Low background crystal growth and purification at CUP

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2023. 09. 15

Underground Physics Workshop @ SNU

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❑ Rare-process search experiments

❑ Radioassay (ICP-MS, HPGe, alpha)

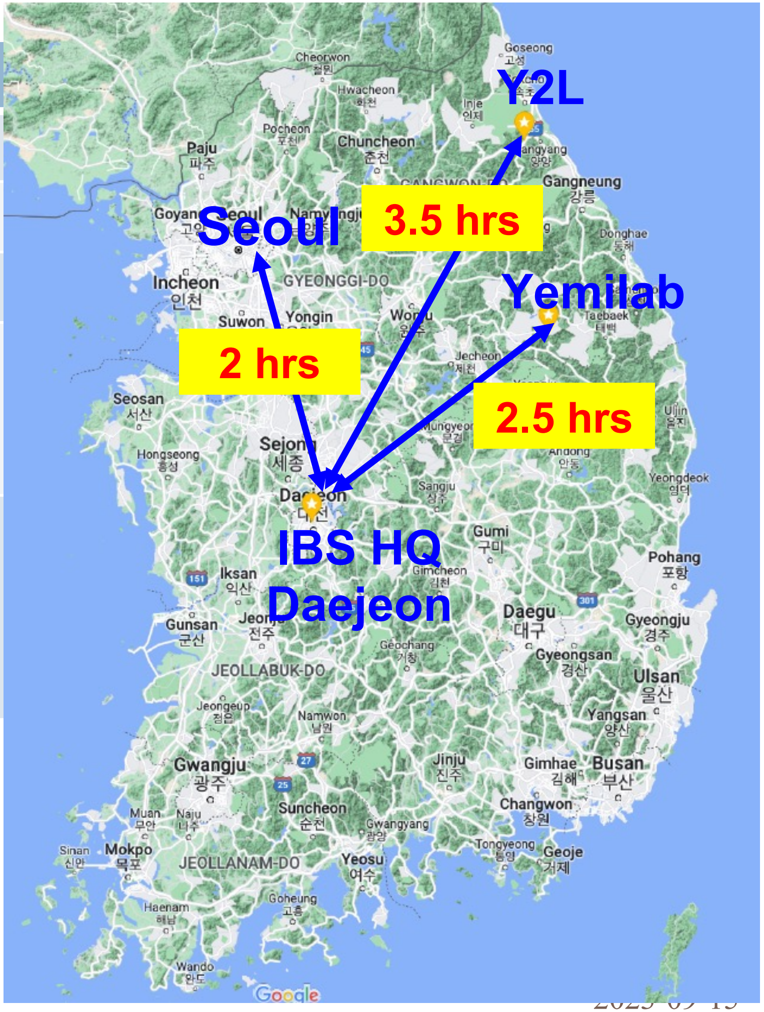
❑ Purification of raw materials for crystal growing

❑ Ultra-pure crystal growth at CUP

❑ Low background scintillating crystals grown

Rare-process search experiments at CUP

	Y2L	Yemilab
Location	Yangyang	Jeongseon
Depth (m)	700	1000
Area (m^2)	350	~3000
Rock Radioactivity (ppm)	U: 3.9(14) Th: 10.5(65) K: 40000	U: 0.8(3) Th: 3.3(4) K: 11800
Experiments	KIMS (WIMP) AMoRE-I ($0\nu\beta\beta$) COSINE-100 (WIMP)	AMoRE-II COSINE-100 upgrade COSINE-200 + …

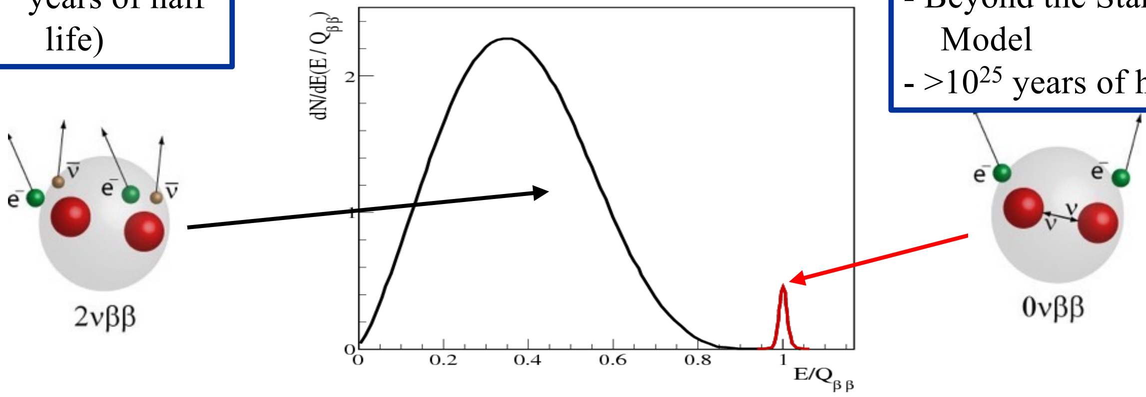


AMoRE: $0\nu\beta\beta$ decay search

The goal of **AMoRE** is to search for neutrinoless double beta ($0\nu\beta\beta$) decay of ^{100}Mo using Mo-based scintillating crystals and low-temperature detectors (LTD).

$2\nu\beta\beta$ decay
- 2^{nd} order beta decay
- Rare nuclear decay
- (>10^{18} years of half life)

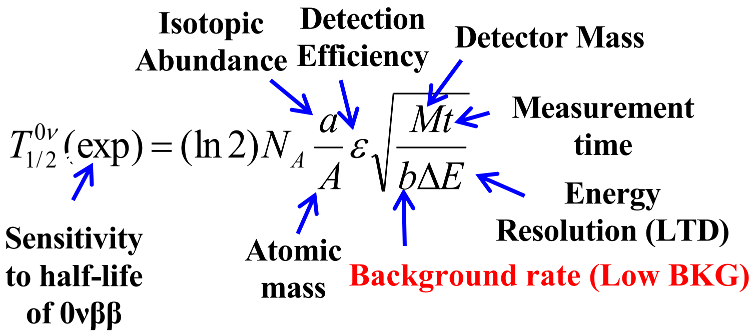
$0\nu\beta\beta$ decay
- Lepton number violation
- Massive neutrino
- Majorana particle
- Beyond the Standard Model
- >10^{25} years of half-life



(Z, A) → (Z+2, A) + $2e^-$ + 2anti-ν_e ($\Delta L = 0$, conserved)
(Z, A) → (Z+2, A) + $2e^-$ ($\Delta L = 2$, violated)

AMoRE: Sensitivity

● Sizable background case:



$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon \sqrt{\frac{Mt}{b\Delta E}}$$

Isotopic Abundance

Detection Efficiency

Detector Mass

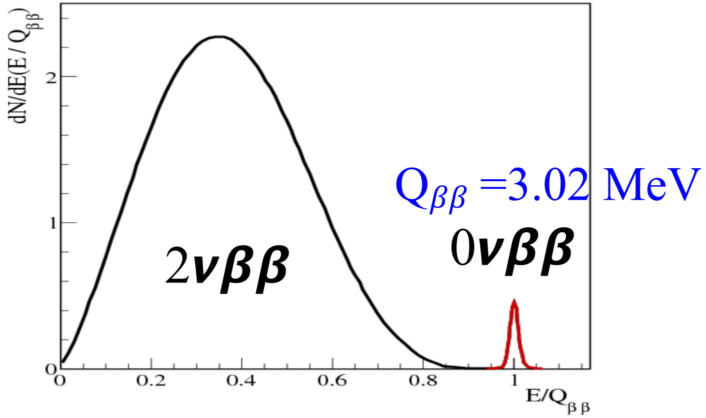
Measurement time

Energy Resolution (LTD)

Sensitivity to half-life of 0νββ

Atomic mass

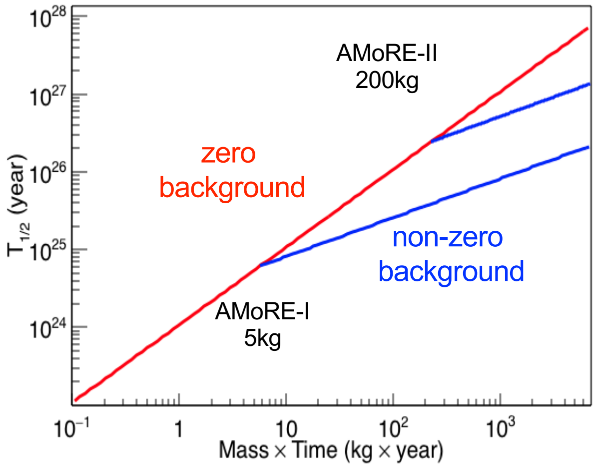
Background rate (Low BKG)



● "Zero" background case:

When b is ~ O(1),

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_A \frac{a}{A} \varepsilon Mt$$

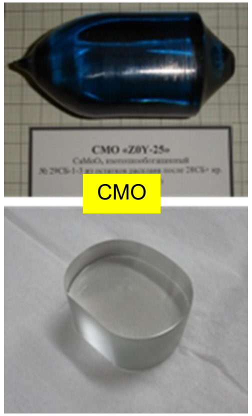


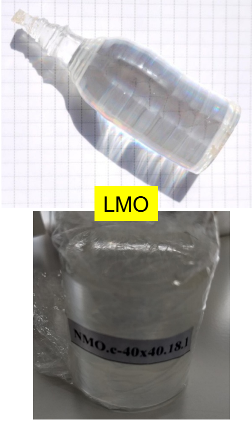
AMoRE is aiming for zero background.

