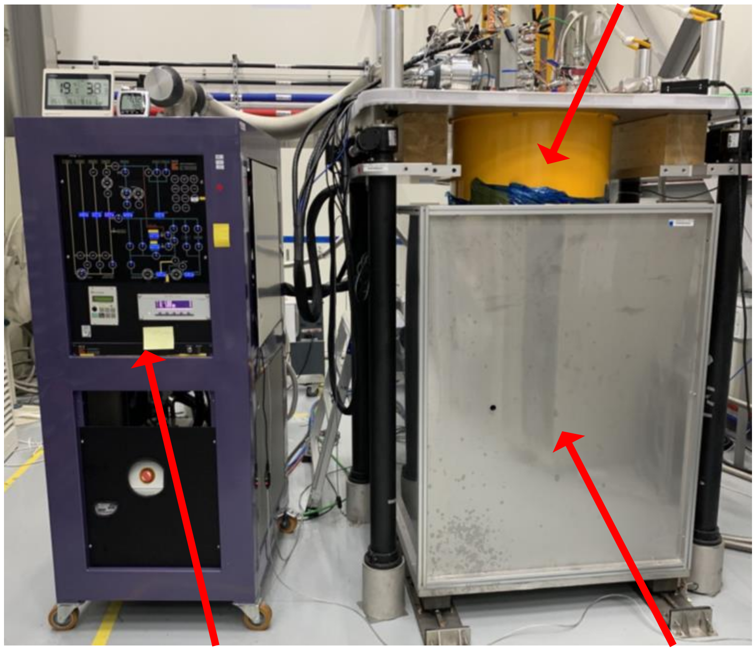
A study to enhance performance for AMoRE-II detector with lithium molybdate crystal absorber

Wootae Kim

Contents

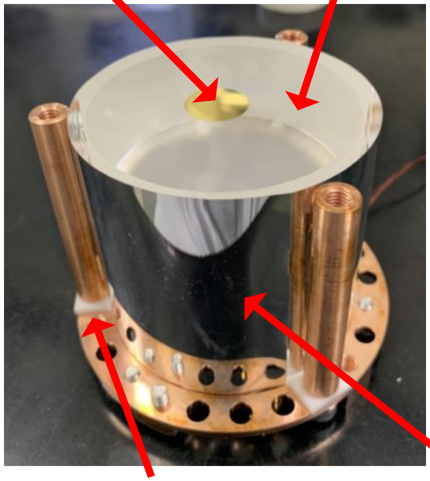
AMoRE R&D Experiment

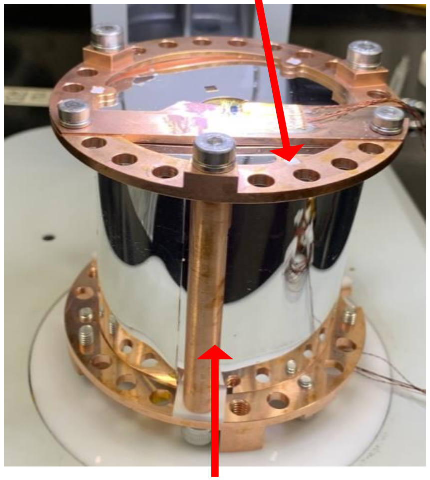
Cryostat



Gas handling system (GHS) **Lead shielding**

Gold film **Li_2MoO_4 crystal** **Teflon**





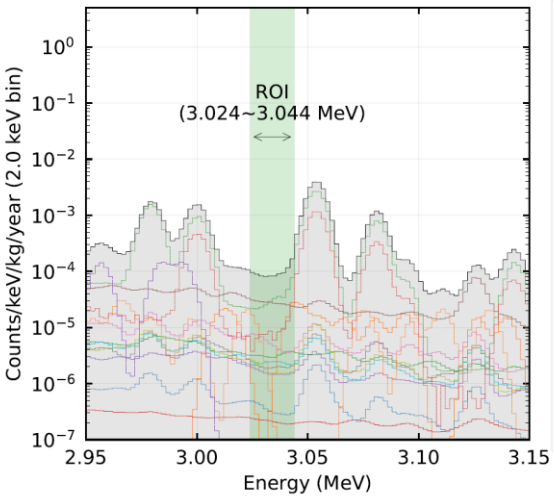
Teflon (to support crystal) **Vikuiti reflector** **Cooper frame**

- Main target material of the AMoRE-II : $Li_2{}^{100}MoO_4$ crystal
- A Cryogen-Free Dilution Refrigerator (Leiden CF-SC81-700) with a cooling power of 400 μW at 100 mK at IBS H.Q. in Daejeon, Korea
- Operation temperature : 10 ~ 30 mK
- The external lead shield of 10 cm is installed surrounding the cryostat to reduce external gamma rays

Motivation – Energy resolution

- Separation between double beta decay (2ν2β) spectrum and neutrinoless double beta decay (0ν2β) (enough)

- **Background events of ^{214}Bi by Pb (Current)**
  - A simulation result of AMoRE-II with 10 keV FWHM energy resolution. (Requirement of background rate in ROI: ~ 10^{-4} ckky)
  - 3053.9 keV → the major background, main reason of the 10 keV resolution
  - ^{100}Mo Q-value: 3034 keV

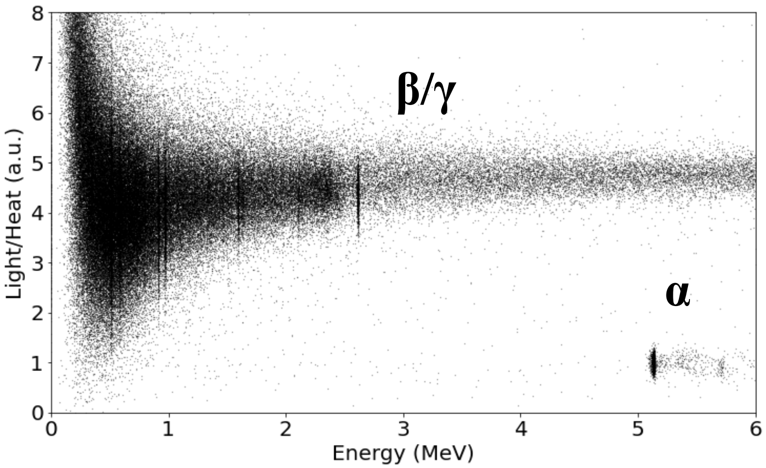


Energy (keV)	Intensity (%)
3000.0	0.0086
3053.9	0.0209
3081.79	0.0059
3094.0	5.9E-4
3142.6	0.00123
3149.0	8.6E-5

