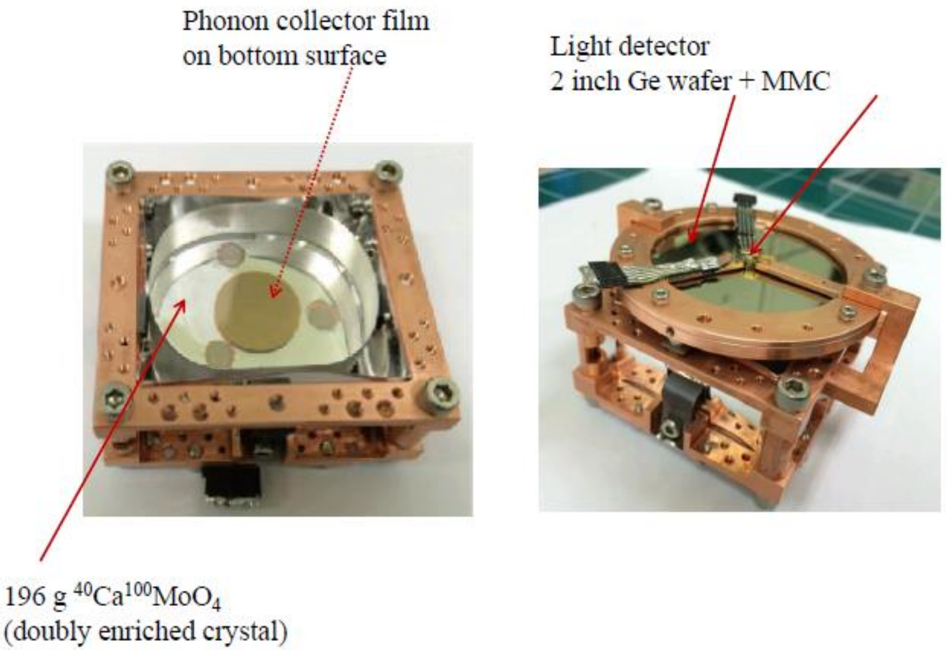
- Fast rising signal : ~0.5 ms (critical to reduce 2νββ random coincidence)
- Fairly easy to attach to absorber.
- Excellent Energy resolution



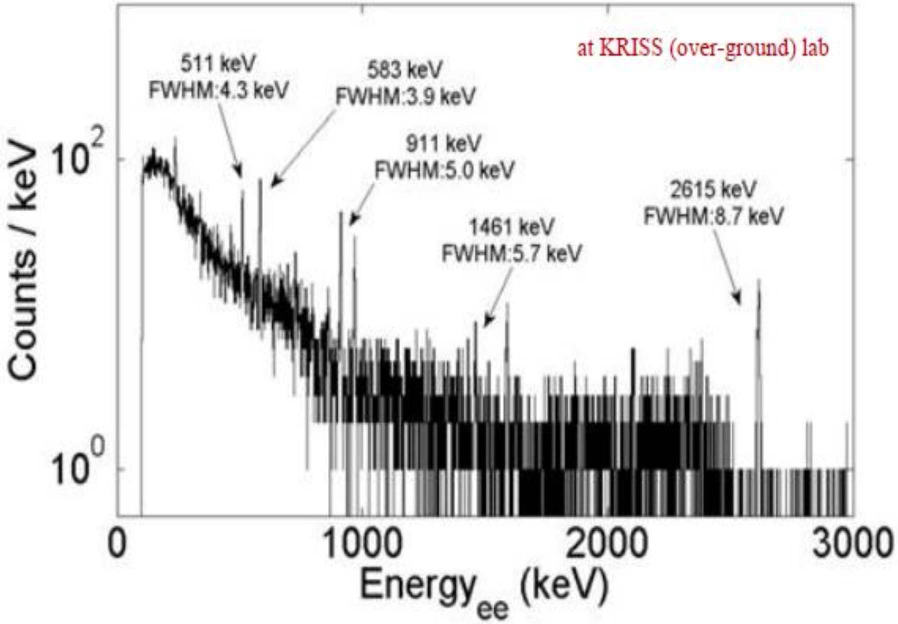


MMC cryogenic technique for AMoRE (I)

Phonon and Light detectors ->



<u>Overground measurement</u>

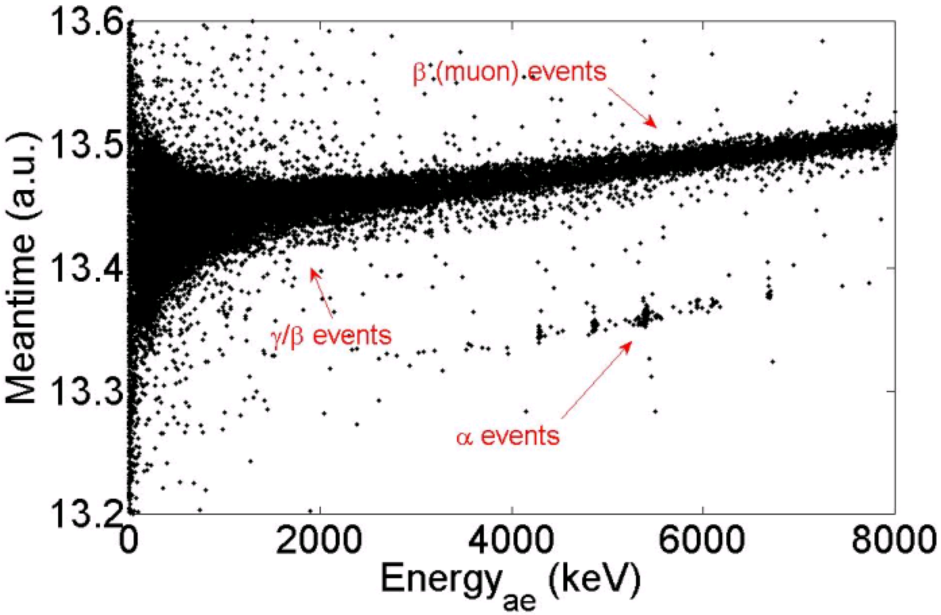


Energy resolution:
< 9 keV @2.6 MeV

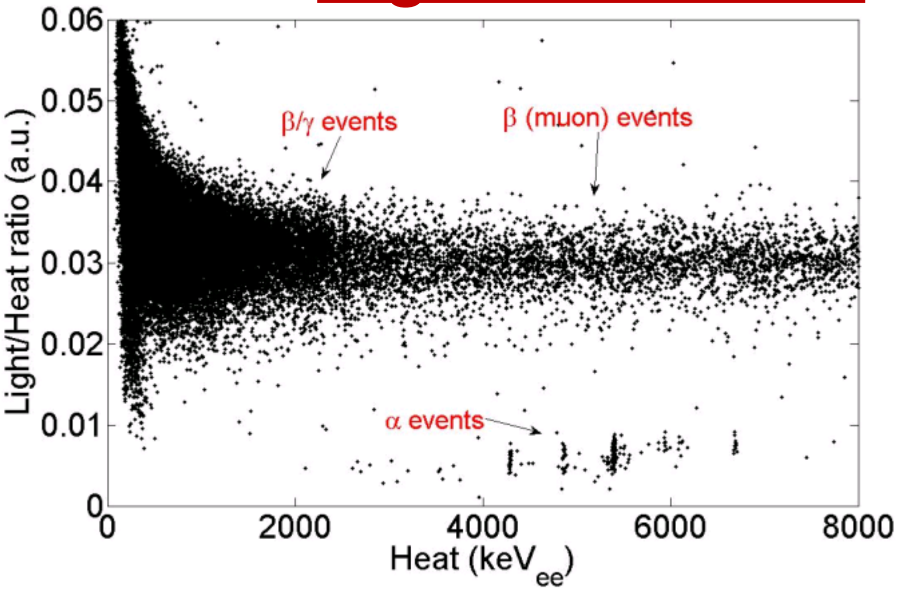
MMC cryogenic technique for AMoRE (II)

Overground measurement

PSD



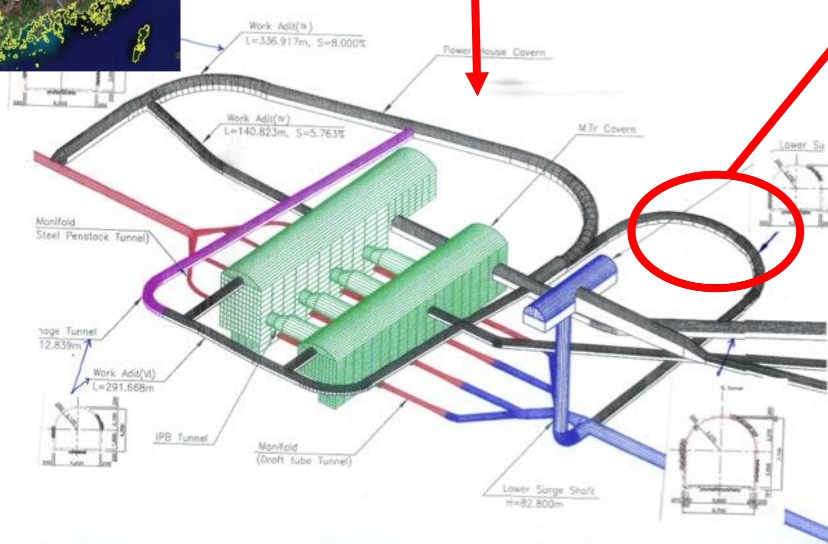
Light/Heat ratio



- **Excellent α/e separation: ~ 15σ**
  - thanks to PSD and both Heat & Light measurements.