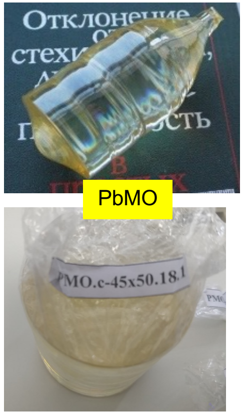
AMoRE Parameters

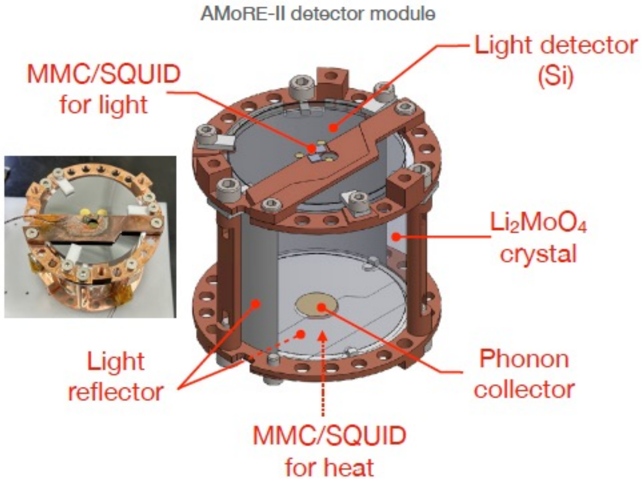
- Crystals: $^{40}Ca^{100}MoO_4$(CMO) or XMO

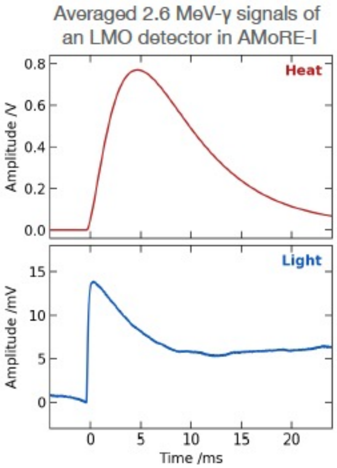
  (X: Li, Na, or Pb studied)
  - ^{100}Mo enriched: > 95%
  - ^{48}Ca depleted: < 0.001% (N.A. of ^{48}Ca: 0.187%)
- Low-temperature (LT) detector: @10 – 30 mK
- Energy resolution: ~5 keV @ 3 MeV (goal)
- Excellent PID for α vs. e/γ

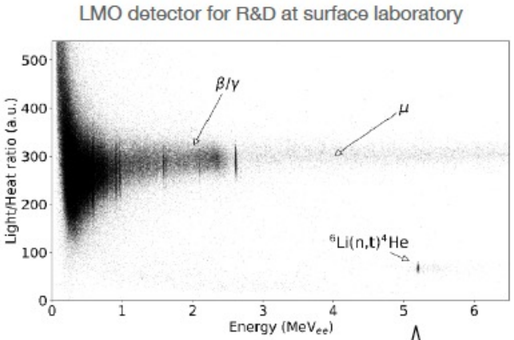










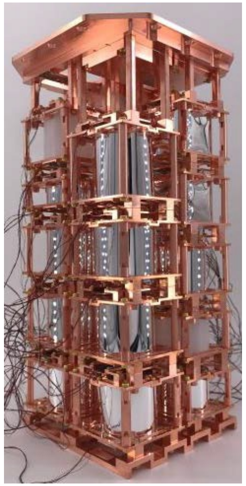


$$\mathrm{DP} = \frac{|\mu_{\beta\gamma} - \mu_{\alpha}|}{\sqrt{\sigma^2_{\beta\gamma} + \sigma^2_{\alpha}}} > 10$$

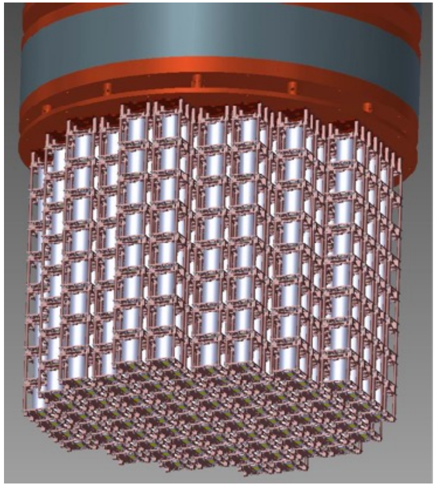
AMoRE phases summary

	Pilot	Phase I	Phase II
Mass (Crystal)	1.9 kg (CMO)	6 kg (CMO + LMO)	~160 kg (CMO + LMO)
BKG [keV ·kg· year]$^{-1}$	< 0.5	< 0.03	$< 10^{-4}$
$T_{1/2}$ Sensitivity [years] 90%CL	$< 3.2\times10^{23}$	$< 3.3\times10^{24}$	6×10^{26}
$<m_{\beta\beta}>$ Sensitivity [meV]	600 - 1000	190 - 340	20 - 35
Location	Y2L (700 m depth)		Yemi Lab (1000m depth)
Run period	2015 - 8	2020 - 2023	2024 -

6 ea



18 ea

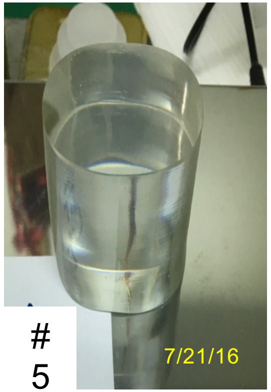


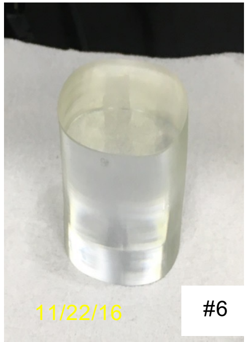
360 ea

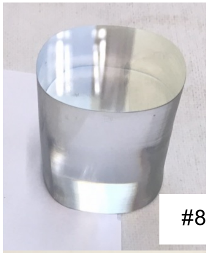
AMoRE CMO crystals (FOMOS)

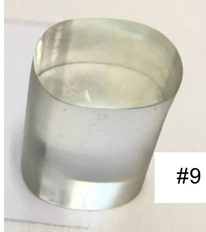
@ AMoRE-Pilot

Total: 3.387 kg









- 3 years (2015-17) for procurement of SE1-9 (9 CMOs)
- LY, resolution, transmittance, RT background measurements done.
- SB28, SB29, S35, SS68 (4 CMOs) already procured before.
- In total, 13 CMOs (4.8 kg).

Critical radioactivity

- ☐ Go through all known nuclei decaying β with $Q_{\beta\beta} > 3.02$MeV in NNDC database.
- ☐ Cosmogenic excitation is negligible after 1 year underground.
- ☐ Only Th and U natural radio-activities are critical for Q > 3.02MeV. → Great advantage to run high Q-value nuclei!

Element	Decay	$T_{1/2}$	Q (MeV)	Mother	Chain	Comment
^{26}Al	EC	$7.4\text{x}10^{5}$y	4.004	N/A		Long lifetime
^{56}Co	EC	0.21y	4.567	N/A		Short lifetime
^{88}Y	EC	0.29y	3.623	^{88}Zr (0.23 y)		Short lifetime
^{106}Rh	B-	30s	4.004	^{106}Ru(1.02y)		
^{126}Sb	B-	12.5d	3.670	^{126}Sn($2.3\text{x}10^{5}$y)		Long lifetime
^{146}Eu	EC	4.61d	3.878	^{146}Gd (0.13 y)		Short lifetime
^{208}Tl	B-	3.05m	4.999	^{228}Th (1.91 y)	^{232}Th	Main
^{209}Tl	B-	2.16m	3.970	^{233}U(159200y)	^{233}U	2.1% branching
^{210}Tl	B-	1.3m	5.482	^{226}Ra(1600y)	^{238}U	0.02% branching
^{214}Bi	B-	19.9m	3.269	^{226}Ra(1600y)	^{238}U	Main