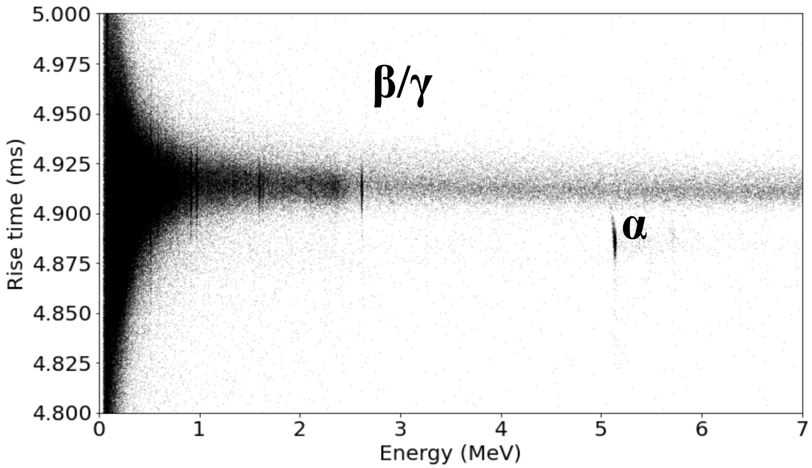
Motivation – Rejection of α background

- **Discrimination between α and β/γ**

- Particle Identification (PID) using light channel



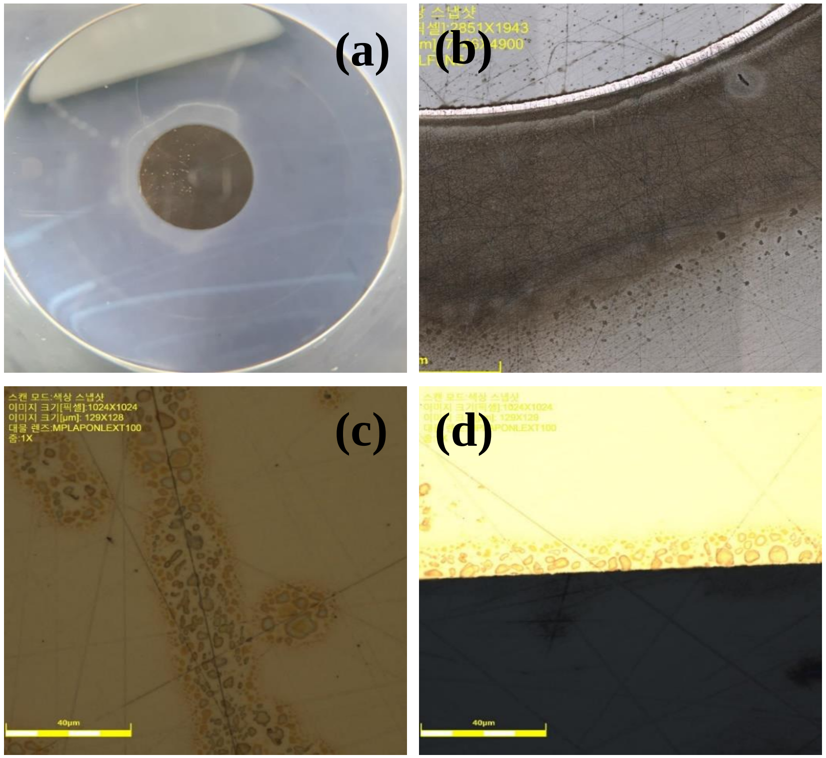
- Pulse shape discrimination (PSD)

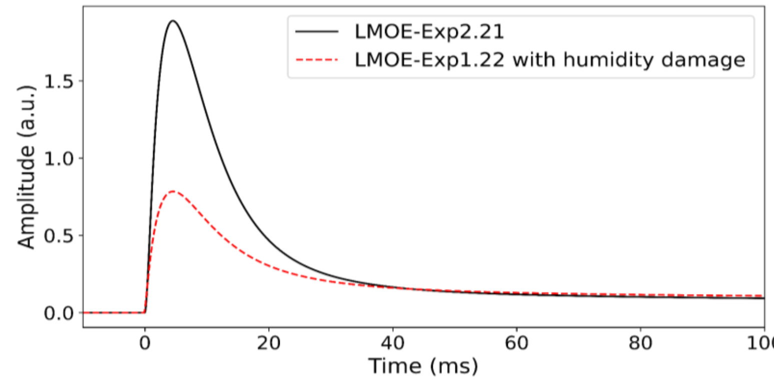


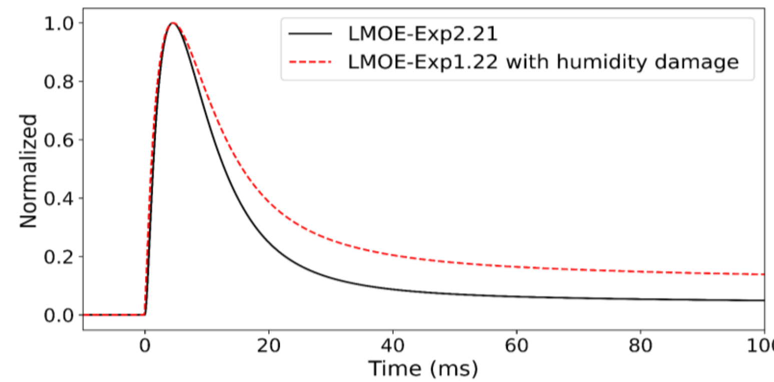
- Highly ionizing particles like alpha particles and nuclear recoils induce suppressed light output compared to electrons, gamma quanta, and cosmic-ray muons of the same energy, resulting in separation of particles with different ionization properties on a light vs. heat scatter-plot.