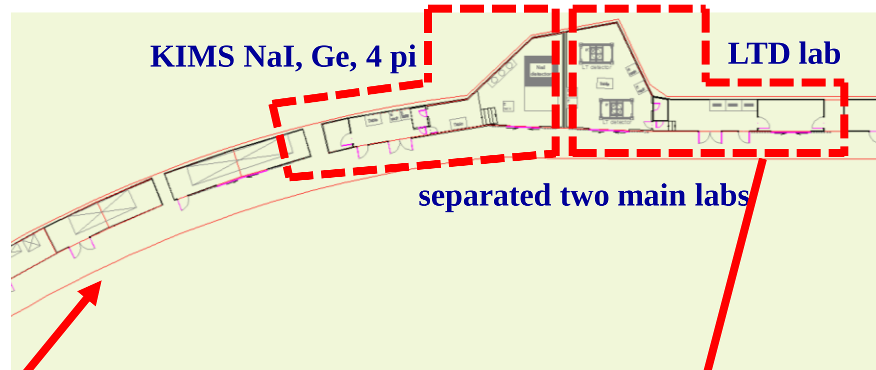
Yangyang underground laboratory (Y2L, South Korea)

Yangyang pumped storage Power Plant
Minimum vertical depth : 700 m
Access to the lab by car : around 2 km



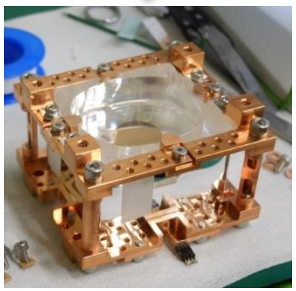
Experiments

- **KIMS : dark matter search experiment**
- **AMoRE : neutrinoless double beta decay search experiment**



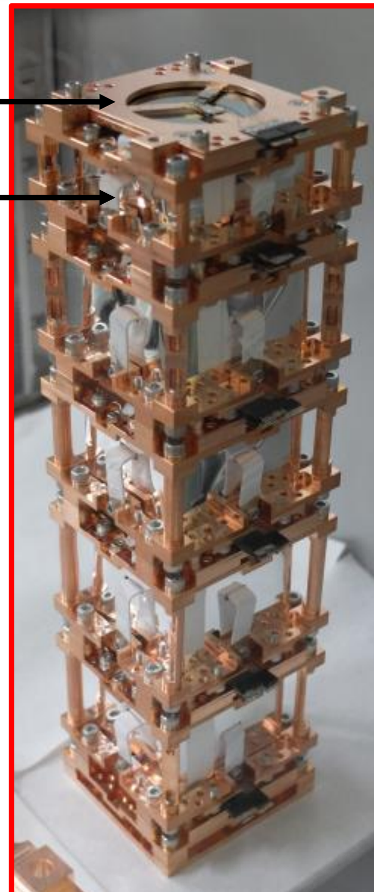
AMoRE-Pilot detector configuration: five $^{40}Ca^{100}MoO_4$ crystals

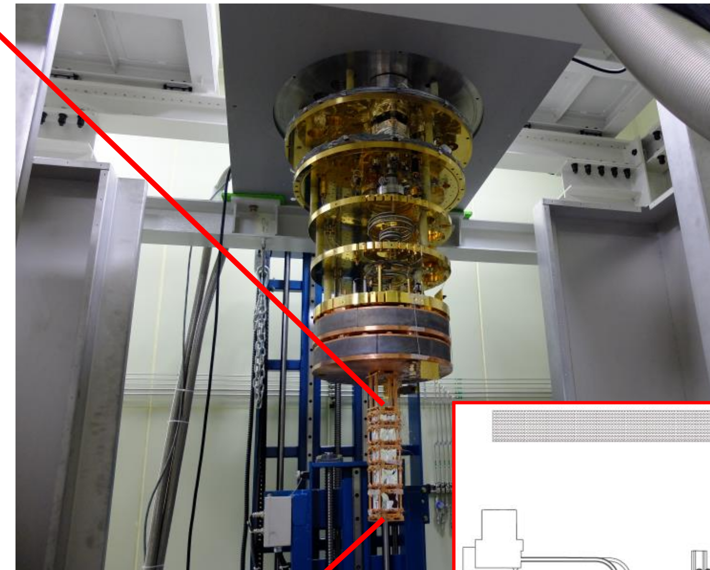
5 crystals: 0.2kg to 0.4kg each, for a total mass of 1.5kg
Each crystal module includes a heat detector and a light detector

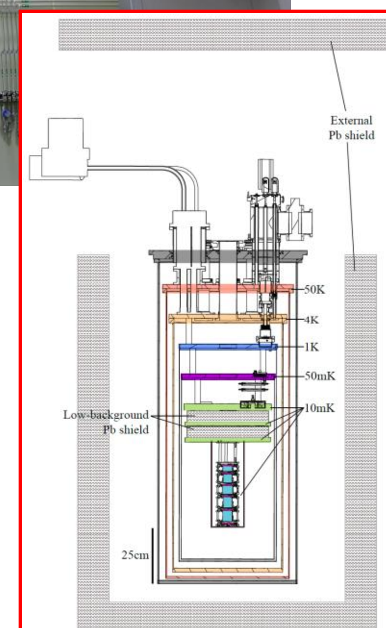


Light detector

Heat detector

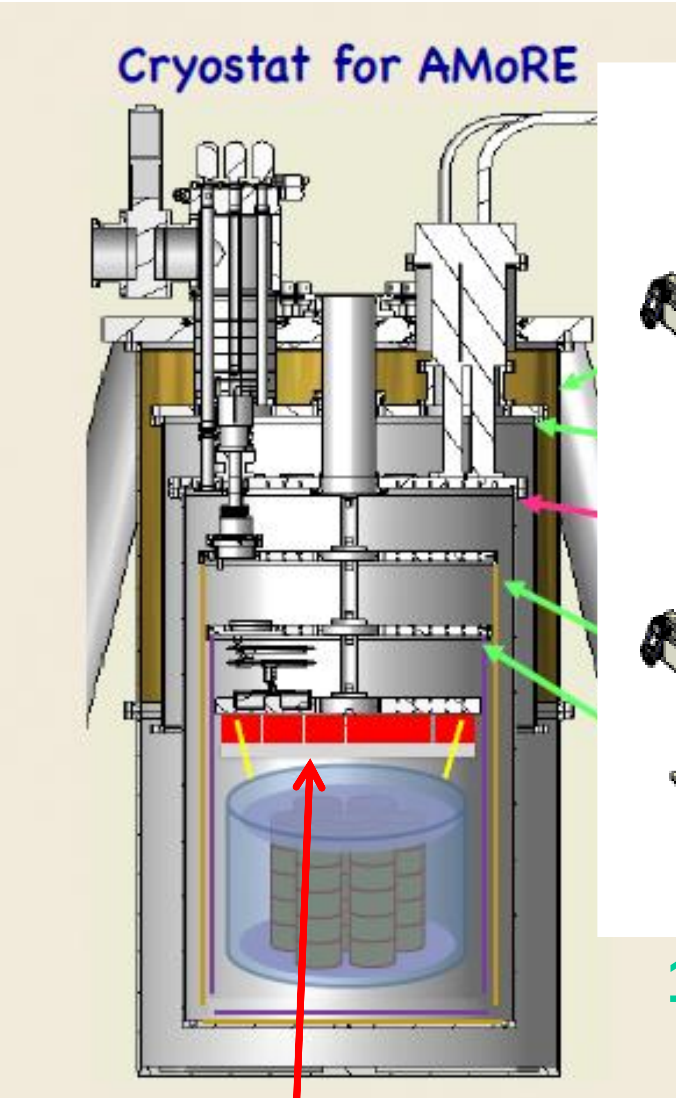


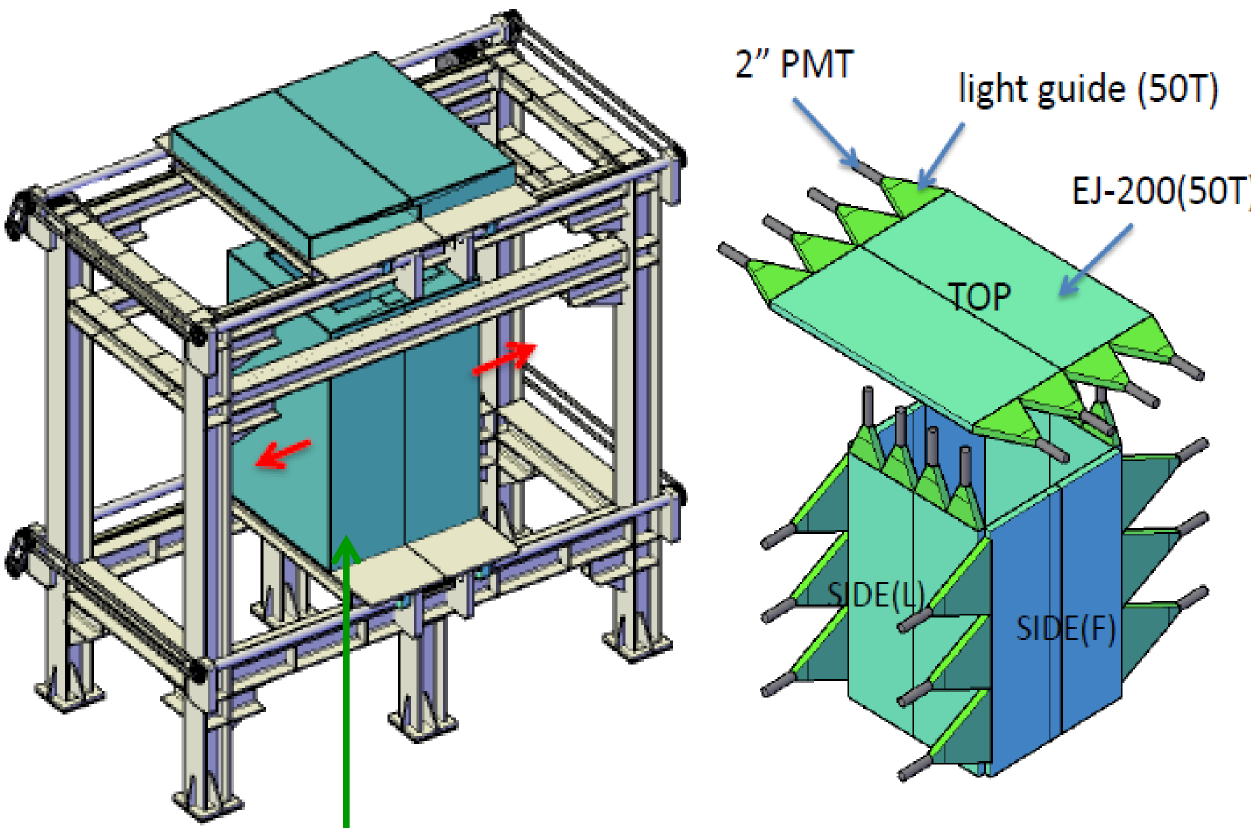




Operating temperatures as low as 8 mK reached using a Cryogen Free Dilution Refrigerator (CF-DR)