AMoRE CMO: RT measurement at 4π setup

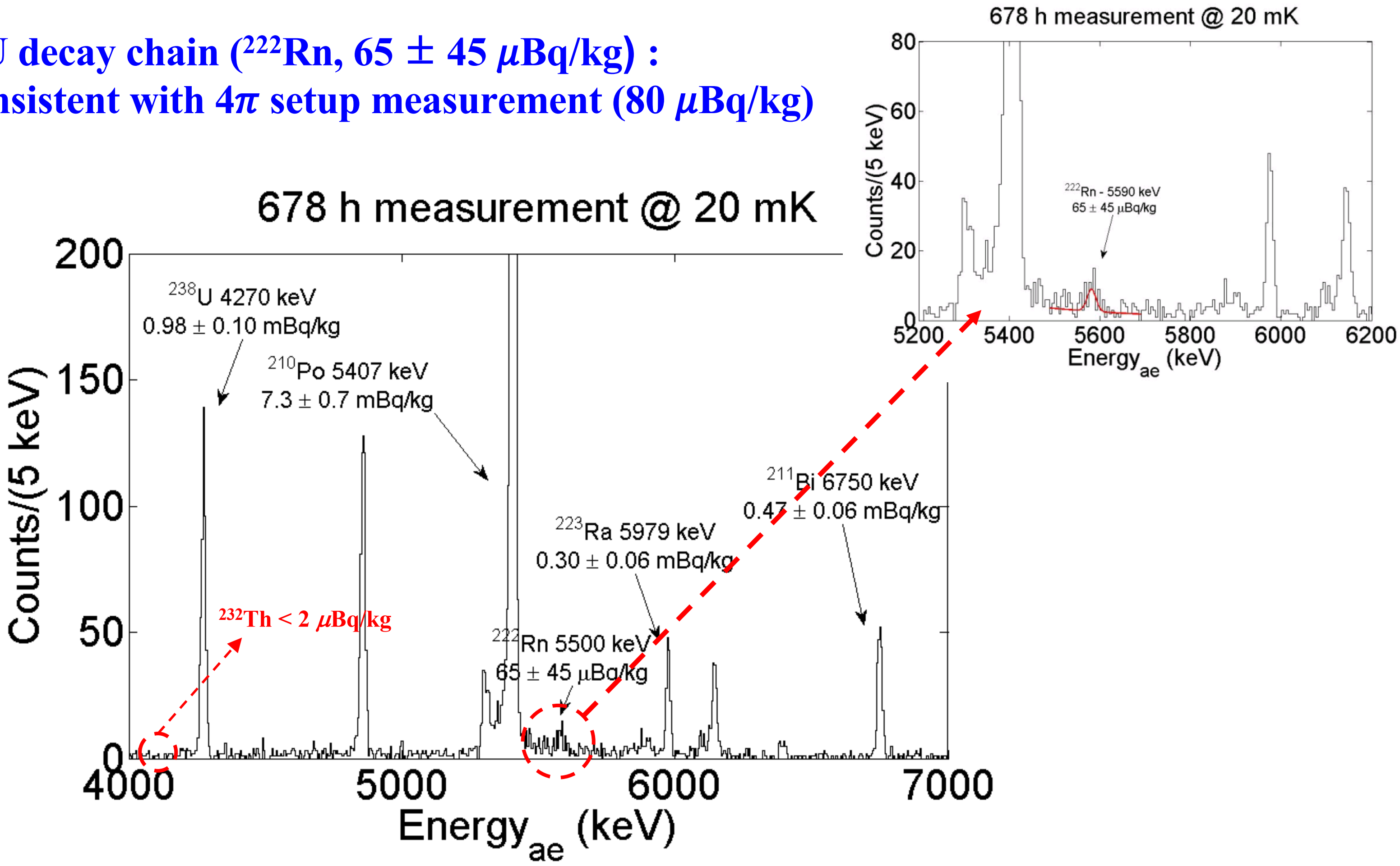
[μB/kg]	^{227}Ac (^{215}Po) (^{235}U family)	^{226}Ra (^{214}Po) (^{238}U family)	^{228}Th (^{216}Po) (^{232}Th family)	Alpha	Relative Light Yield
Qualification*	<500	<100	<50	<1000	
SE1	60 ± 8	40 ± 6	50 ± 6		0.43
SE2	90 ± 10	20 ± 3	< 100		0.58
SE3	30 ± 6	6 ± 3	30 ± 6	28000	0.75
SE4	30 ± 6	10 ± 3	10 ± 3	3200	0.60
SE5	40 ± 6	10 ± 3	10 ± 3		0.70
SE6	35 ± 6	100 ± 10	70 ± 10		0.62
SE7	80 ± 10	30 ± 5	65 ± 10		0.60
SE8	40 ± 6	20 ± 5	40 ± 6		0.55
SE9	0 ± 6	<11	50 ± 6		0.66

***Expect to have 10^{-3} counts/keV/kg/y at AMoRE-I**

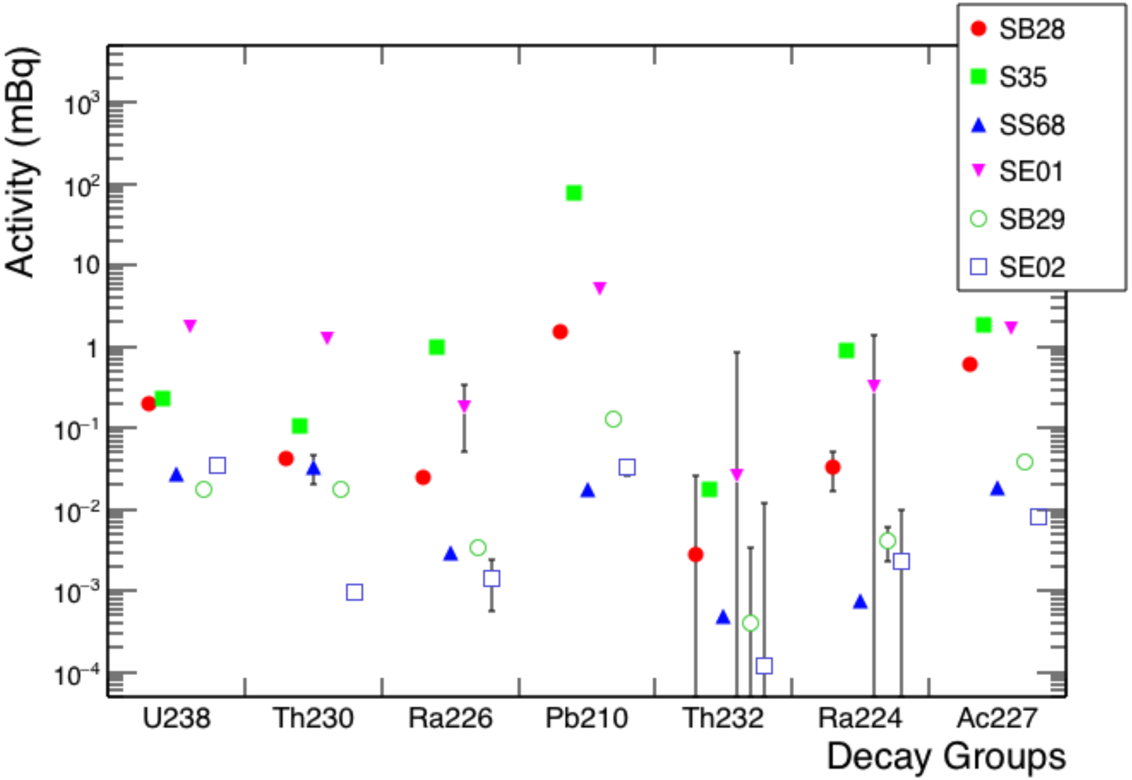
J.Y. Lee et al., IEEE TNS vol. 65 No. 8 (2018) 2041

Internal alpha background of SB28 (AMoRE-Pilot)

- ^{238}U decay chain (^{222}Rn, 65 ± 45 μBq/kg) : Consistent with 4π setup measurement (80 μBq/kg)



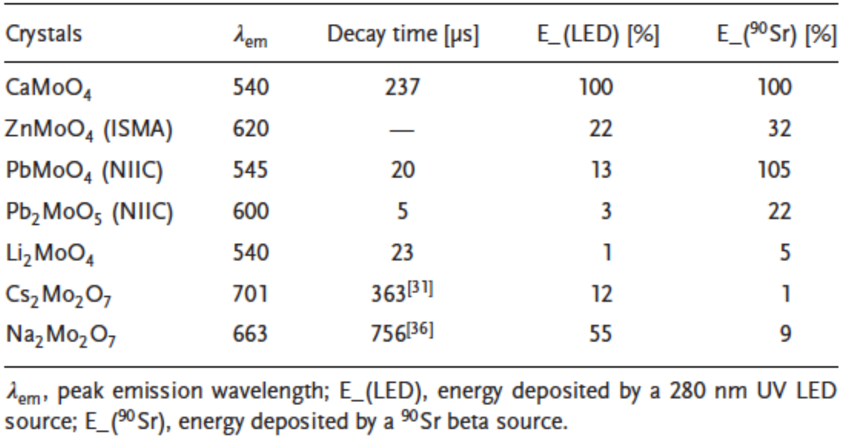
AMoRE-Pilot: Internal Activities from α rates



- Most of the ^{210}Pb are bulk contribution.
- Internal backgrounds between crystals differ more than an order, even two orders.

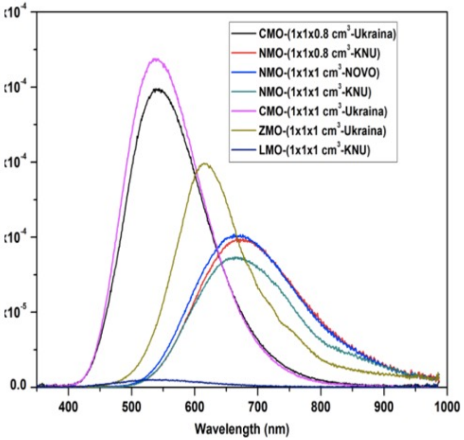
Decision on crystals for AMoRE-II

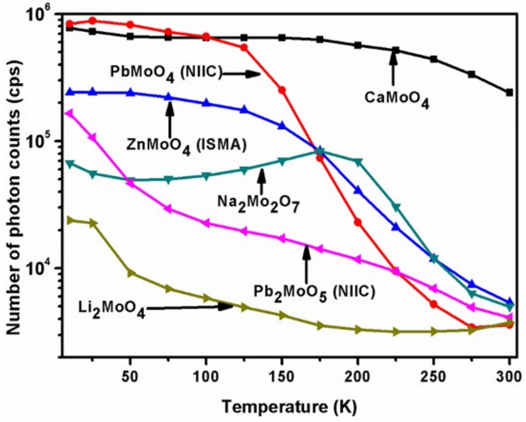
- ❑ CMO ($CaMoO_4$) is a very good crystal with the largest light output, but CMO has a disadvantage in that we need ^{48}Ca depleted isotopes, expensive.
- ❑ CUPID-Mo group decided to use LMO (Li_2MoO_4).
- ❑ We worked on LMO, PMO ($PbMoO_4$), & NMO ($Na_2Mo_2O_7$) crystals, and LMO was chosen due to its easiness of growth and machining and low background.