- The corresponding quenching factor of the α events with respect to β events is about 23% at ~ 4.8 MeV

Damage by humidity

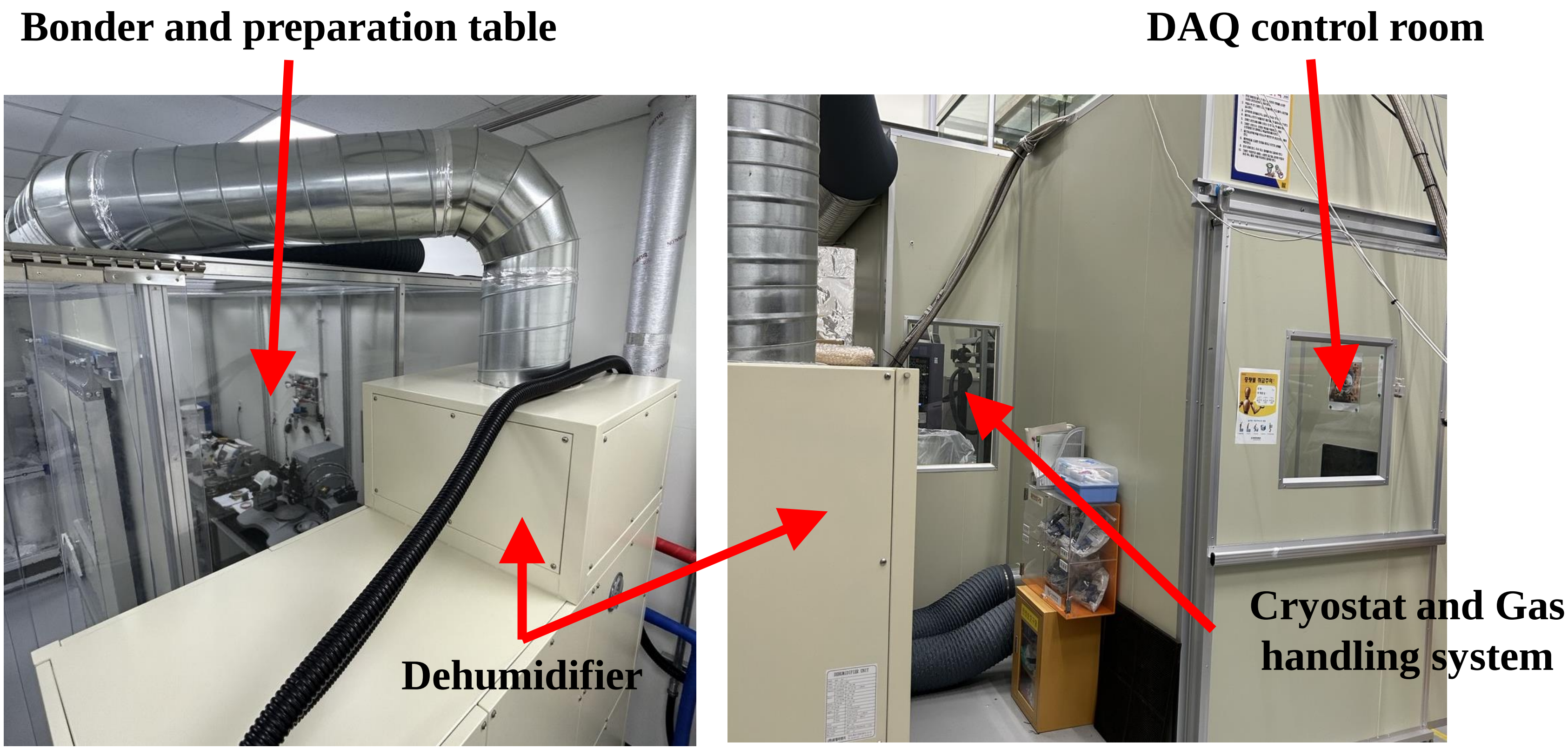






- Li_2MoO_4 crystal is weak to moisture. (9 g of solubility in 100 g of water)
- A crystal used in the experiment exhibited humidity damage around the phonon collector, resulting in a blurry area due to the presence of moisture.
- The decay part of signal by damaged crystals with humidity has a long tail. It can affect to make poor energy resolution.

Damage by humidity – Dehumidifier system



	Preparation room		Cryostat room	
	Temperature (°C)	**Humidity (ppm)**	**Temperature (°C)**	**Humidity (ppm)**
Before	20 ~ 25	4000 ~ 10000	< 20	3000 ~ 9000
After	20 ~ 25	400 ~ 600	< 20	1000 ~ 1400

Experiments of R&D condition

	LMOA – Exp1.21	LMO6 – Exp1.21	LMO6 – Exp2.21	LMOC UP – Exp2.21	LMOE – Exp2.21	LMOE – Exp1.22	LMOC UPE – Exp1.22	LMO6 AL – Exp1.22	LMO6S L – Exp1.22	LMO6 – Exp2.22	LMO6E – Exp2.22	LMOCUP EP – Exp2.22	LMOCUP EII – Exp2.22
Crystal	Li_2MoO_4	Li_2MoO_4	Li_2MoO_4	Li_2MoO_4	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	Li_2MoO_4	Li_2MoO_4	Li_2MoO_4	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
From	NIIC	NIIC	NIIC	CUP	NIIC	NIIC	CUP	NIIC	NIIC	NIIC	NIIC	CUP	CUP
Volume (H x D, cm)	5 x 5	6 x 6	6 x 6	5 x 5	5 x 5	5 x 5	5 x 5	6 x 6	6 x 6	6 x 6	6 x 6	5 x 5	5 x 5
Condition of phonon collector side	Sandpaper (1500)	Polished	Polished	Polished	Polished	Polished	Polished	diffusive	Polished	Polished	Polished	Polished	Polished
Condition of side	Polished	Polished	Polished	diffusive	diffusive	diffusive	diffusive	diffusive	diffusive	diffusive	diffusive	diffusive	diffusive
Light detector (with Si0x coating)	2inch Si wafer (Thickness : 280 μm)	X	Octagonal Si wafer (Thickness : 380 μm)	2inch Si wafer	2inch Si wafer	2inch Si wafer	X	2inch Si wafer	2inch Si wafer	2inch Ge wafer	2inch Si wafer	6 cm Si wafer w/ annealing	6 cm Si wafer w/ annealing
Thermal link on MMC	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes
MMC type	Ag:Er, Both Side	Ag:Er, One side	Ag:Er, One side	Ag:Er, Both Side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side	Ag:Er, One side