Shielding structure of AMoRE-pilot & AMoRE-I



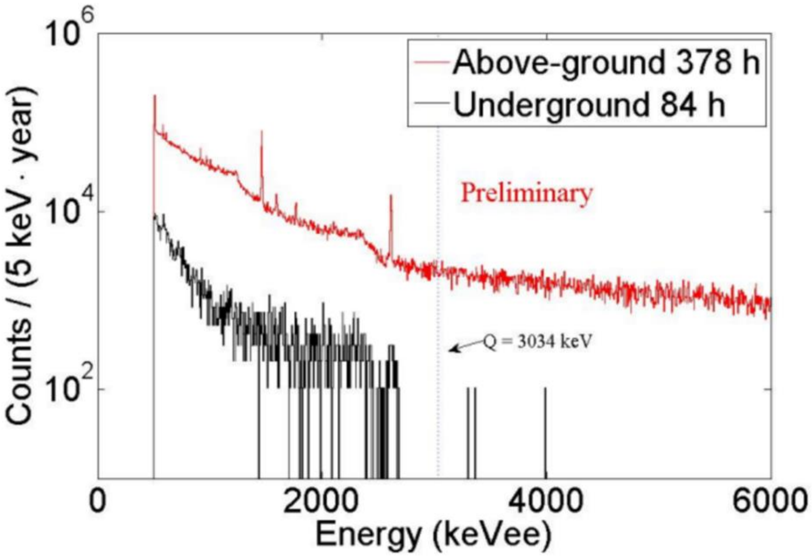


muon shielding structure

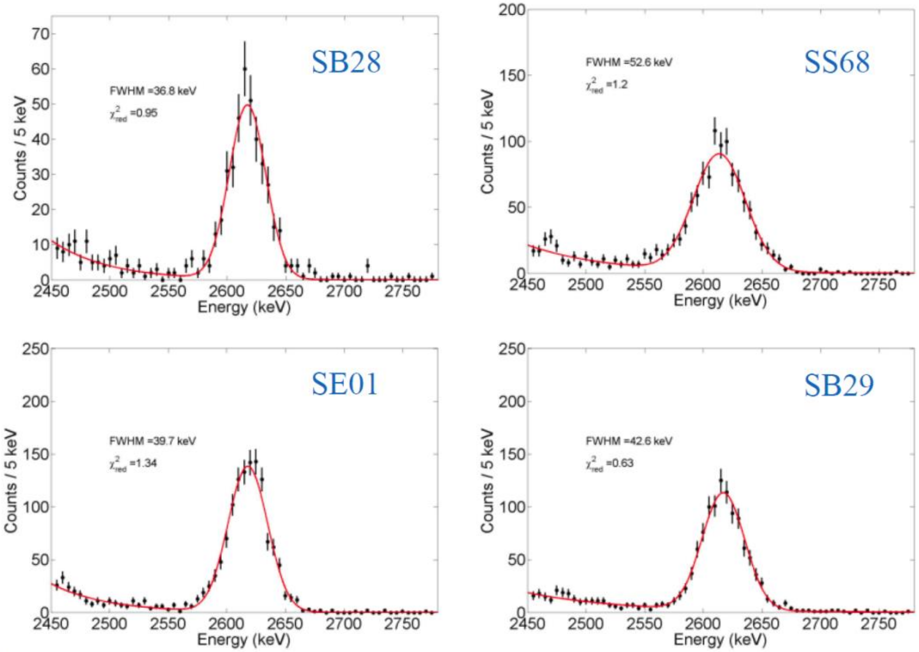
15cm low background Pb

10cm ultra-low background Pb

AMoRE-Pilot run-1 measurements



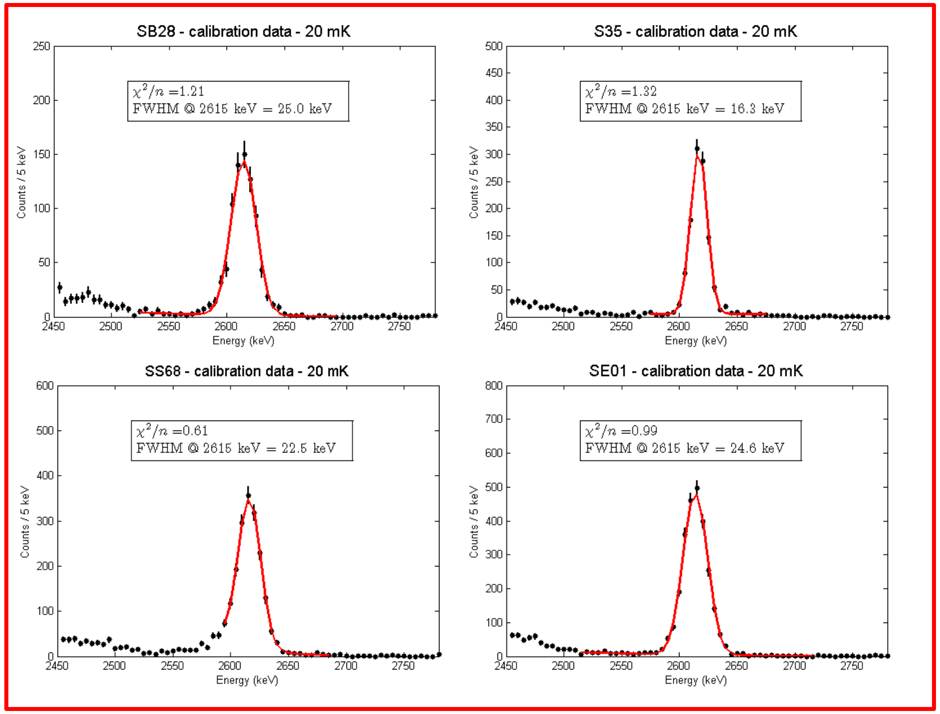
FWHM energy resolution from run-1 (S35 not available)



- **Muon band was suppressed**
- **S35 phonon channel was not working**
- **Large vibration noise**

Energy resolution in AMoRE-Pilot run-2

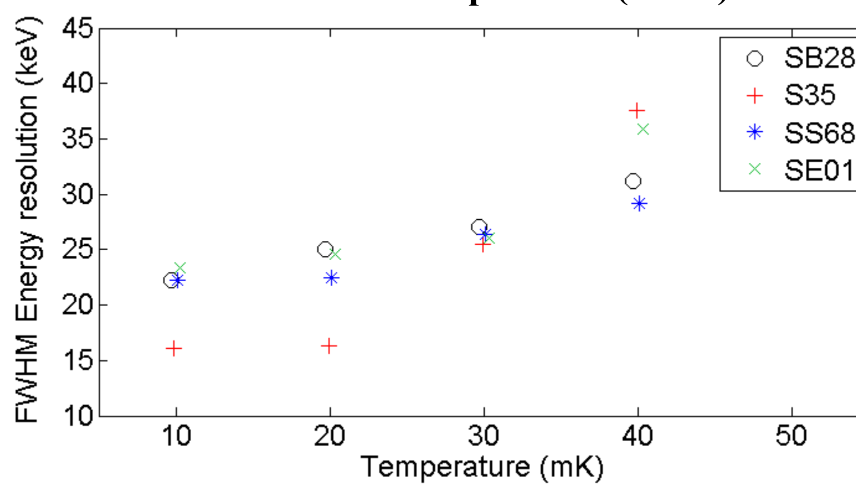
Pilot run-2 (SB29 not available)



FWHM energy resolution @ 2.6 MeV, at 20 mK

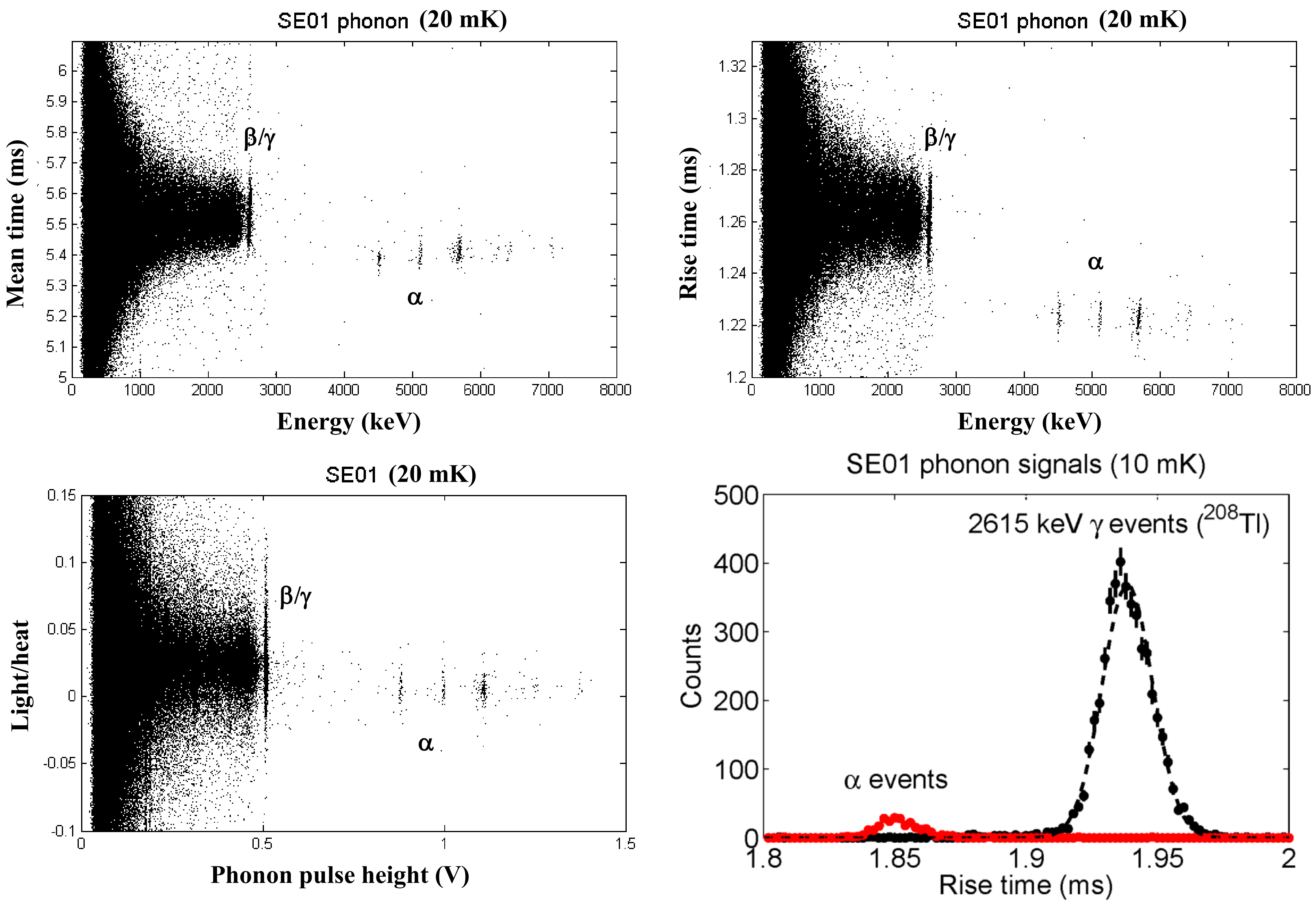
Crystals	Mass	AMoRE-Pilot run-1	AMoRE-Pilot run-2
SB28	0.20 kg	36.8 keV	25.0 keV
S35	0.25 kg	N/A	16.3 keV
SS68	0.35 kg	52.6 keV	22.5 keV
SE01	0.35 kg	39.7 keV	24.6 keV
SB29	0.40 kg	42.6 keV	N/A