Crystals	λ_{em}	Decay time [μs]	E_(LED) [%]	E_(^{90}Sr) [%]
$CaMoO_4$	540	237	100	100
$ZnMoO_4$ (ISMA)	620	—	22	32
$PbMoO_4$ (NIIC)	545	20	13	105
Pb_2MoO_5 (NIIC)	600	5	3	22
Li_2MoO_4	540	23	1	5
$Cs_2Mo_2O_7$	701	363[31]	12	1
$Na_2Mo_2O_7$	663	756[36]	55	9

λ_{em}, peak emission wavelength; E_(LED), energy deposited by a 280 nm UV LED source; E_(^{90}Sr), energy deposited by a ^{90}Sr beta source.

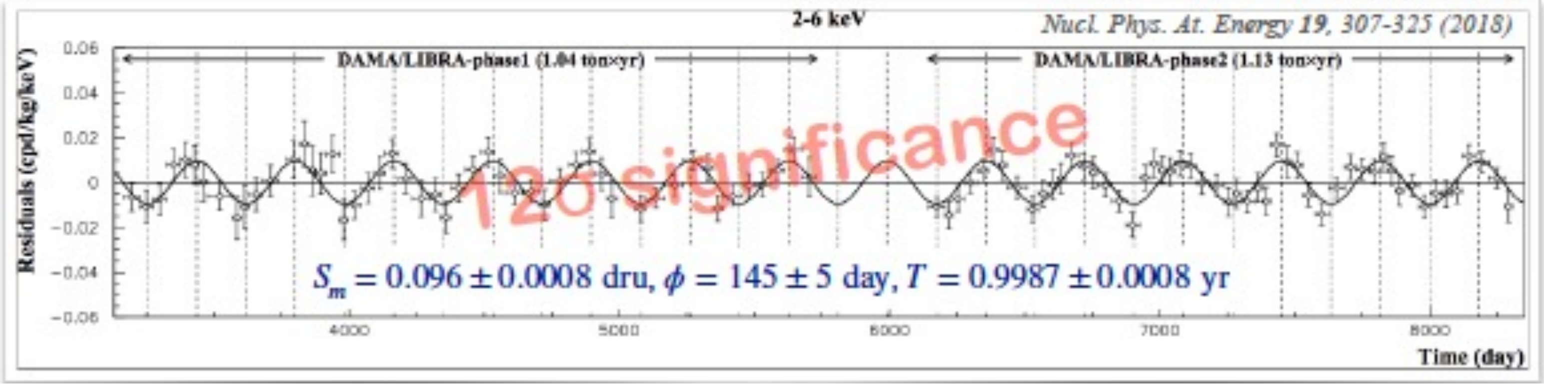


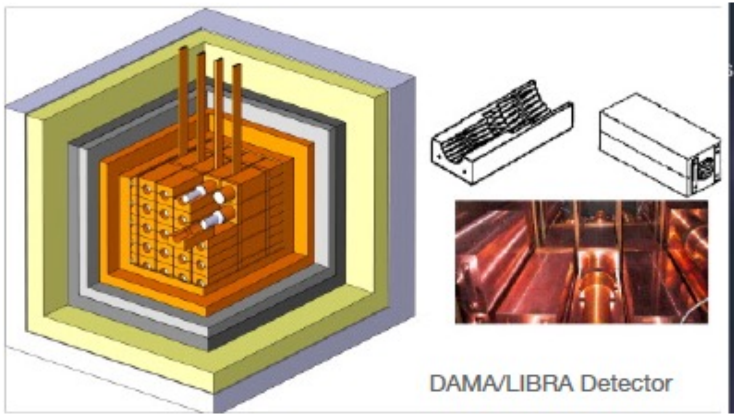


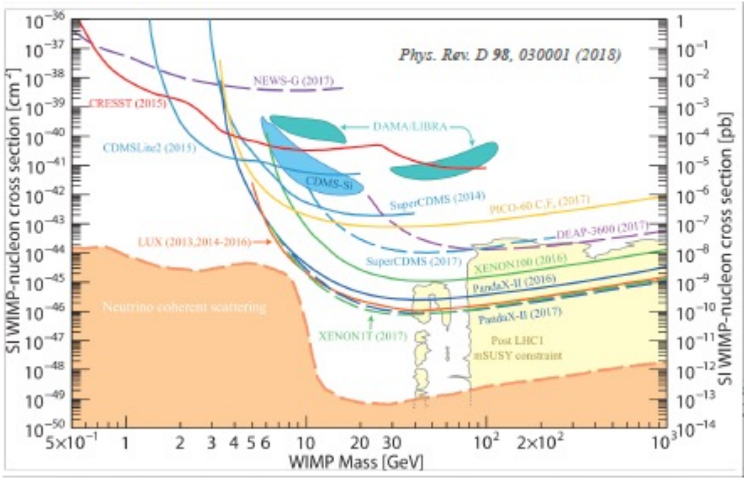
H.J. Kim et al., Crystal Research & Technology, Nov. 2019

WIMP DM search: COSINE-100

❑ To test the DAMA/LIBRA's annual modulation signal with the same NaI(Tl) detectors.







No other experiments succeeded in observing the DM signal.

COSINE-100 instrument

JINST 13 T02007 (2018)

4π Muon Counter
37 plastic scintillator panels
2-inch PMT(H7195)s for muon counter

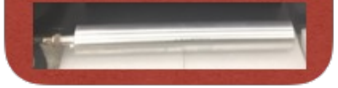
Nucl. Instrum. Meth. A 851 103 (2017)

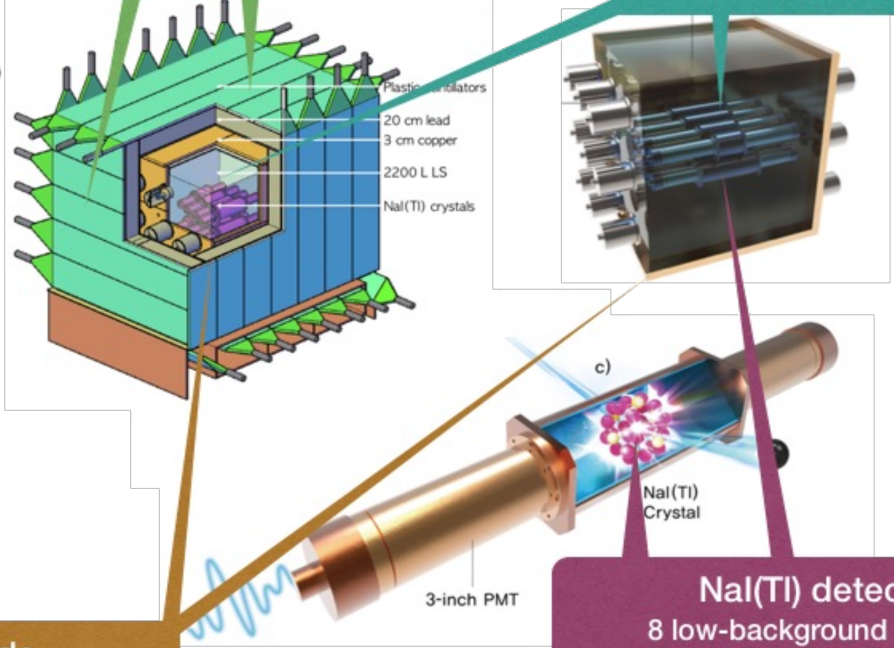
Liquid Scintillator
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector

JINST 13 T06005 (2018)

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

Thermal neutron detector
(^{3}He gas detector)

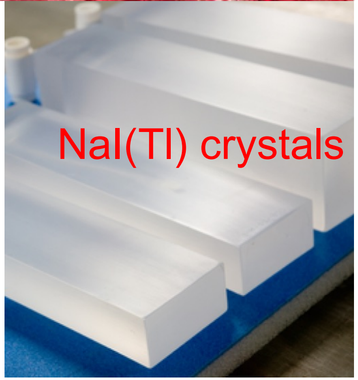




Shields
3-cm thick copper box
20-cm thick lead shielding

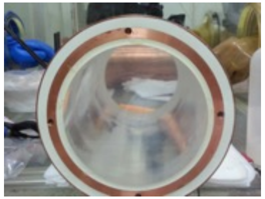
NaI(Tl) detector
8 low-background crystals
Each crystal is encapsulated in copper
Two 3-inch PMTs for each crystal
(R12669SEL)

Eur. Phys. J. C. 78 107 (2018)