Main conditions For R&D Experiments

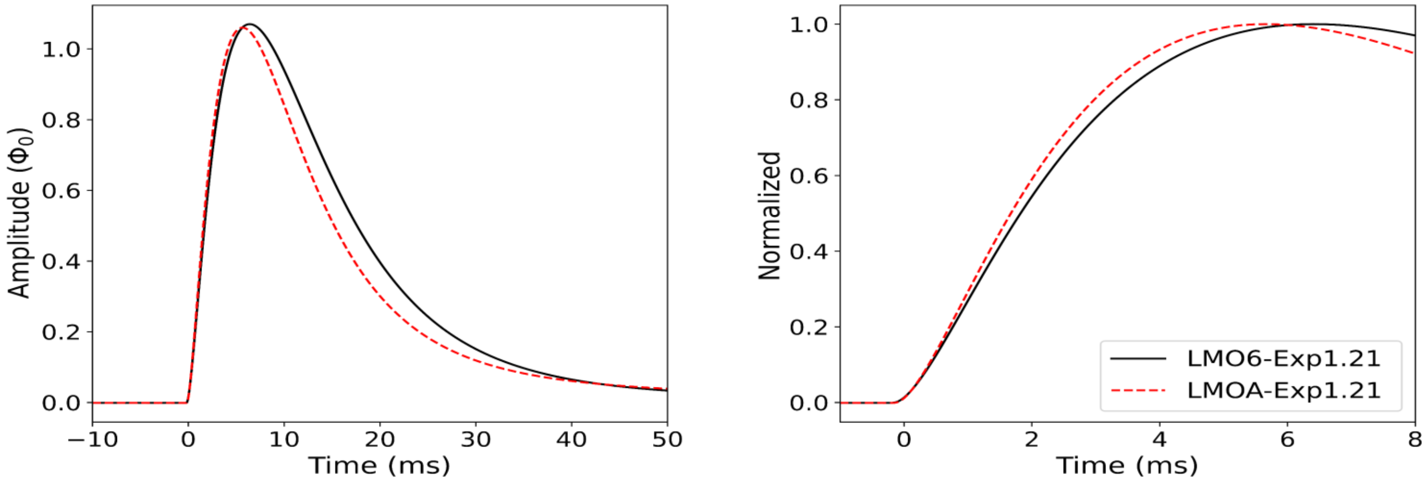
1. Crystal volume: For reduction number of channel
   - Signal size, energy resolution, light-heat ratio
   - Position dependence issue

2. Diffusive surface: To improve light correction and check a phonon signal
   - Light : light yield
   - Heat : Signal, energy resolution

3. Light detector performance improvement: For particle identification
   - Re-design detector
   - Diffusive surface result.