FWHM energy resolution as a function of temperature (run-2)



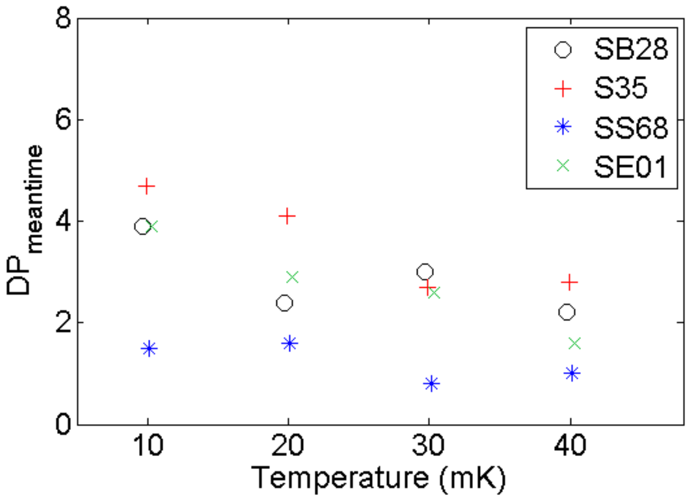
- **From run-1 to run-2, the energy resolution of phonon channels have been improved by vibration reduction**
- **Photon channels need further improvements**

PSD in AMoRE-Pilot run-2

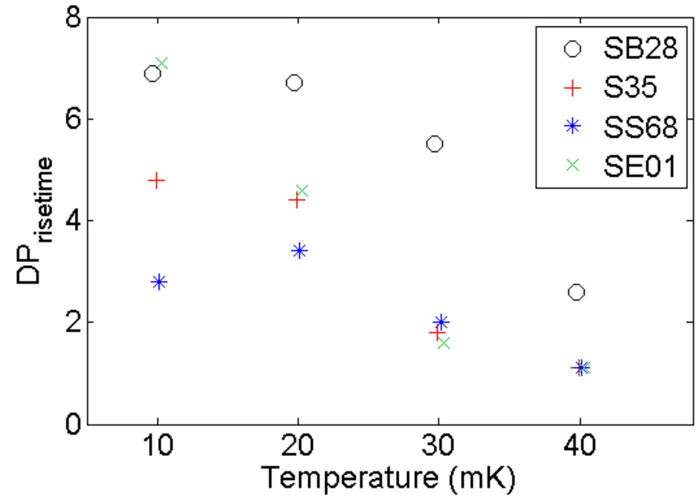


AMoRE-Pilot run-2: PSD as a function of temperature

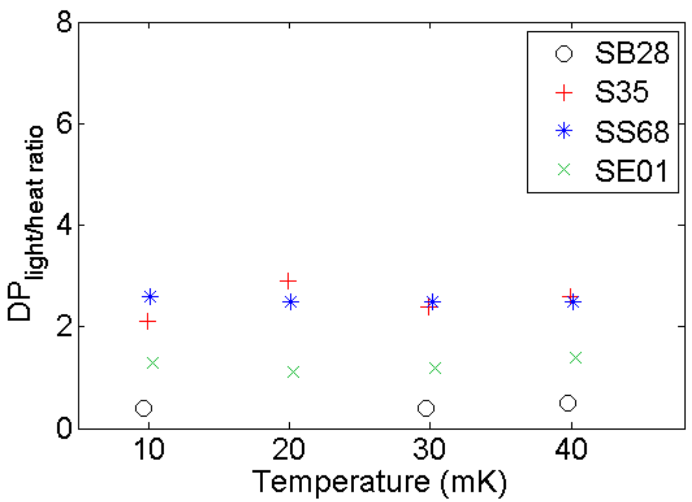
DP mean time



DP rise time



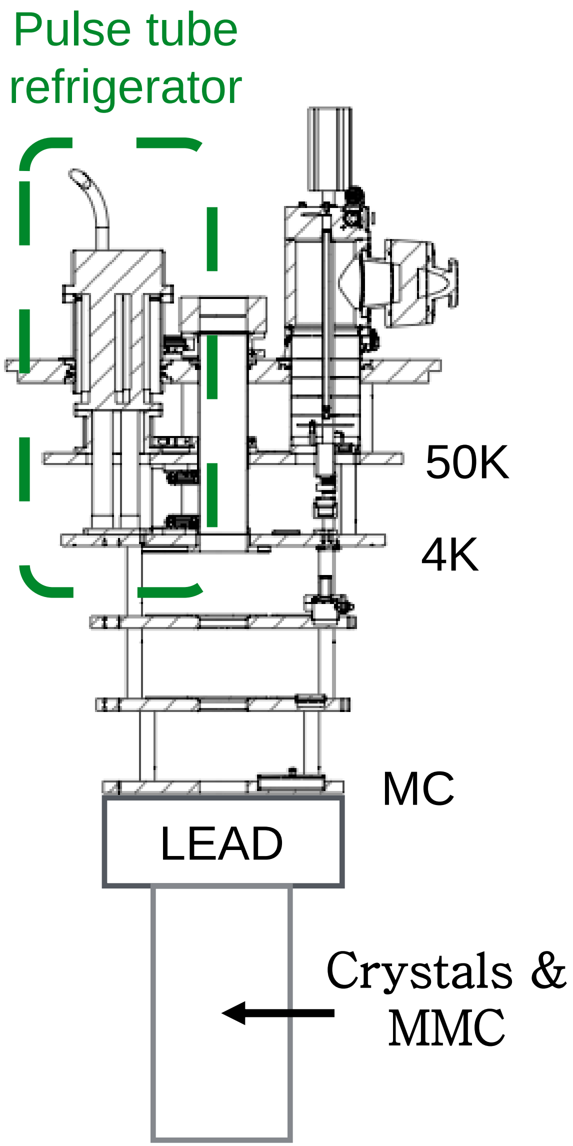
DP light/heat

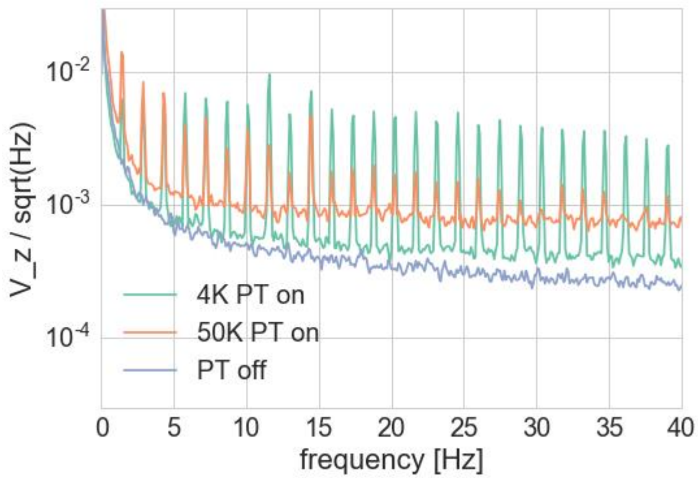


$$DP = \frac{X_{\beta/\gamma} - X_{\alpha}}{\sqrt{\sigma^{2}_{\beta/\gamma} + \sigma^{2}_{\alpha}}}$$

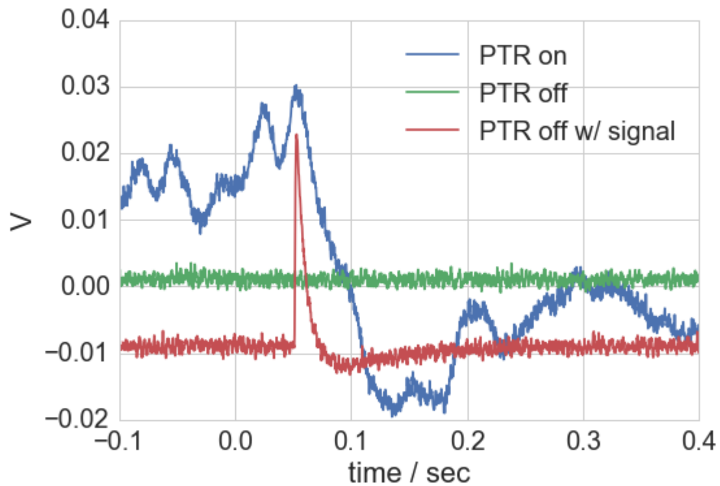
- **PSD vary from one crystal to another**

Vibration from the pulse tube refrigerator (PTR)