COSINE-100 NaI(Tl) crystal detector

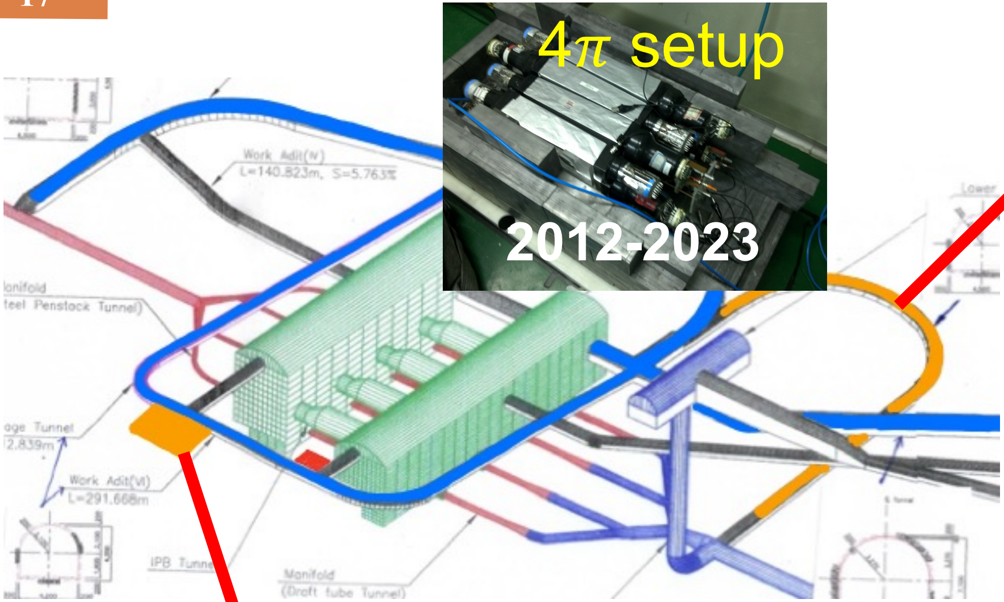
- 8 ultra low-background NaI(Tl) crystals with a mass of 106 kg in total
- U/Th/K levels are less than DAMA, but total alphas (^{210}Pb) are higher than DAMA.
- Higher light yield (15 p.e/keV) than DAMA
- Can make the threshold lower easily
- Total background level is 2-3 times that of DAMA.



Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS II	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WS III	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WS III	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
Crystal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5

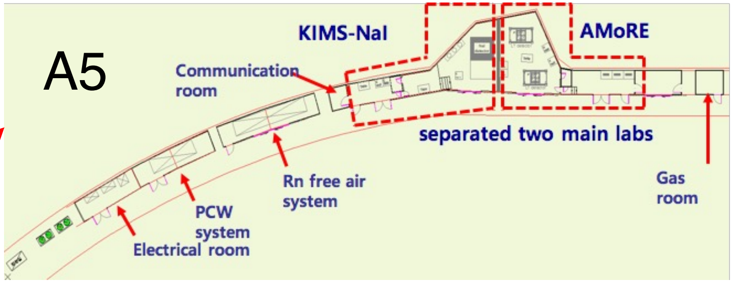
Eur. Phys. J. C. 78 107 (2018)

Experiments at the Y2L



4π setup

2012-2023



A5

AMoRE

(0νββ Decay)

2015 - 2023

A5

HPGe array

2017-

A6 **2003-**

KIMS-CsI (WIMP)

HPGe, 4π setup

2003-

KIMS

CsI(Tl)

A5

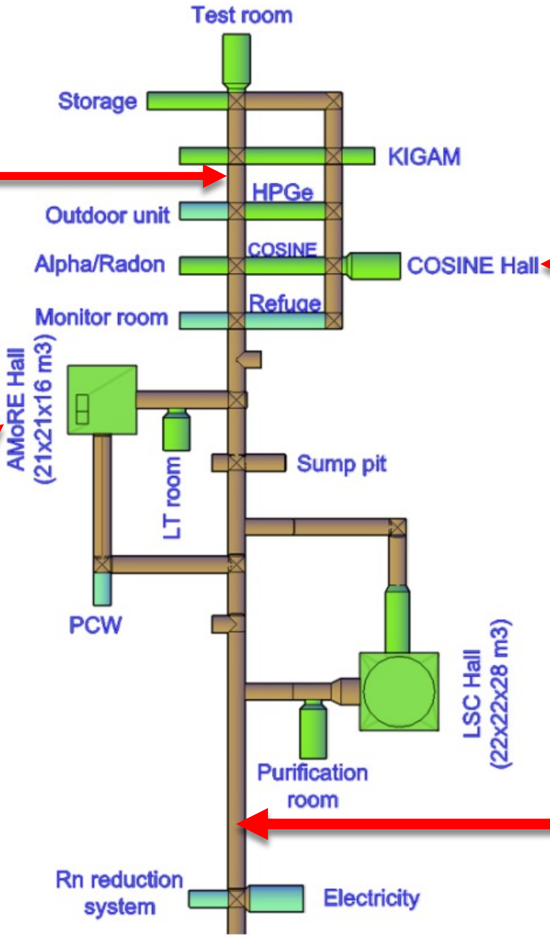
COSINE-NaI

(WIMP)

2016 - 2023

Yemilab: Underground experiments

Ladder type
2023-



COSINE-100 upgrade
2024-

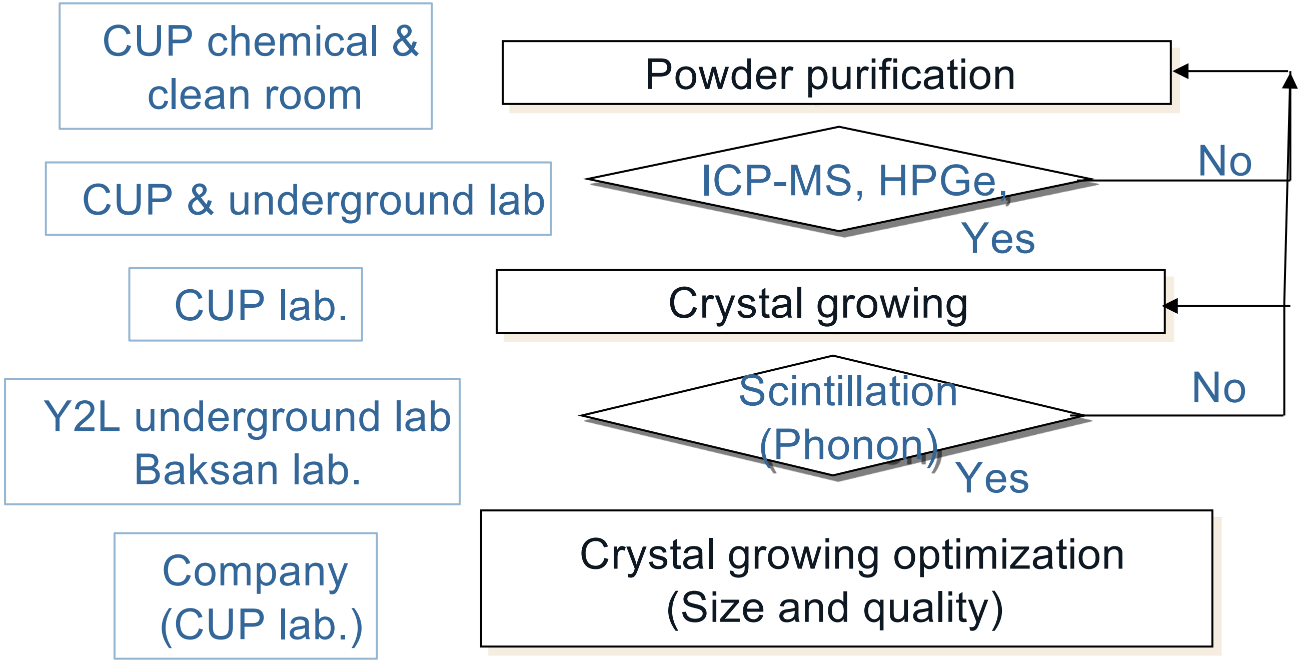
AMoRE-II
2024-

Access tunnel

Ultra-low background crystal production

Ultra-low background powder R&D is difficult and needs **quick feedback**

(Purification and measurement of 10 μBq/kg ^{238}U, ^{232}Th & total radioactivity of alpha < 1 mBq)



CUP chemical & clean room

Powder purification

CUP & underground lab

ICP-MS, HPGe,

No

Yes

CUP lab.

Crystal growing

Y2L underground lab
Baksan lab.