Crystal volume

- **Crystal size : 5 cm VS 6 cm (mass : ~70% increasing)**

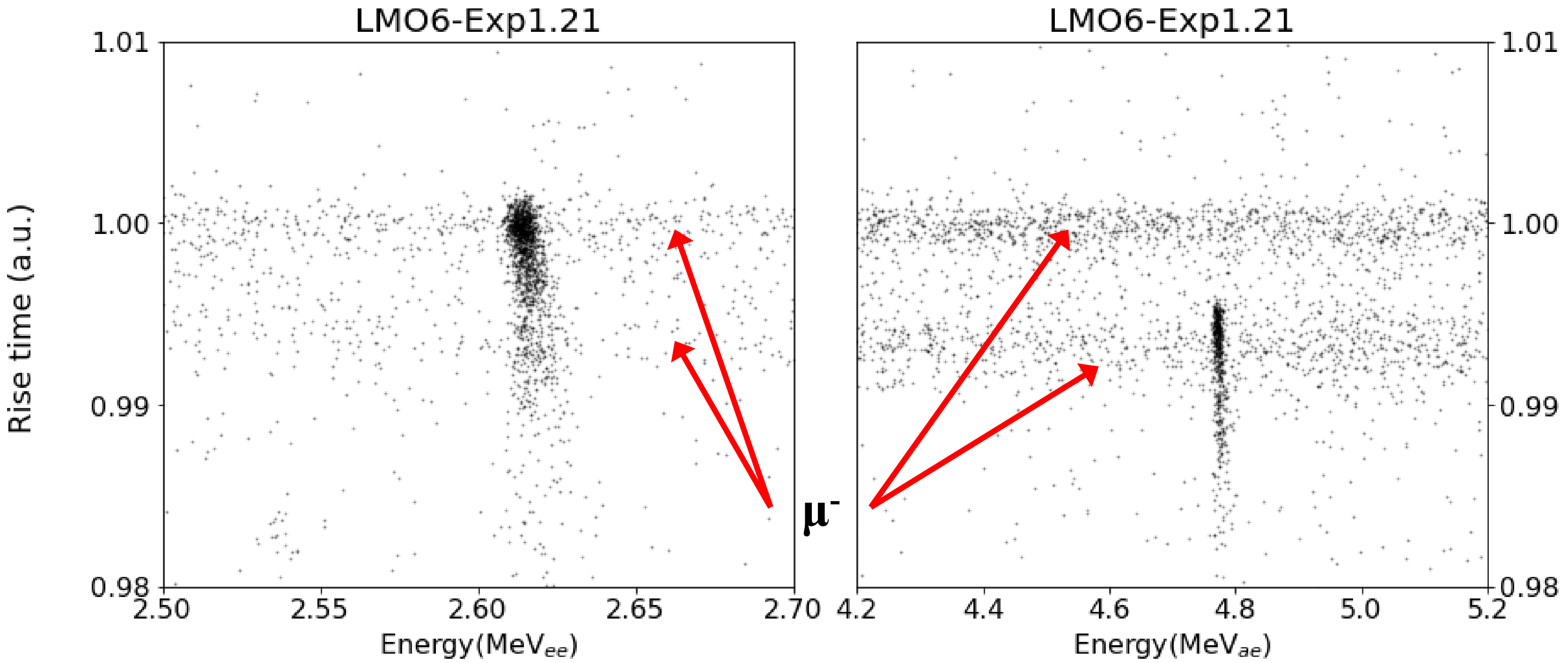


CRYSTAL	Crystal volume	Signal size	Rise time	Energy resolution at 2.615MeV (FWHM)
LMO6-Exp1.21	60 x 59.79 mm^2, 516.4g	1.07 Φ_0	3.7ms	11.5 $\pm$ 0.5 keV
LMOA-Exp1.21	50 x 44.05 mm^2, 261.4g	1.06 Φ_0	3.3ms	15.9 $\pm$ 0.8 keV

- If crystal size was increased from 5 to 6cm,
  - The number of channels in AMoRE-II will be reduced (1.7 times).
- If crystal size will be 6cm, we consider amplitude and risetime of heat signal , scintillation light collection for separation between α and β/γ

Crystal volume – Position dependence issue

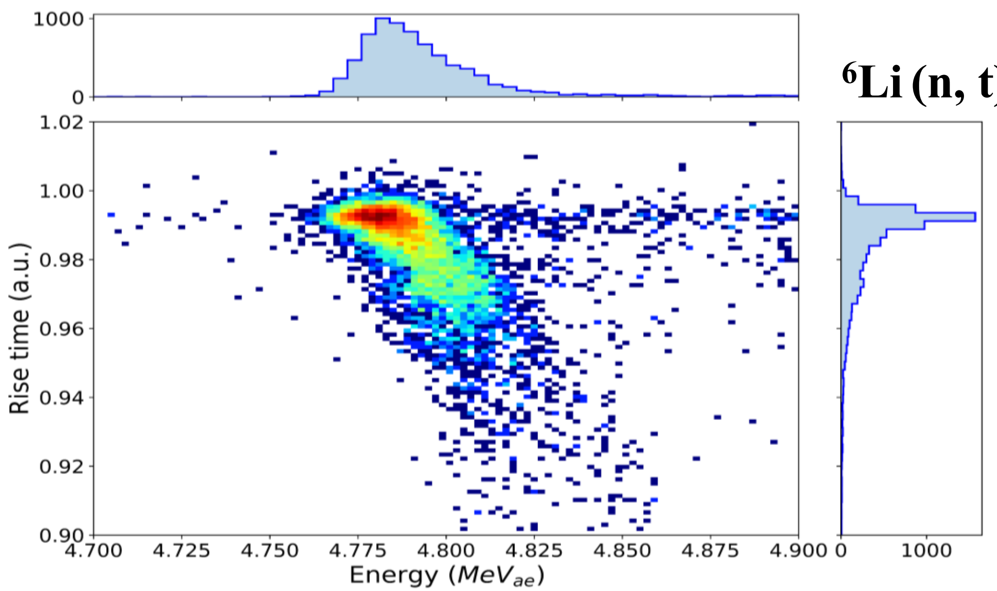
- **Muons**
  - There are two group on the risetime of muon events of 6cm LMO crystal with polished surface. That is why muon remain energy at the edge of the crystal.
  - Unfortunately, it is hard to separate alpha and beta/gamma events using the risetime. because the rise time of alpha events ($^{6}Li(n, t)^{4}He$, 4.8MeV) is between two muon bands.



Crystal volume – Position dependence issue

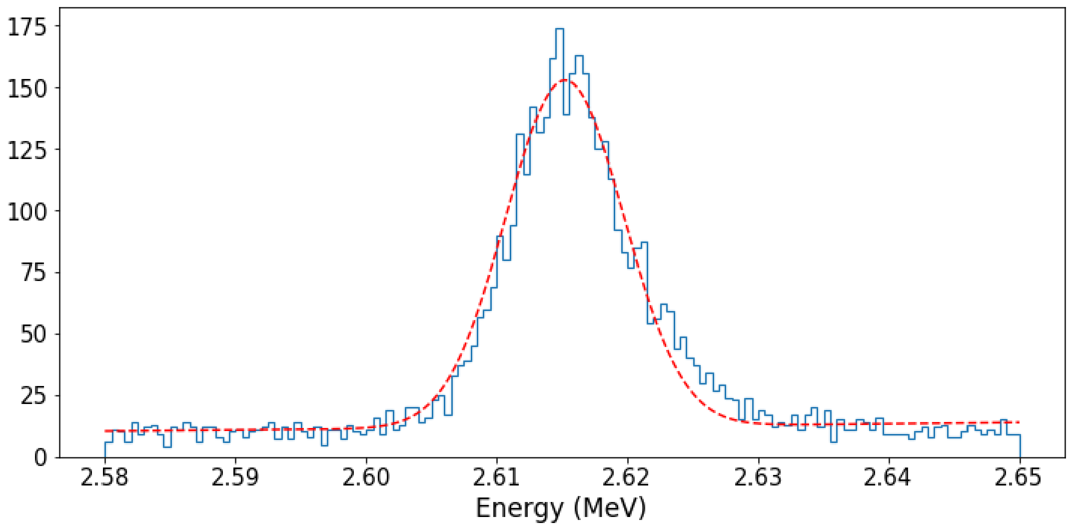
- **Muons**
  - There are two group on the risetime of muon events of 6cm LMO crystal with polished surface. That is why muon remain energy at the edge of the crystal.
  - Unfortunately, it is hard to separate alpha and beta/gamma events using the risetime. because the rise time of alpha events ($^{6}Li(n, t)^{4}He$, 4.8MeV) is between two muon bands.
- **Alpha**
  - Attenuation length of α particle into LMO is a ~ 20 μm (5 MeV, SRIM). It mean that α events have larger position dependence.