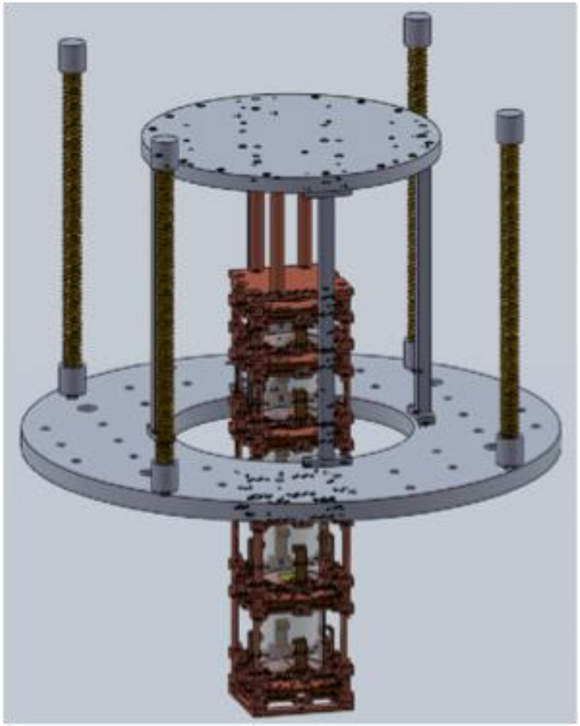


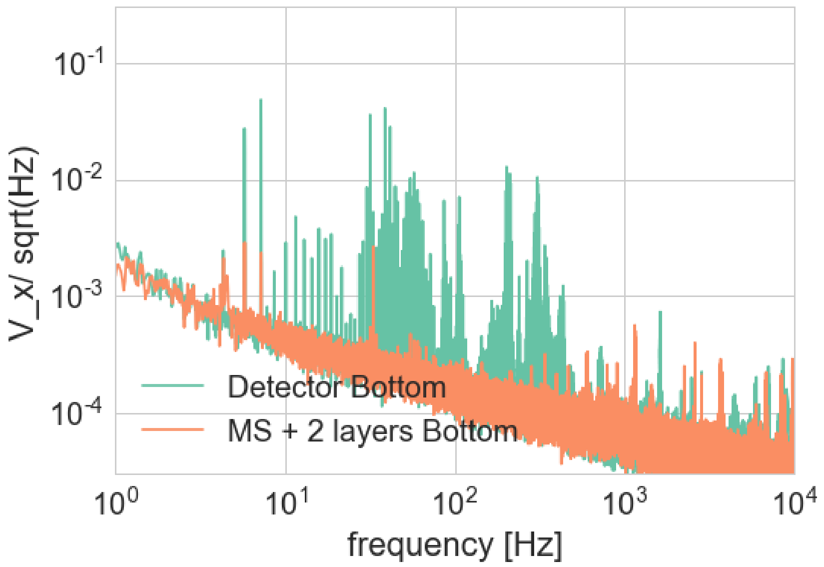
Comparison of vibration level between PTR on and PTR off as a function of frequency

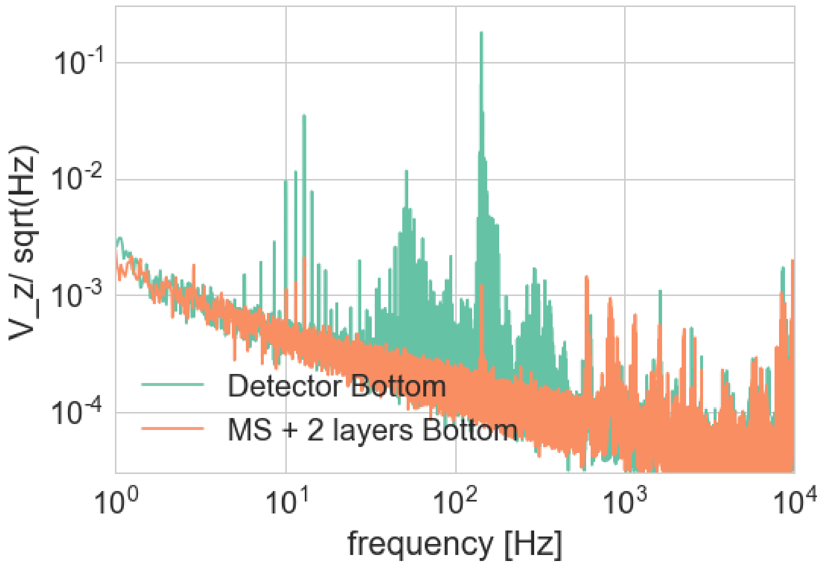


The pulse tube refrigerator of the cryostat generates mechanical vibration which turns into heat noise and disturbs the baseline

Mass-spring system

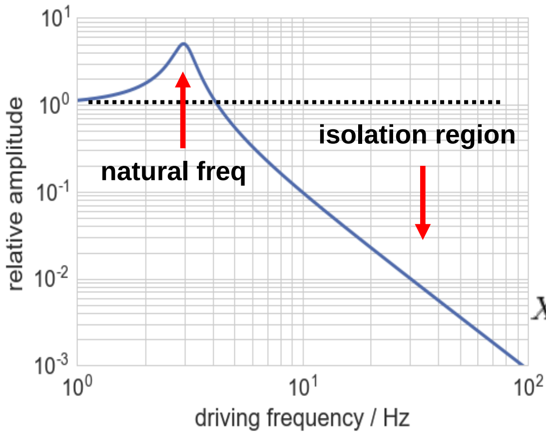


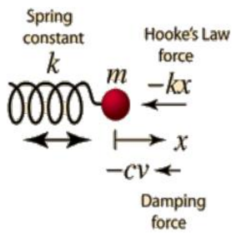




- **Use of four phosphorus copper springs**
- **Room temperature test successful**

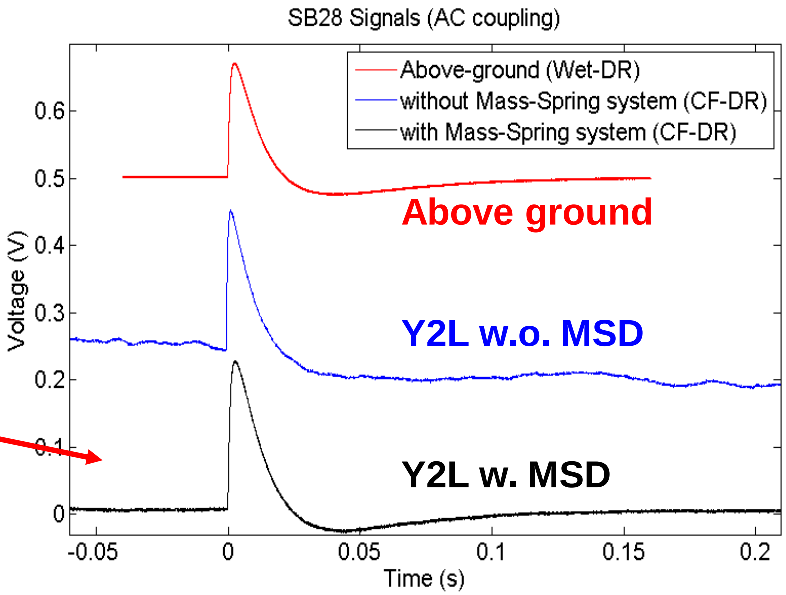
Mass Spring Damper : Recent improvement





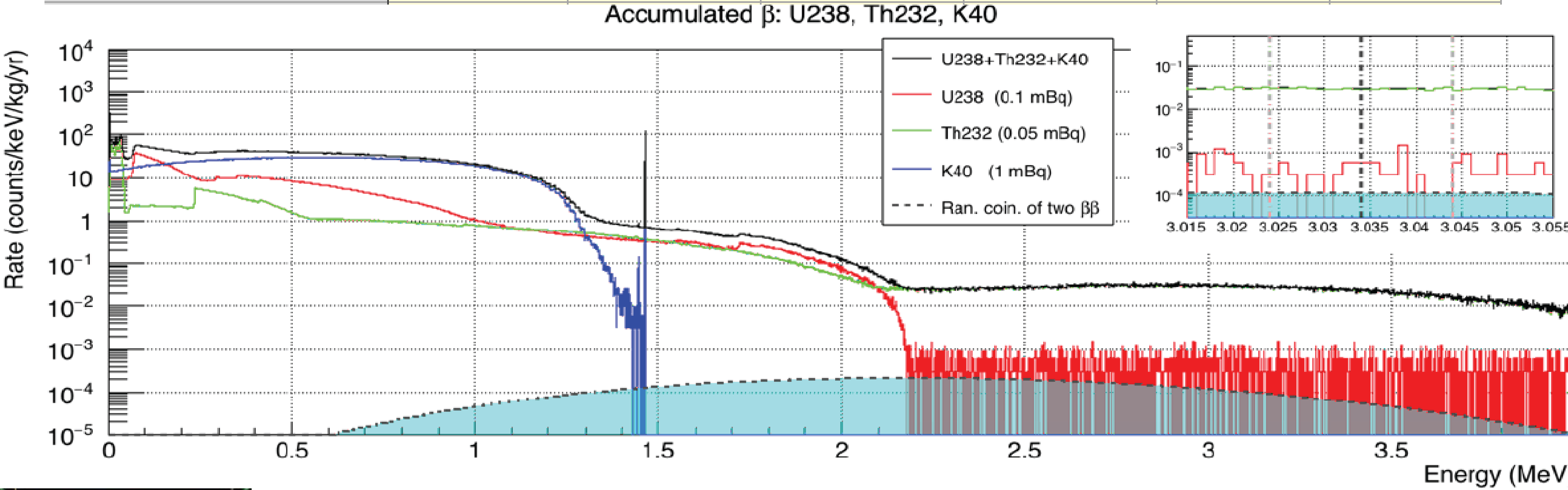
$$X = \frac{F_0}{k} \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}}$$

- Higher frequency region than the natural one is isolated.
- Damping is essential to reduce resonance.



Internal background simulation for AMoRE-I

		Pb210	U238	Th232	K40	U235
Concentration		10 mBq/kg	0.1 mBq/kg	50 µBq/kg	1 mBq/kg	1 mBq/kg



- ^{208}Tl with α-tagging : less than 8.3x10^{-4} DBU.
- Random coincidence of 2νββ of ^{100}Mo: 1.2x10^{-4} DBU.