Scintillation (Phonon)

No

Yes

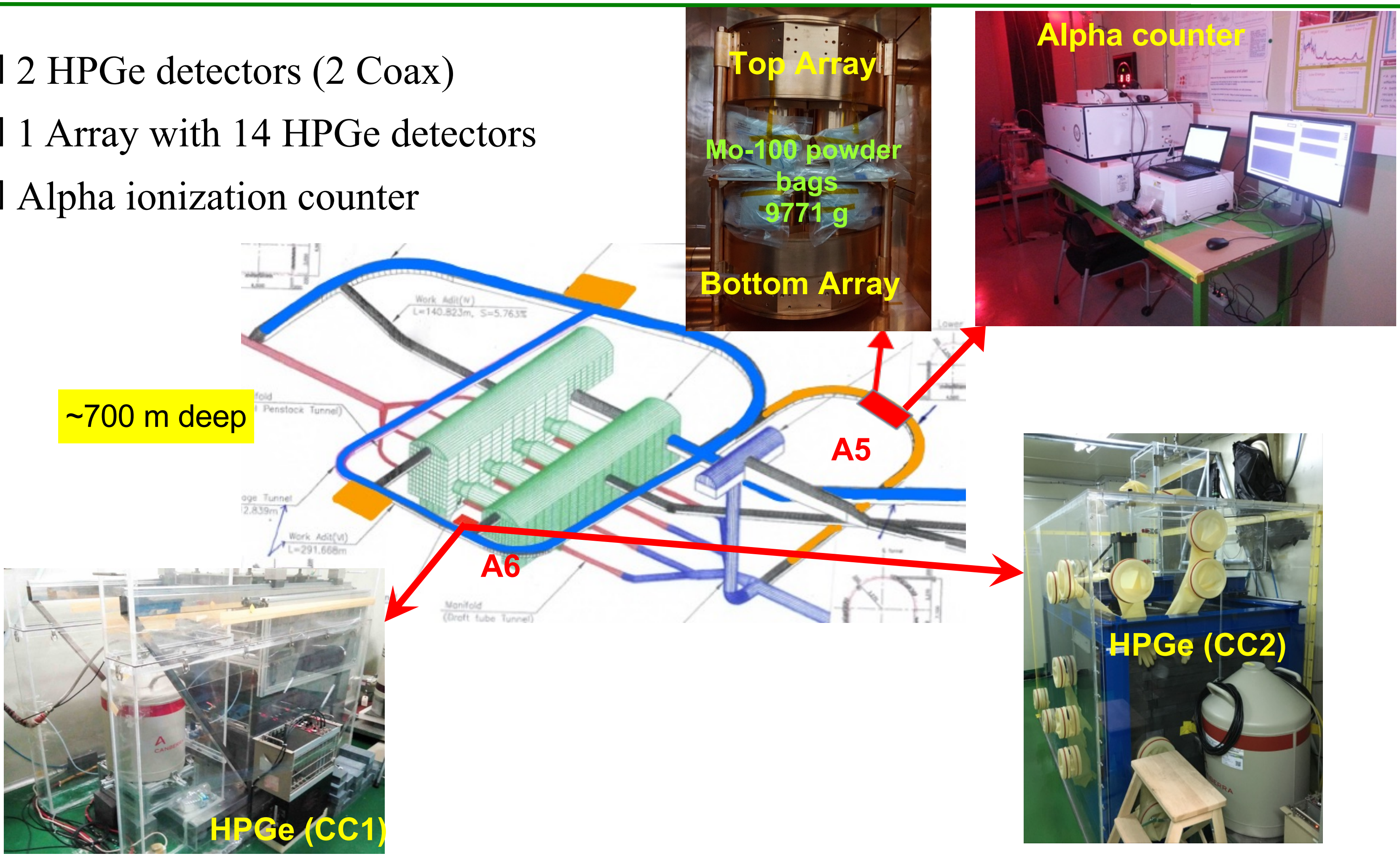
Company (CUP lab.)

Crystal growing optimization (Size and quality)

Re-crystalization

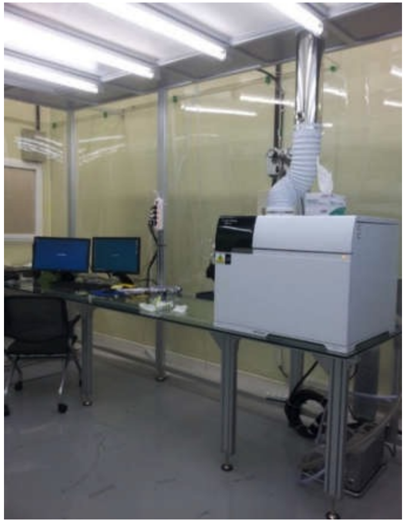
Radioassay at Y2L

- ☐ 2 HPGe detectors (2 Coax)
- ☐ 1 Array with 14 HPGe detectors
- ☐ Alpha ionization counter



Radioassay at IBS HQ, Daejeon: ICP-MS

- ☐ Agilent 7900, the highest sensitivity single MS system in 2015 when purchased.
- ☐ Under operation since Oct. 2015. (Moved to IBS HQ in spring 2018)
- ☐ In a cleanroom nominally designed as class 1000, > 150 air changes/hour.
- ☐ A Millipore DI system, in-house acid distillation with a 3 linear meters of chemical hood space.
- ☐ Dissolve sample in liquid form, uptake in argon (Ar) gas stream, ionize gas, extract into mass spectrometer, measure trace contaminants.
- ☐ Confirmation of purification methods by measuring isotopic or chemical tracers.
- ☐ Confidence in systematics at ultra-trace levels is not easily achievable through outsourced measurements.

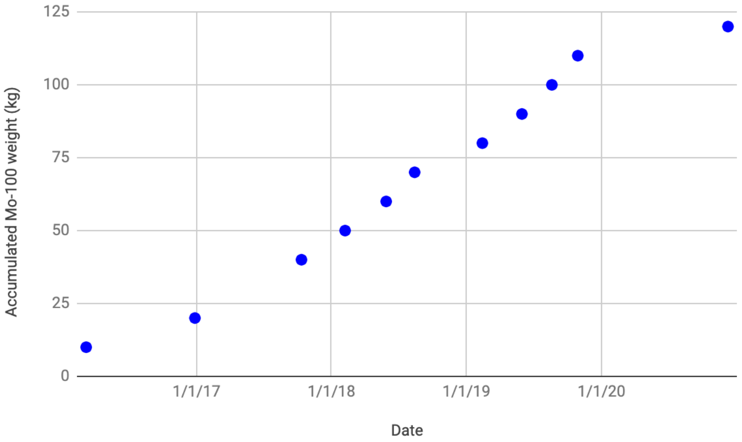


^{100}MoO3 powder (ECP) for AMoRE-II

Total 120 kg of ^{100}Mo

Date(weight)	Lot	Delivery@ Y2L
2015 (10 kg)	#1(3172)	3/9/16
	#2(3328)	
2016 (10 kg)	3434	12/28/16
2016 (10 kg)	3497	10/12/17
2016 (10 kg)	3535	
2017 (10 kg)	3589	2/7/18
2017 (10 kg)	3649	5/29/18
2017 (10 kg)	3675	8/14/18
2017 (10 kg)	3741	2/13/19
2018 (10 kg)	3803	5/31/19
2018 (10 kg)	3824	8/20/19
2018 (10 kg)	3848	10/29/19
2018 (10 kg)	3922	12/8/20

Last delivery Dec. 2020



HPGe Array meas. (9/13 – 11/28/2017)

- ^{226}Ra chain (^{238}U):1.6 ± 0.3 mBq/kg
- ^{228}Th chain (^{232}Th): 244 ± 50 μBq/kg (first measurement)
- ^{88}Y: 33 ± 8 μBq/kg (cosmogenic)

Purification & Crystal: Motivation & Manpower

- **Motivation**
  - Lack of commercial producers for ultra-pure crystals needs in AMoRE-II and COSINE-200.
  - The company who produced $CaMoO_4$ for AMoRE-pilot & I does not want to provide information which is critical in improving the background levels at the grown crystals.
  - The company who produced ultra-pure NaI(Tl) crystals for DAMA/LIBRA does not know how to grow the ultra-pure pure NaI(Tl) crystals any more.
  - The company who produced pure NaI(Tl) for COSINE-100 could not provide ultra-pure crystals for COSINE-200.
- **Manpower**
  - Purification working group (Led by Dr. Olga Gileva)

    - 4 peoples: 1 Chemist (PhD), 2 Material Scientists (MS), 1 Chemist (BS)
  - Crystal growing and machining working group (Led by Mr. SeJin Ra)
    - 4 peoples: 4 Scientists (MS)

  - Collaborators
    - Prof. Vitaly Milyutin, IPCE RAS, Russia (Purification)
    - Dr. Yan Vasiliev / Dr. Vladimir Shlegel, NIIC, Russia (AMoRE crystals)
    - Mr. Alan Iltis (NaI crystal, Former Saint Gobain employee)
    - Prof. HongJoo Kim at Kyungpook National University, Daegu, Korea (Crystal R&D)
    - Prof. HyangKyu Park at Korea University, Sejong, Korea (Purification)

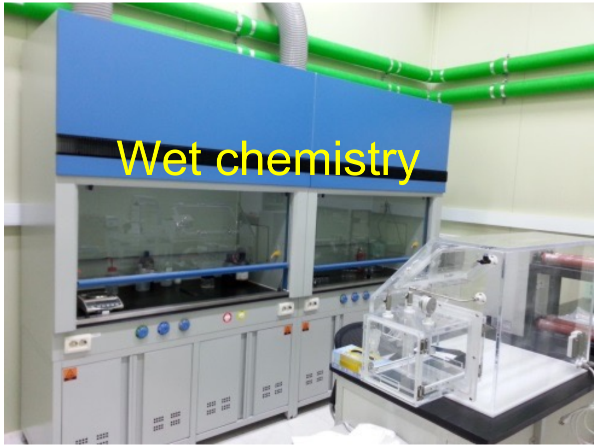
Purification facility for AMoRE

- □ Main goal: Low BKG raw materials for crystals growing.
- □ Deep purification of Li_2CO_3 MoO_3 powders (< 50 µBq/kg for U, Th chains) for AMoRE-II (The goal achieved).