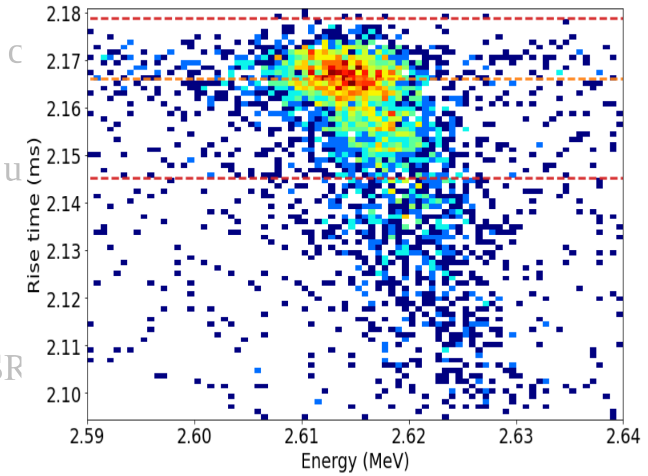
    → It have trend that faster risetime is larger energy



$^{6}Li\,(n, t)^{4}He$ events

Crystal volume – Position dependence issue

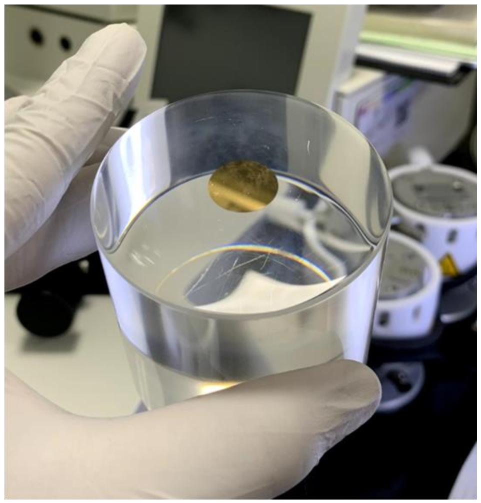


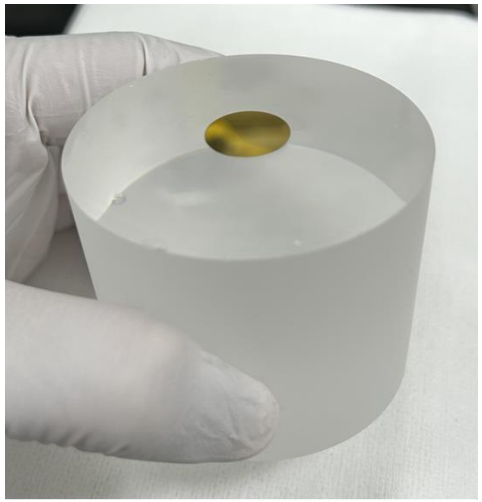


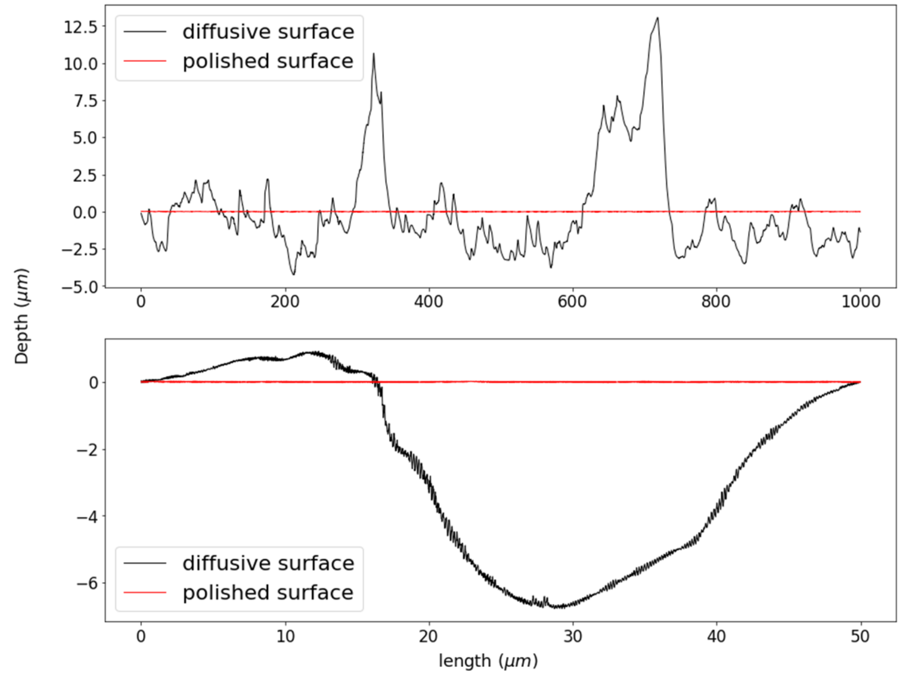
- **Gamma**
  - The 6cm LMO crystals exhibit an asymmetric normal distribution of the risetime and energy spectrum at 2.615 MeV.
  - Gamma events by 6cm LMO crystal at 2.61 MeV have left long tail in rise time. It have trend that faster risetime is larger energy. It seem like to show gamma position dependence on crystal.