-> Goal of 0.002 for AMoRE-I can be achieved

Major backgrounds from radionuclides for AMoRE-II

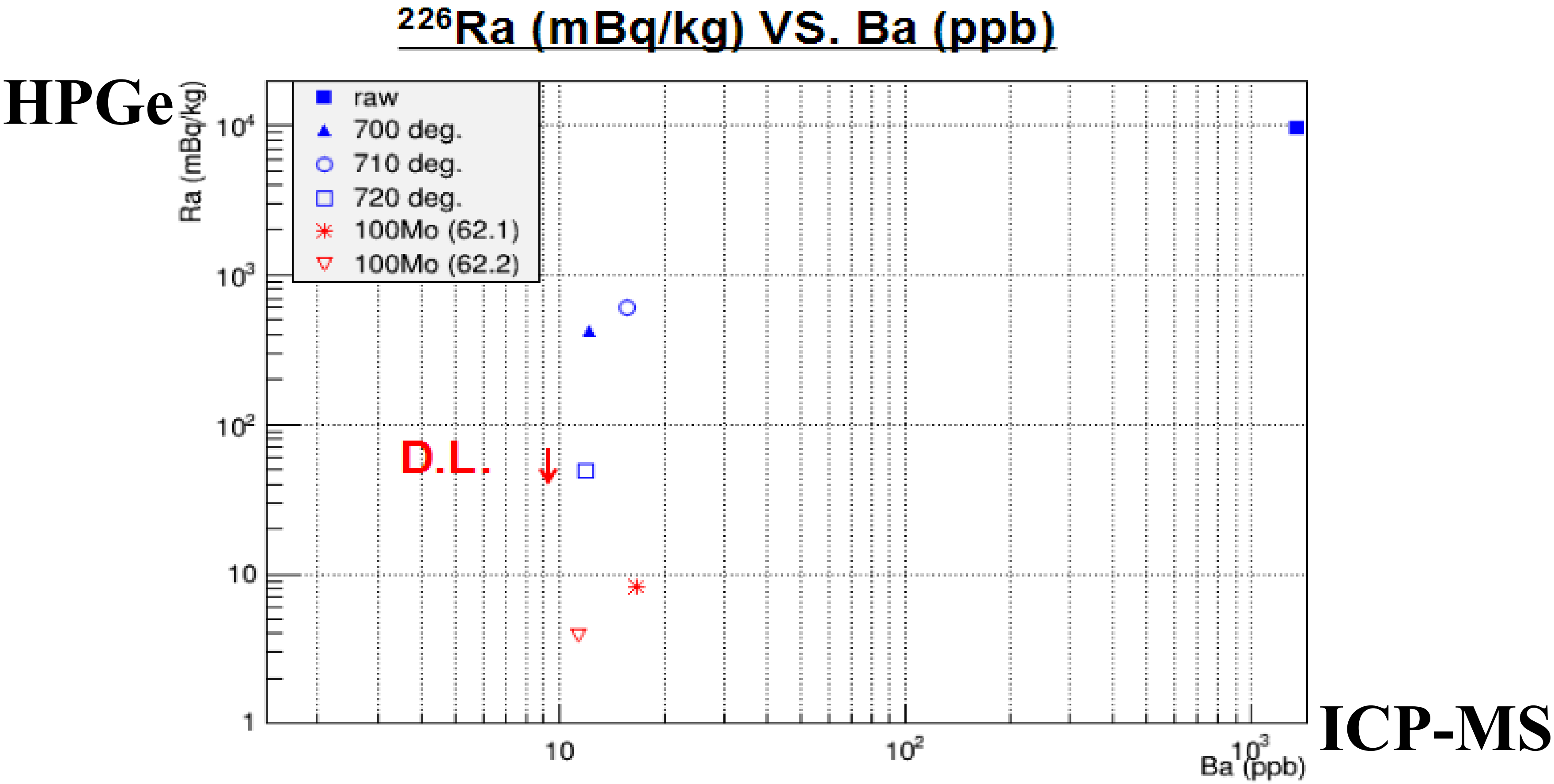
Background source	**Activity [μBq/kg]**	**Bg [10^{-4} cnt/keV/kg/yr]**	**Bg reduced by PSD [10^{-4} cnt/keV/kg/yr]**
Tl-208, internal	10 (^{232}Th)	0.36	
Tl-208, in Cu	16 (^{232}Th)	0.22	
BiPo-214, internal	10	0.11 [1)]	≤ 0.01
BiPo-214, in Cu	60	1.8 [1) 2)]	≤ 0.18
BiPo-212, internal	10 (^{232}Th)	0.08 [1)]	≤ 0.01
BiPo-212, in Cu	16 (^{232}Th)	0.36 [1) 2)]	≤ 0.04
Y-88, internal	20	0.19	
Σ int. (w/o 2β2ν)		0.74	≤ 0.57
Σ Cu		2.40	≤ 0.44
Rand. coinc. from 2β2ν decays of ^{100}Mo	8.7×10^{3} (single evts.)	3.1 [3)]	1.2
Total		**6.2**	**≤ 2.2**

1) Can be reduced x0.1 by alpha/beta PSD
2) Can be reduced by teflon coating of Cu (to remove surface alphas)?
3) Can be reduced by the leading edge separation with Δt=0.5 ms

Muon background : ~1.4×10^{-4} counts/keV/kg/yr @Y2L

Ultra-low background crystals for AMoRE-II (I)

- MoO_3 powder purifications with sublimation method.
  - Results are monitored by ICP-MS and HPGe -> ^{226}Ra can be reduced by ~100.



Ultra-low background crystals for AMoRE-II (II)

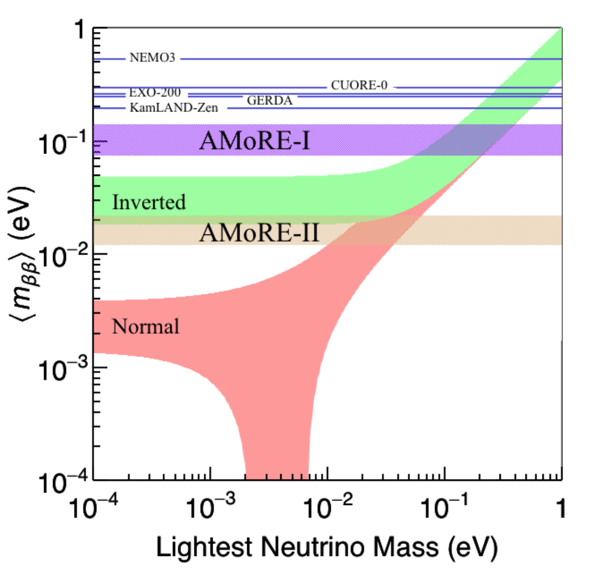
- **Crystal growing equipment:**
  1 Czochalski, 2 Kyropoulous, 1 Bridgman crystal grower

Czochalski machine

The 1^{st} CMO crystal by us.

Summary

- AMoRE-pilot with 1.5 kg CMO are running.
- AMoRE-I with ~4.5kg of crystals in next year.
- We are performing on R&D programs for AMoRE-II



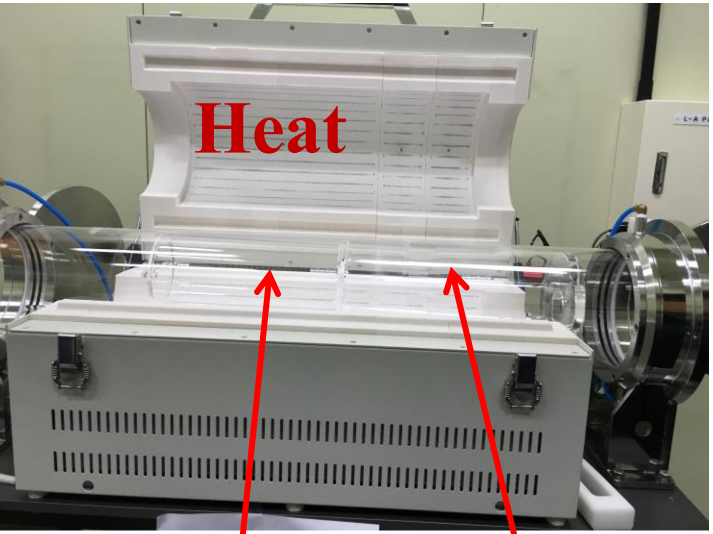
	Pilot	Phase I	Phase II
Detector Crystal	$^{48depl}Ca^{100}MoO_4$	$^{48depl}Ca^{100}MoO_4$	New crystal?
Detector Mass	1.5 kg	~5 kg	~200 kg
Background (keV /kg /year)	0.01	0.001	0.0001
Sensitivity of $T_{1/2}$ (year)	$\sim 10^{24}$	$2.7\text{x}10^{25}$	$1.1\text{x}10^{27}$
Sensitivity of $M_{\beta\beta}$ (meV)	< 300-900	70-140	12-22
Location	Y2L	Y2L	Handuk mine
Schedule	2016-2017	2017-2019	2020-2025

Thank you

Purification of MoO_3 powder: Sublimation method (I)

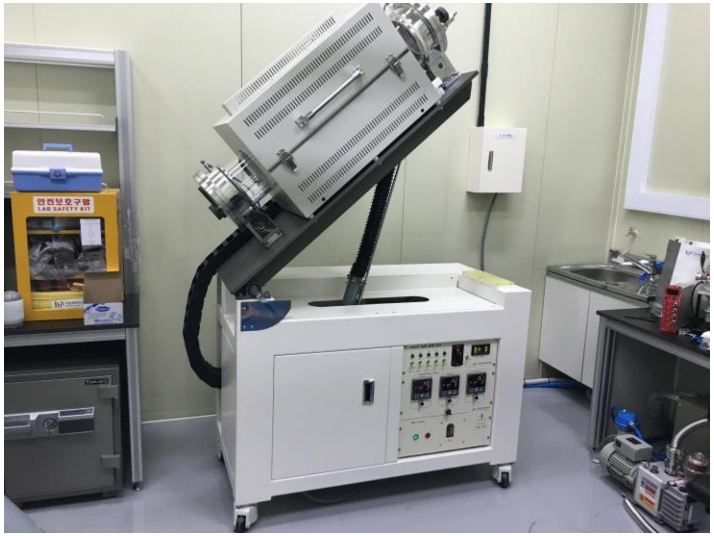
- **MoO_3 has the transition from the solid to the gas phase around 700 ^{o}C.**

  -> Some impurities, U/Th, are still in the solid phases.

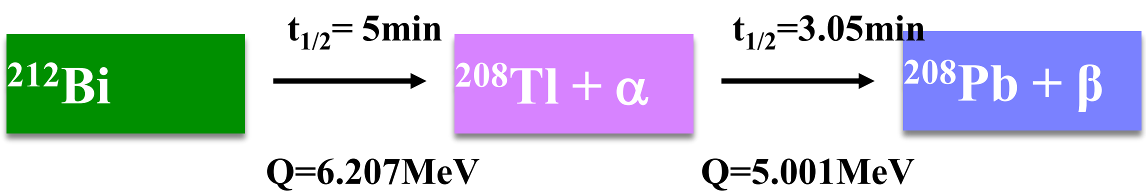


powder loading

purified powder



Event Rejection using α-tagging



- Event Rejection
  - Events are tagged for 15 mins (~5×$t_{1/2}$) after α event with 6.027 MeV (decay of ^{212}Bi to ^{208}Tl).
  - When events were tagged for 15 mins after α event with 6.027 MeV appeared, about 94.4% of β decay event from ^{208}Tl to ^{208}Pb were rejected.
  - Similarly, tagging for 21 mins, 95.7% events were rejected.