A sublimation device for ~1.5 kg powder load

Purified powder after sublimation


Sublimated MoO3 powder


Wet chemistry

Purified $^{100}MoO_3$ powder (examples)

S/N	Amount (kg)	Al (ppb)	K (ppb)	Cr (ppb)	Mn (ppb)	Fe (ppb)	Ni (ppb)	Cu (ppb)	W (ppb)	Sr (ppb)	Ba (ppb)	Pb (ppb)	Th ppt	U ppt
1	1.1	585	409	<200	<30	39	<20	<200	33	<0.15	3.9	0.3	<10	<7
31	1.2	<30	153	<200	<30	136	<20	<200	711	<0.15	<3.0	<0.5	<10	<7
32	1.3	<30	150	<200	<30	26	<20	<200	648	<0.15	<3.0	<0.5	<10	<7

Purification facility for COSINE(-200)

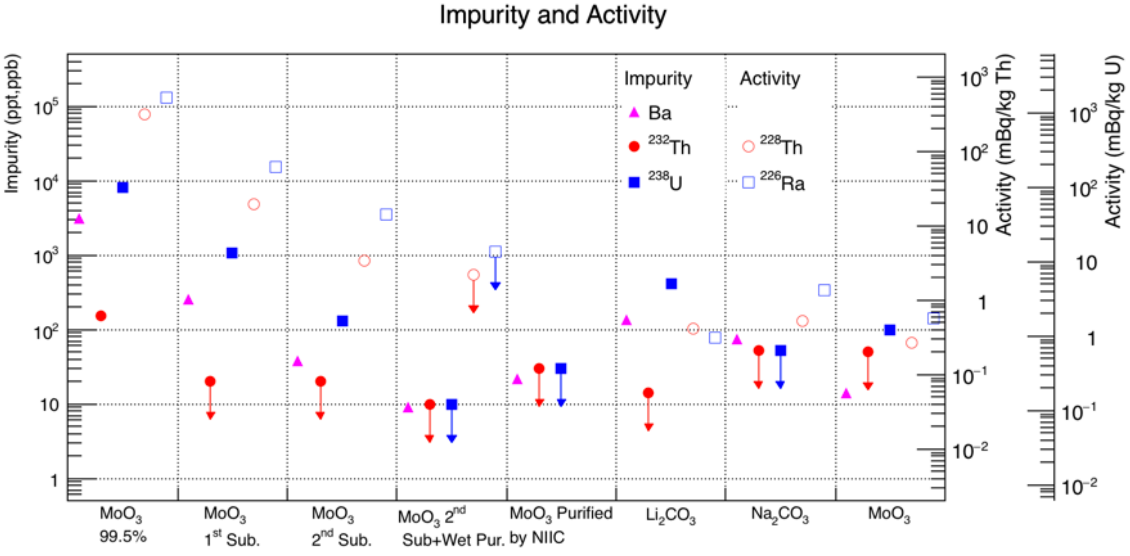
- ❑ Extremely pure crystal development
  - Background level less than that of DAMA/LIBRA (1 dru)
  - In-house development for the entire processes
    - Purification of NaI powder achieved the goal.

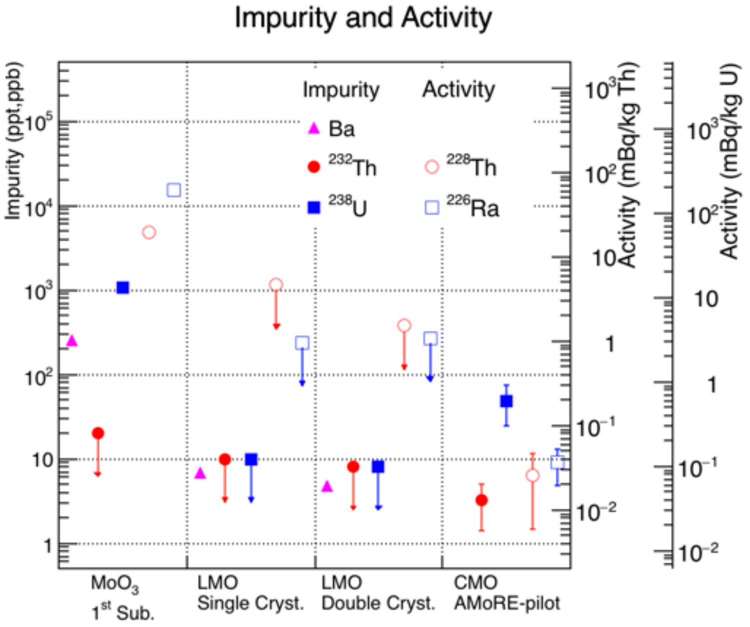
Crystal grade NaI [99.99(5) %]

Material	Initial [ppb]	Purified [ppb]
^{39}K	45.1	6.0
^{208}Pb	3.3	0.8
^{232}Th	< 0.1	< 0.1
^{238}U	< 0.1	< 0.1

J. Rad. Nucl. Chem. 317 1329 (2018)

AMoRE-II: Purification of XMO crystals





☐ Ba is a good indicator for Ra since they are in the same family.

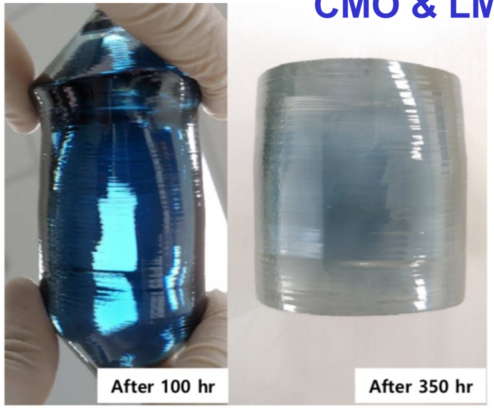
Molybdate crystals growth at CUP

- Successful in growing molybdate crystals. Growing time ~ 1 week.
- The purities of the grown crystals are measured by ICP-MS and confirmed.
- Enriched LMO crystals have been growing at NIIC and CUP for AMoRE-II.

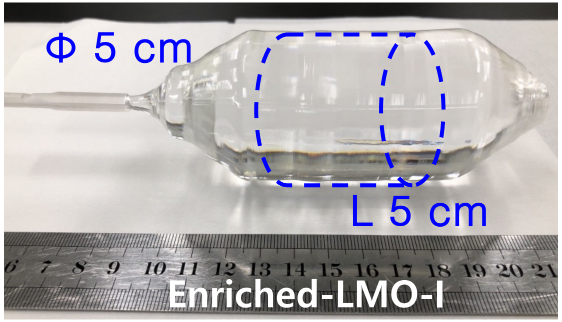
$CaMoO_4$ (CMO) & Li_2MoO_4 (LMO) crystals

- Czochralski growers (3 in total)
  - Crystal size & weight:
- Φ ~5 cm × L ~14 cm, ~600 g

CMO & LMO crystals by CUP



Purified CMO (Ir, Annealed)

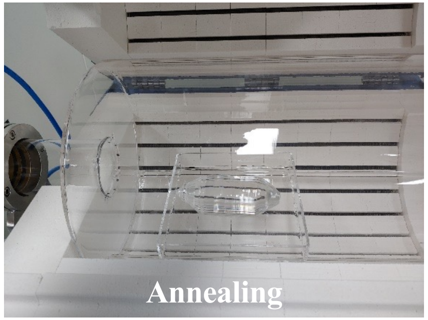


$^{48depl}Ca^{100}MoO_4$ (AMoRE-Pilot/I): Excellent but $^{48depl}Ca$ & Ca deep purification necessary .

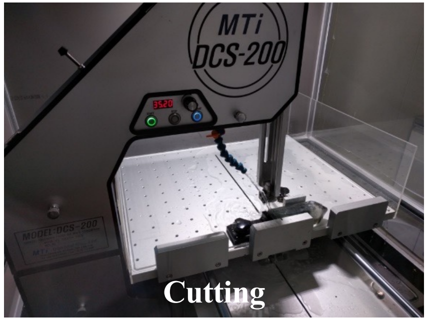
Crystal production at CUP (AMoRE)


Growing

- Czochralski grower 3 ea (2014 ~)
- Fused alumina refractory (less impurities)
- Platinum crucible (99.95 %) 1600 ℃
- High purity (99.999 %) Air

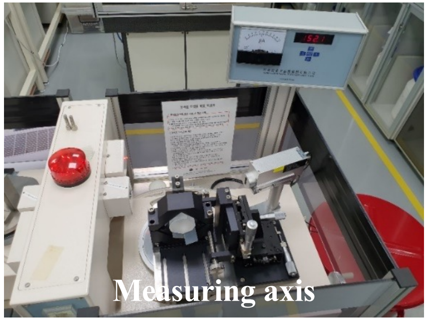

Annealing

- Annealing furnace (2019)
- Quartz tube
- High purity (99.999 %) Air
- Temperature : 500 ℃

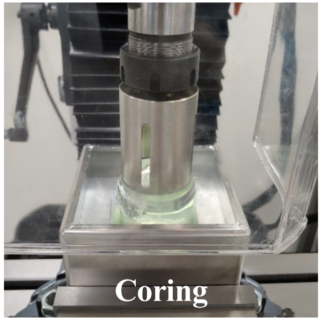


Cutting

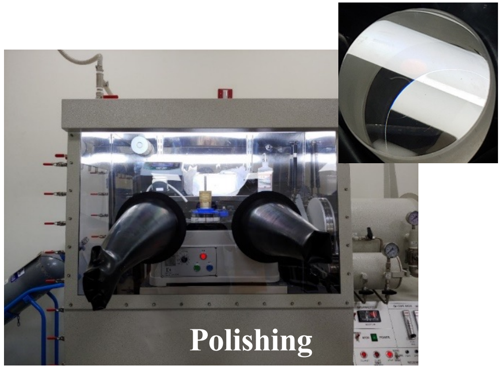
- Cutting machine (2017)
- Diamond band saw
- Mineral oil (for hygroscopic crystal)