  → Solutions: correction & diffusive surface

LMO crystal with diffusive surface


Polished surface

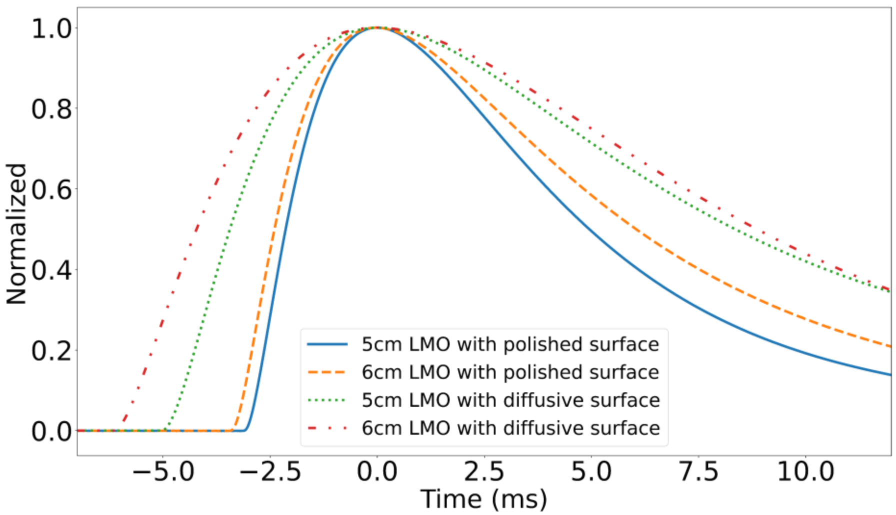

Diffusive surface

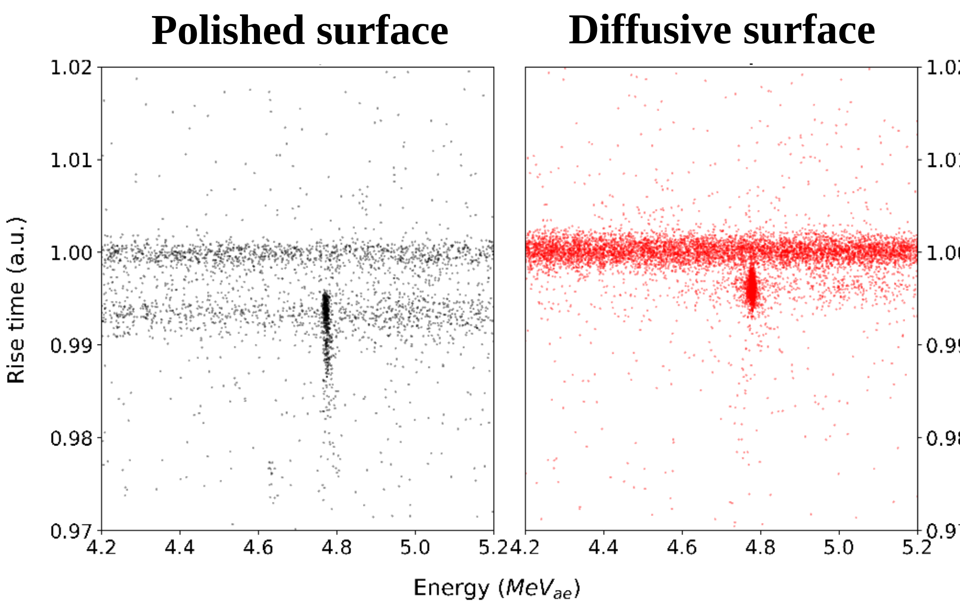


- For checking the improvement performance of LMO crystal’s scintillating light with diffusive surface, we tested using LMO crystals. → No improvement
- It has an effect on the diffusive surface in phonon signal.

LMO crystal with diffusive surface

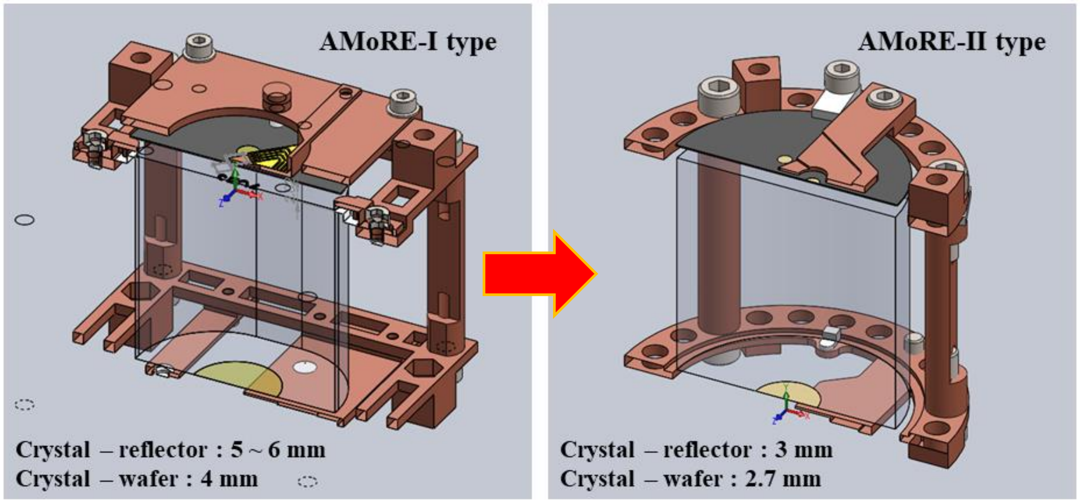
- **Pulse shape analysis**

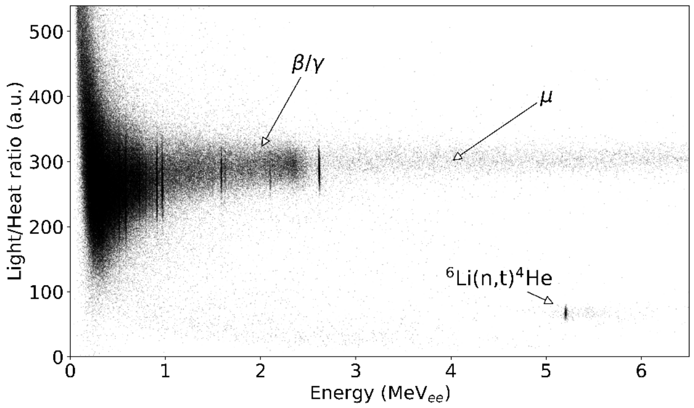




- Li_2MoO_4 crystals with diffusive surface has longer rise time and slower decay.
- Although crystal volume is 6 cm, diffusive surface had less spread of muon events, leading to better alpha discrimination based on risetime.
- Diffusive surface resulted in longer travel time for energetic phonons to reach phonon collector due to enhanced diffuse scattering, possibly weakening position dependence among pulses.