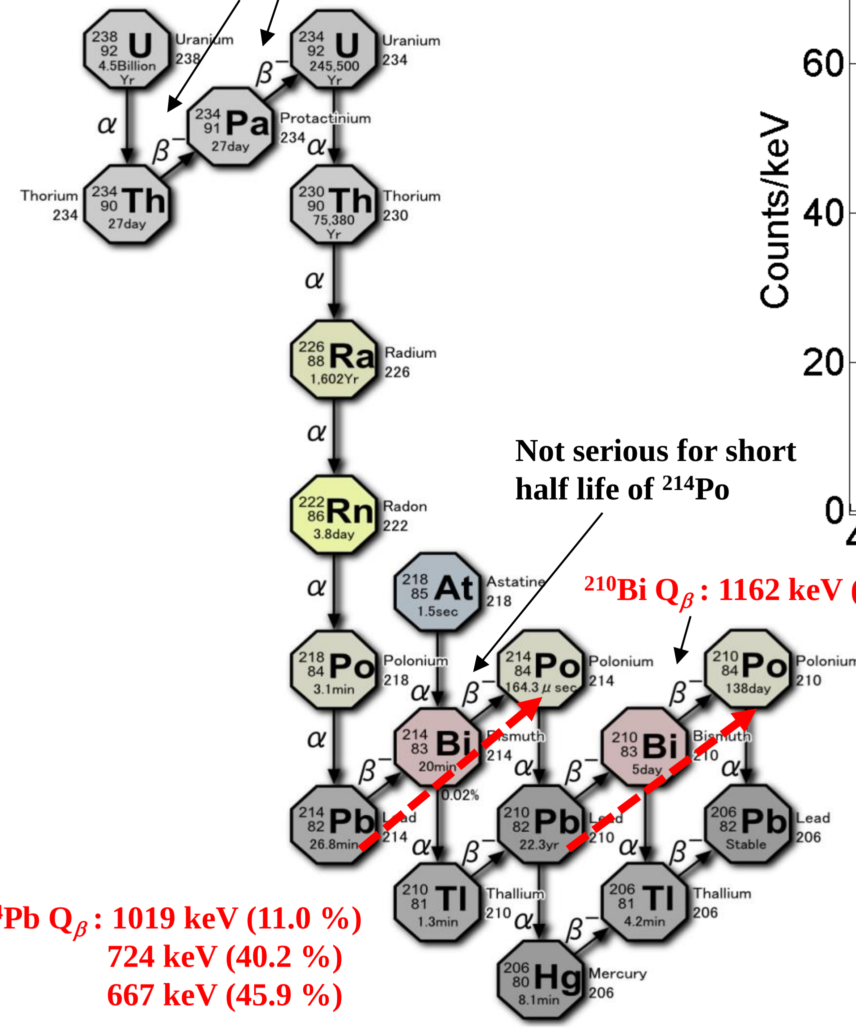
- In our recent measurement, concentration of ^{232}Th inside the CMO crystal was < 2 μBq/kg.
  - As long as concentration of ^{232}Th is below 50 μBq/kg, the background rate is lower than our goal after rejecting events.

Concentration	Corrected Rate (/keV/kg/yr)
50 μBq/kg	0.0015
10 μBq/kg	0.0003

Considerable beta decays (^{238}U)

^{234}Th Q_β : 199 keV (78.0 %)

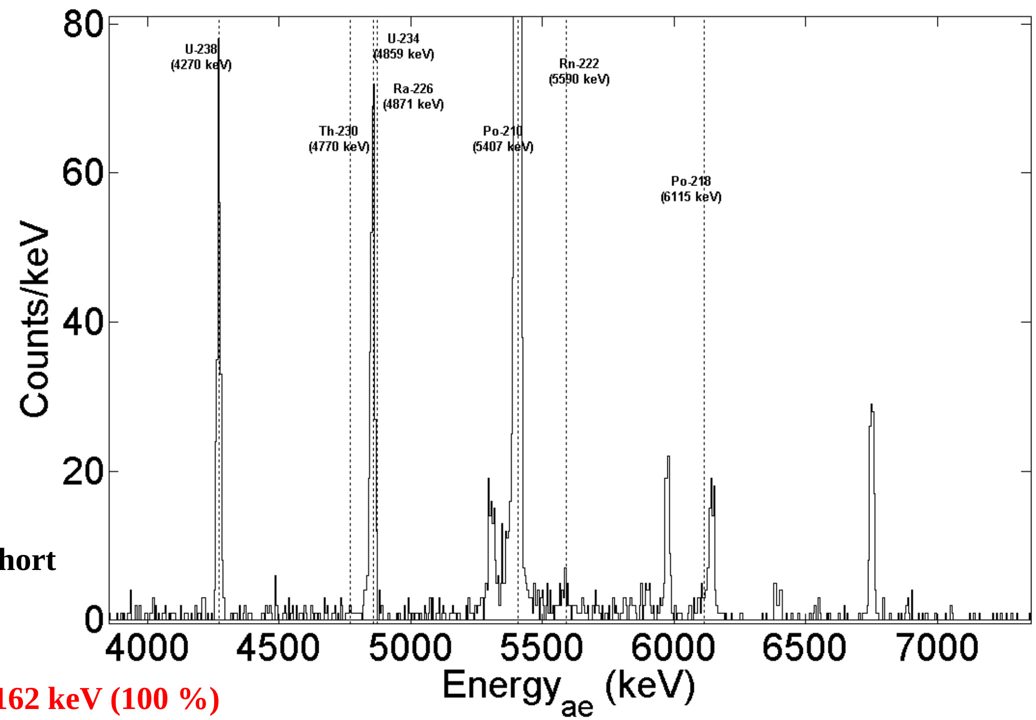
^{234}Pa Q_β : 2269 keV (97.6 %)



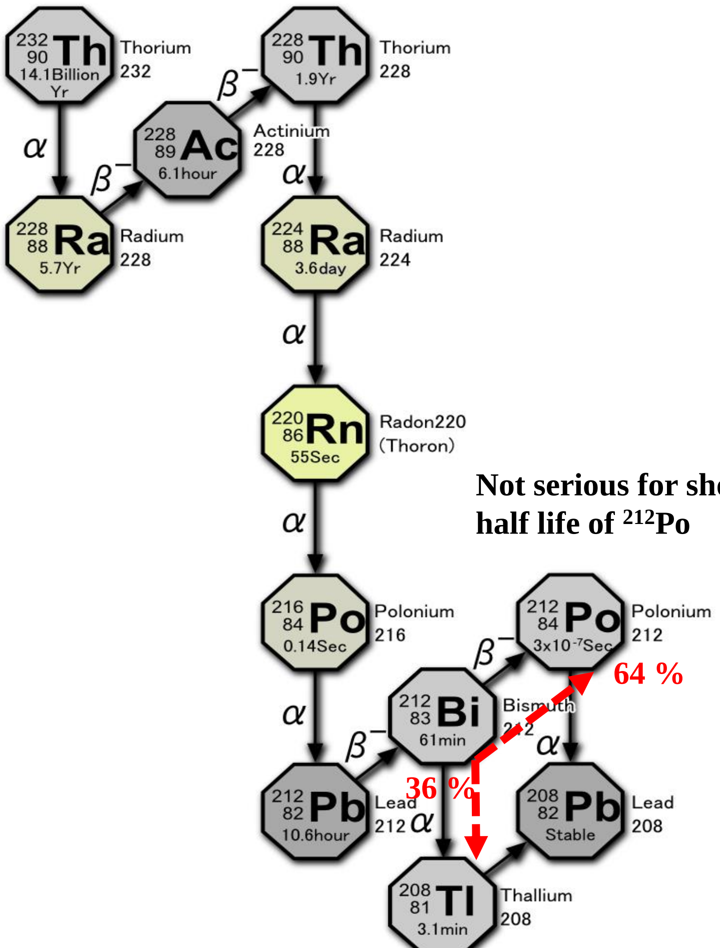
Not serious for short half life of ^{214}Po

^{210}Bi Q_β : 1162 keV (100 %)

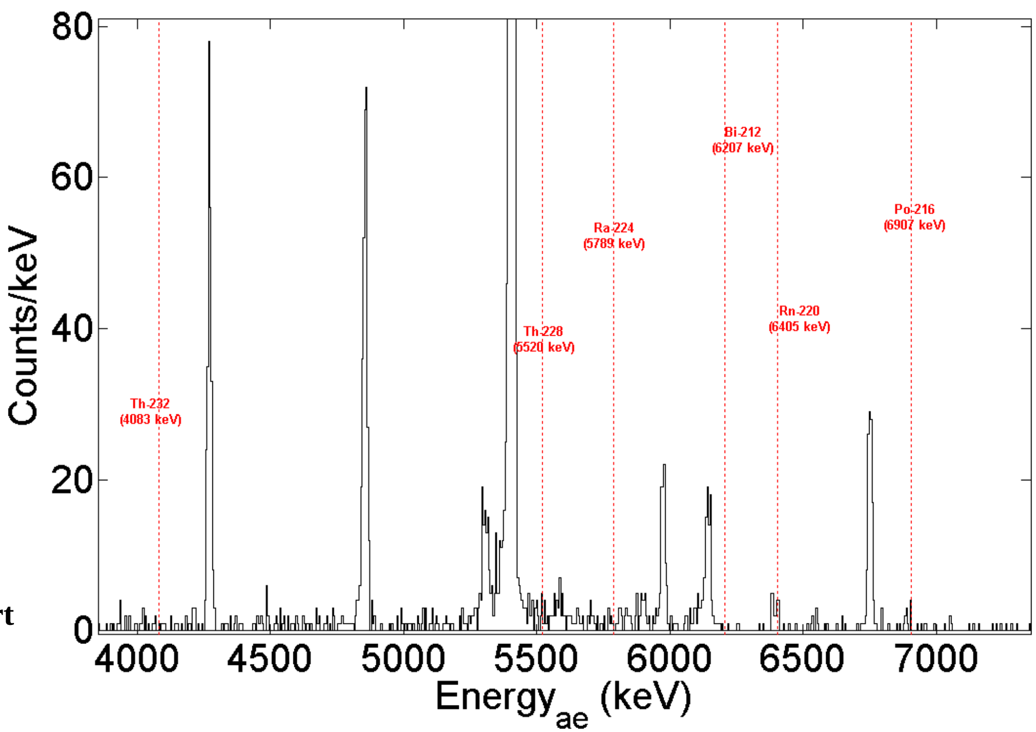
^{214}Pb Q_β : 1019 keV (11.0 %)
724 keV (40.2 %)
667 keV (45.9 %)