Measuring axis

- Crystal orientation unit (2019)
- X-ray goniometer


Coring

- Milling machine (2020)
- Diamond core drill bit
- Mineral oil (for hygroscopic crystal)


Polishing

- Polishing machine in a glove box (2019)
- SiC + oleic acid and colloidal silica
- Polytex pad

Purities of CUP grown LMO crystals

Element		Al	K	Ba	Sr	Pb	Th	U
No.	sample	(ppb)	(ppb)	(ppb)	(ppt)	(ppt)	(ppt)	(ppt)
Single crystallized natural LMO (w/o purification)								
CMD 113	L1701-1	48.1	347.3	5.445	<15	<300	<15	<16
CMD 113	L1701-2	21.7	449.2	5.401	75	<300	<15	<16
Single crystallized natural LMO (MoO_3 sublimed)								
CMD163.1	CZ02-L1706-T	<11	38	7.579	<50	<100	<8	<8
CMD163.2	CZ02-L1706-B	<11	83	9.617	<50	<100	<8	<8
Double crystallized natural LMO (MoO_3 sublimed)								
CMD191.1	CZ02-L1801-T	<11	<30	4.744	<50	<100	<8	<8
CMD191.2	CZ02-L1801-B	<11	<30	5.814	<50	<100	<8	<8
Enriched LMO (w/o purification)								
CMD00236.2	CZ02-L1803E-T	1437	<40	6.82	<31	<225	<6	<6
CMD00236.3	CZ02-L1803E-B	1484	<40	7.07	<31	<225	<6	<6
CMD00236.1	CZ02-L1803E-RM	3824	249	28.58	4110	12290	71	472

Ultra-pure LMO crystals grown at CUP

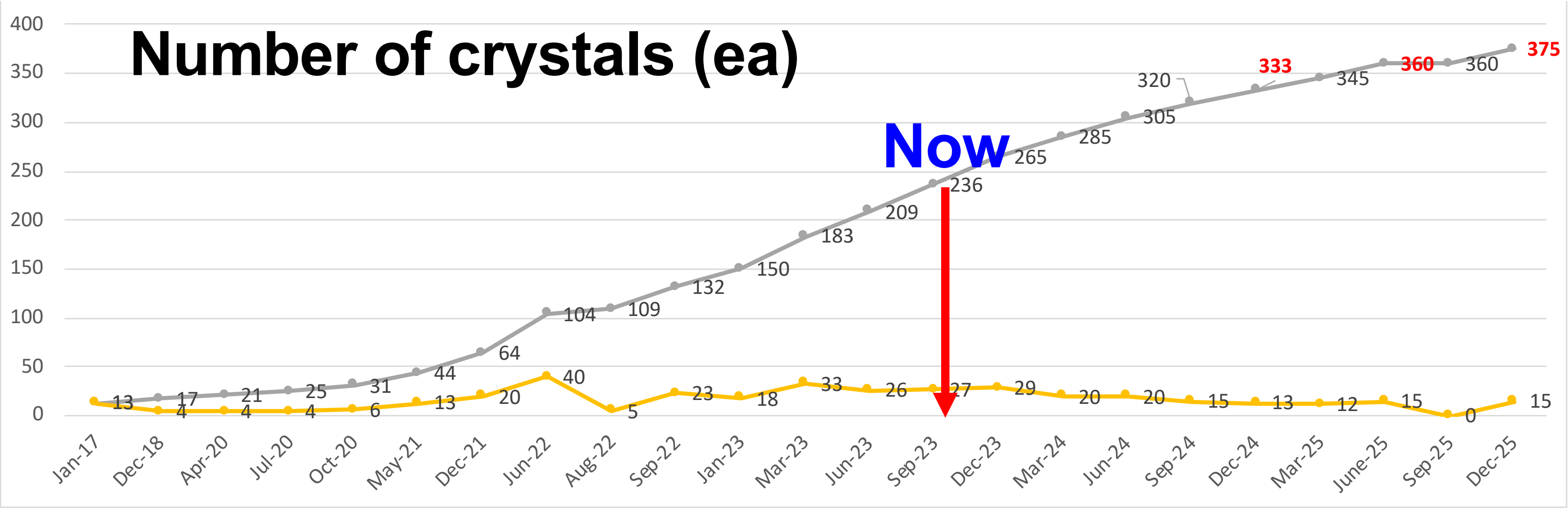
LMO sample name	K	Ba	Sr	Zr	Ir	Pb	Th	U
	(ppb)	(ppb)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)
CZ01-L2110ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2110ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2111ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2111ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2112ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2112ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2113ED-4-T	<50	<3	<50	<150	<70	<150	<6	<6
CZ01-L2113ED-4-B	<50	<3	<50	<150	<70	<150	<6	<6

- ☐ CUP-grown LMO crystals with CUP-purified raw materials ($^{100}MoO_3$ and Li_2CO_3 powders) give detection limit values in ICP-MS measurements.
- ☐ We have a great progress toward AMoRE-II crystals. Waiting for confirmation of the background levels at the low temperature (~10 mK) with cryogenic detectors.

AMoRE-II crystal production schedule

Total at CUP:

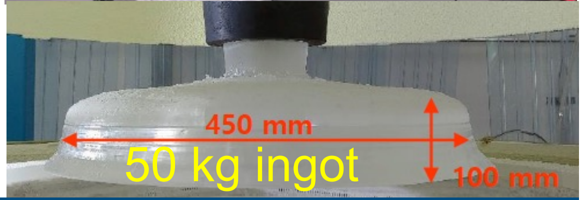
- ❑ 15 CMO, 108 (5 cm) & 77 (6 cm) LMO
- ❑ 200 ea, ~ 75.4 kg
- ❑ Production both at NIIC and CUP

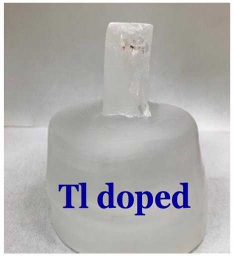


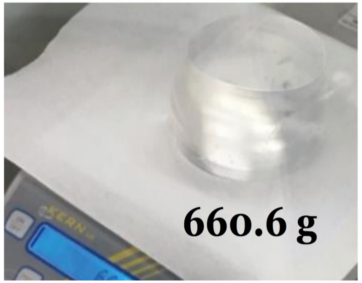
- ❑ **By the end of 2024: 143 kg, 333 ea**
- ❑ **By mid 2025: 157 kg, 360 ea (Max.)**

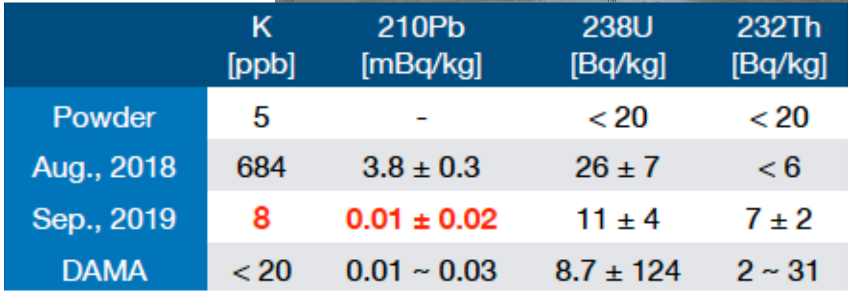
NaI(Tl) crystal growth for COSINE(-200)

- ☐ Extremely pure crystal development
  - Background level less than that of DAMA/LIBRA (1 dru)
  - In-house development for the entire processes
    - Full-size NaI(Tl) crystal grower
- ☐ The current COSINE-100 shield is designed to accommodate sixteen 12.5 kg crystals (200 kg).









	K [ppb]	210Pb [mBq/kg]	238U [Bq/kg]	232Th [Bq/kg]
Powder	5	-	< 20	< 20
Aug., 2018	684	3.8 ± 0.3	26 ± 7	< 6
Sep., 2019	8	0.01 ± 0.02	11 ± 4	7 ± 2
DAMA	< 20	0.01 ~ 0.03	8.7 ± 124	2 ~ 31

Summary

- ❑ CUP has two major rare process experiments running in the Y2L & Yemilab (AMoRE DBD & COSINE DM).
- ❑ CUP has been running an ultra-low background radioassay facility in the Y2L and IBS HQ to screen raw materials for the detector components (i.e., crystals) since 2014.
- ❑ Background levels of AMoRE-Pilot CMO crystals measured both in RT and LT are consistent with each other.
- ❑ Background levels of nine FOMOS CMO crystals measured in RT confirmed that they meet the requirement of 10^{-3} ckky in AMoRE-I.
- ❑ AMoRE-II with 200 kg of crystals requires an even lower background level of 10^{-4} ckky.
- ❑ Purification and growth of molybdate crystals at the CUP started in 2016, are in the mass-production stage for AMoRE-II (LMO).
- ❑ COSINE-100 has 106 kg of NaI(Tl) crystals with similar or lower background levels in ^{40}K/U/Th than those of the DAMA except ^{210}Pb. It has 2-3 more background than that of the DAMA in low energy.
- ❑ COSINE's next phase is going to use ultra-pure NaI(Tl) crystals with ~200 kg mass to confirm/dispute the DAMA's annual modulation in a model-independent way.
- ❑ Purification and crystal growth of NaI(Tl) started at the CUP in 2017 and are in good progress.