Considerable beta decays (^{232}Th)

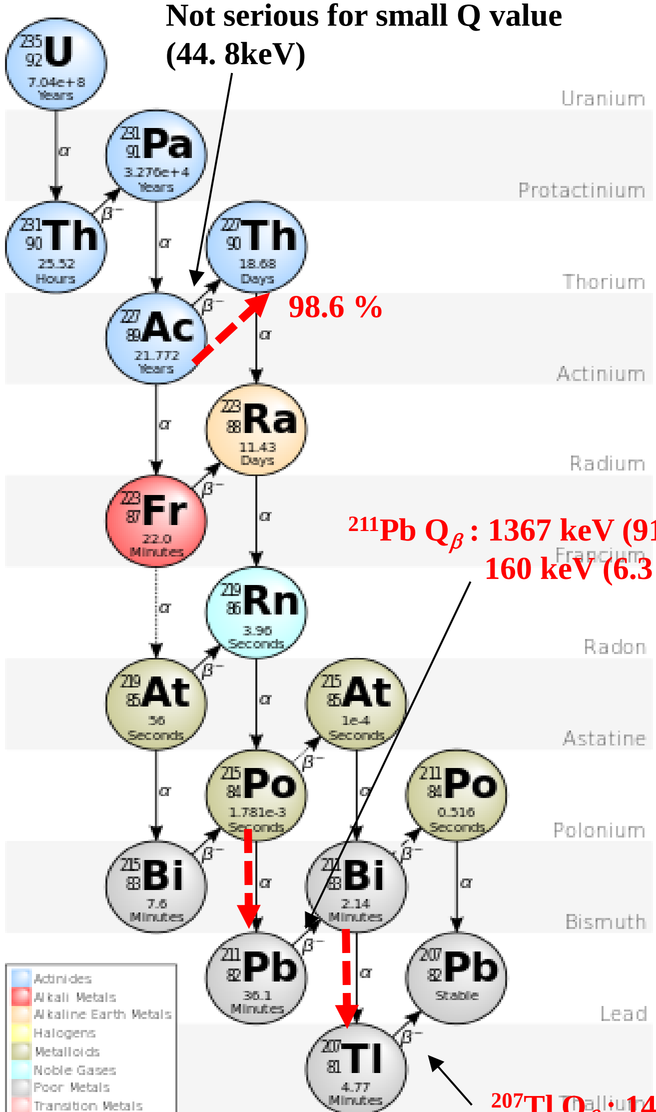


Not serious for short half life of ^{212}Po



Considerable beta decays (^{235}U)

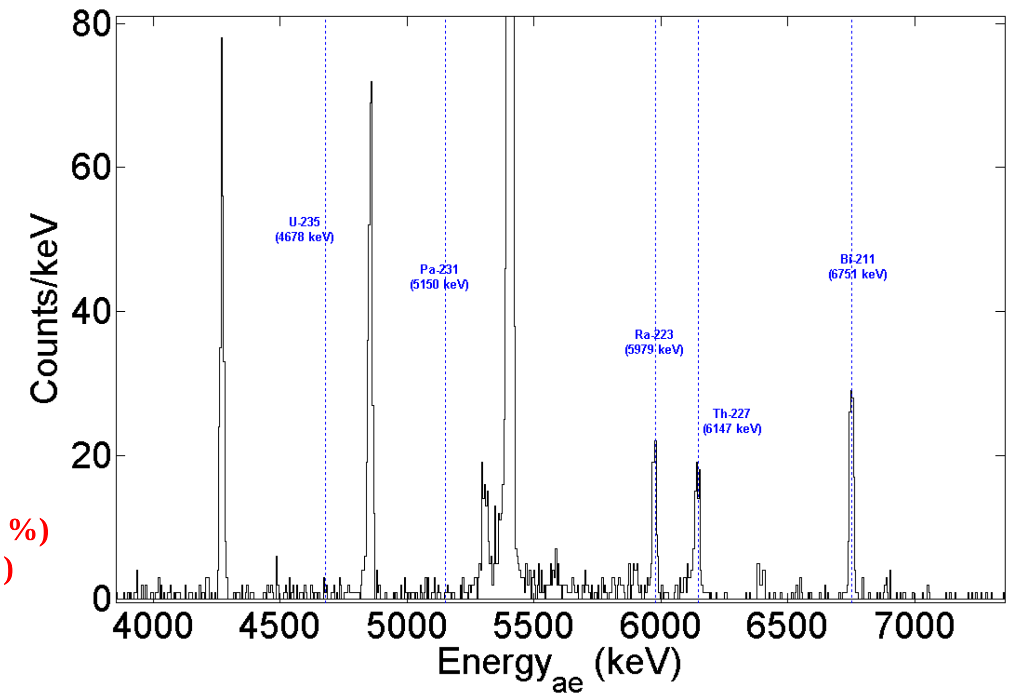
Not serious for small Q value (44. 8keV)

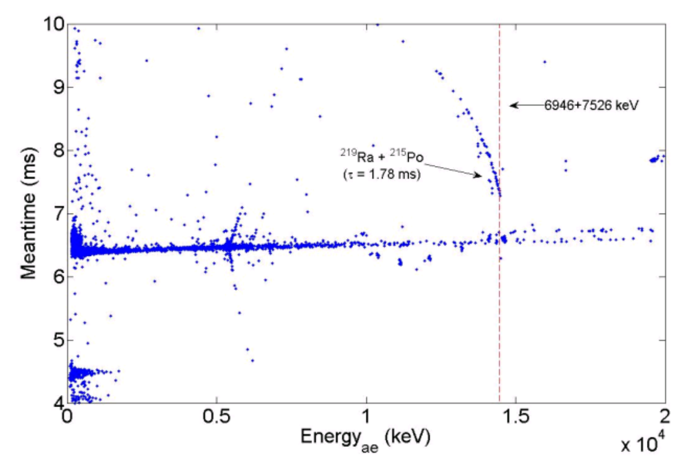


98.6 %

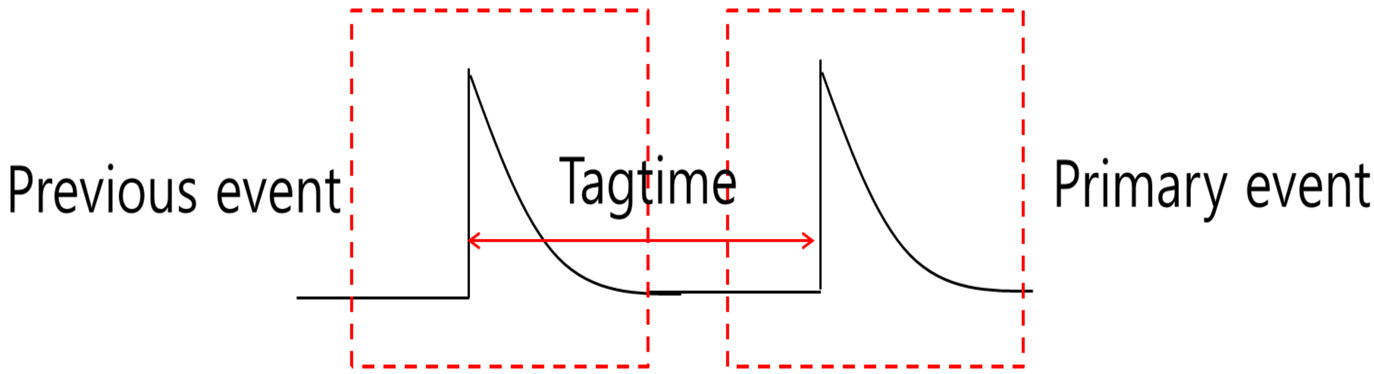
^{211}Pb Q_β : 1367 keV (91.3 %)
160 keV (6.3 %)

^{207}Tl Q_β : 1418 keV (99.7 %)





Time-Amplitude analysis method

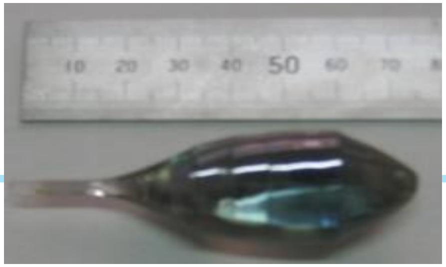


U-235 chain : **Rn-219 (3.965 s) → Po-215 (1.78 ms) → Pb-211**

U-238 chain : **Bi-214 (20 m) → Po-214 (164 us) → Pb-210**

Th-232 chain : **Rn-220 (55.6 s) → Po-216 (0.145 s) → Pb-212**

History of CaMoO4



1) 2002 : Idea and try to grow CMO in Korea
2) 2003 : Collaboration with V.Kornokov.
3) 2004 : CMO test and Conference presentation (VIETNAM2004), Extended idea of XMoO4, cryogenic detector of CMO
4) 2005-2007 : Large CMO with 1st ISTC project
5) 2006 : Collaboration with F. Danevich group (CMO by Lviv)
6) 2007 : CMO R&D in cryogenic temperature started.
7) 2008 : 2nd ISTC project : 1kg of $^{48depl}Ca^{100}MoO_4$ crystal
8) 2009 : AMORE collaboration formed
9) 2010-11 : $^{40}Ca^{100}MoO_4$ internal background study
10) 2012 : Russian group (FOMOS) got funding for production line
11) 2013 : AMoRE project funded (Under Center for Underground Physics, Institute for Basic Scinece)
12) 2014 : Upgrade of Y2L lab for AMoRE-pilot and AMoRE-I

$^{40}Ca^{100}MoO_4$ Crystals for AMoRE-pilot

SB28 (196 g)

SB29 (390 g)

S35 (256 g)

SS68 (350 g)

SE1 (354 g)

Total mass : 1.546 kg

- **All crystals for AMoRE-pilot are in the cryostat.**