Particle Identification with light detector





* Near 4.8MeV alpha (1MeV)

	Light detector design	Surface	*DP with light heat ratio
LMOA-Exp1.21	**AMoRE - Pilot/I**	Polished	**6.97 ± 0.20**
LMOE-Exp2.21	**AMoRE - Pilot/I**	diffusive	**14.25 ± 0.06**
LMO6AL-Exp1.22	**AMoRE - II**	diffusive	**14.68 ± 0.06**
LMOCUPII-Exp2.22	**AMoRE - II with annealing**	diffusive	**19.50 ± 0.09**
LMO6E-Exp2.22	**AMoRE - II with annealing**	diffusive	**13.82 ± 0.16**

- Reduction of gap is important role in light detector improvement .
- Vibration noise is dominant in the performance of the light detector.

Summary Table

Detector ID	LMOA – Exp1.21	LMO6 – Exp1.21	LMOE – Exp2.21	LMOC UP – Exp2.21	LMO6 – Exp2.21	LMOE – Exp1.22	LMOC UPE – Exp1.22	LMO6AL – Exp1.22	LMO6SL – Exp1.22	LMOC UPEP – Exp2.22	LMOC UPEII – Exp2.22	LMO6E – Exp2.22	LMO6 – Exp2.22
Volume	5 x 5	6 x 6	5 x 5	5 x 5	6 x 6	5 x 5	5 x 5	6 x 6	6 x 6	5 x 5	5 x 5	6 x 6	6 x 6
crystal	Li_2MoO_4	Li_2MoO_4	$Li_2^{100}MoO_4$	Li_2MoO_4	Li_2MoO_4	$Li_2^{100}MoO_4$	$Li_2^{100}MoO_4$	Li_2MoO_4	Li_2MoO_4	$Li_2^{100}MoO_4$	$Li_2^{100}MoO_4$	$Li_2^{100}MoO_4$	Li_2MoO_4
Surface	Polished	Polished	Diffusive	Diffusive	Polished	Diffusive	Diffusive	Diffusive	Diffusive	Diffusive	Diffusive	Diffusive	Diffusive
Signal size (Φ_0)	1.06	1.07	1.07	0.47	0.75	0.24	2.46	0.03	1.65	0.39	0.49	0.30	1.39
Rise time (ms)	3.3	3.7	4.8	5.8	3.1	2.8	3.3	2.2	5.0	3.5	5.9	5.1	3.8
Baseline resolution (keV)	4.54 ± 0.05	3.23 ± 0.02	2.40 ± 0.02	4.78 ± 0.02	2.12 ± 0.02	6.66 ± 0.05	4.22 ± 0.07	27.90 ± 0.24	2.57 ± 0.02	3.37 ± 0.02	3.34 ± 0.02	3.39 ± 0.00	3.20 ± 0.02
Energy resolution at 2.615 MeV (keV)	15.87 ± 0.77	11.67 ± 0.47	7.74 ± 0.46	14.70 ± 1.31	6.87 ± 0.19	11.24 ± 0.18	10.64 ± 0.27	41.76 ± 0.88	8.55 ± 0.22	9.81 ± 0.15	8.35 ± 0.19	7.55 ± 0.26	8.82 ± 0.16
DP with light-heat ratio	6.97 ± 0.20	-	14.25 ± 0.06	-	6.30 ± 0.08	13.27 ± 0.04	-	14.68 ± 0.06	12.37 ± 0.09	11.55 ± 0.04	19.50 ± 0.09	13.82 ± 0.16	18.89 ± 0.08
DP with PSD	3.08 ± 0.19	-	5.18 ± 0.12	3.30 ± 0.12	-	4.31 ± 0.12	2.17 ± 0.15	-	-		5.10 ± 0.15	5.27 ± 0.09	-

Summary

Detector ID	LMOE – Exp2.21	LMOCUPEII – Exp2.22	LMO6E – Exp2.22
Volume	5 x 5	5 x 5	6 x 6
crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Surface	Diffusive	Diffusive	Diffusive
Signal size (Φ_0)	1.07	0.49	0.30
Rise time (ms)	4.8	5.9	5.1
Baseline resolution (keV)	2.40 ± 0.02	3.34 ± 0.02	3.39 ± 0.00
Energy resolution at 2.615 MeV (keV)	7.74 ± 0.46	8.35 ± 0.19	7.55 ± 0.26
DP with light-heat ratio	14.25 ± 0.06	19.50 ± 0.09	13.82 ± 0.16
DP with PSD	5.18 ± 0.12	5.10 ± 0.15	5.27 ± 0.09

- The LMO crystals with a diffusive surface exhibit an energy resolution of approximately 8 keV at 2.615 MeV.
- Furthermore, these crystals with re-designed detector demonstrate better Particle IDentification with light detector.

Conclusion

- The Li_2MoO_4 (LMO) crystal have been tested with several conditions for optimization for AMoRE-II; surface condition, light detector design, volume, humidity control
- Although LMO crystal with diffusive surface has a long risetime, it has the better energy resolution, discrimination power with light-heat ratio & Pulse shape parameter (such as Risetime).
- Position dependence issue by 6cm LMO crystal → 6 cm LMO crystal with diffusive surface
- To achieve optimization of the light detector

- Diffusive surface crystal + optimized light detector :
  - Energy resolution: < 10 keV at 2.615 MeV
  - Particle Identification → DP with light-heat ratio: > 14 (near 4.8 MeV_{ae})
  - DP with pulse shape analysis: > 4 (near 4.8 MeV_{ae})
- AMoRE-II will use the optimized condition by this R&D experiment.

Thank you

Back up

Current best results for 0νββ

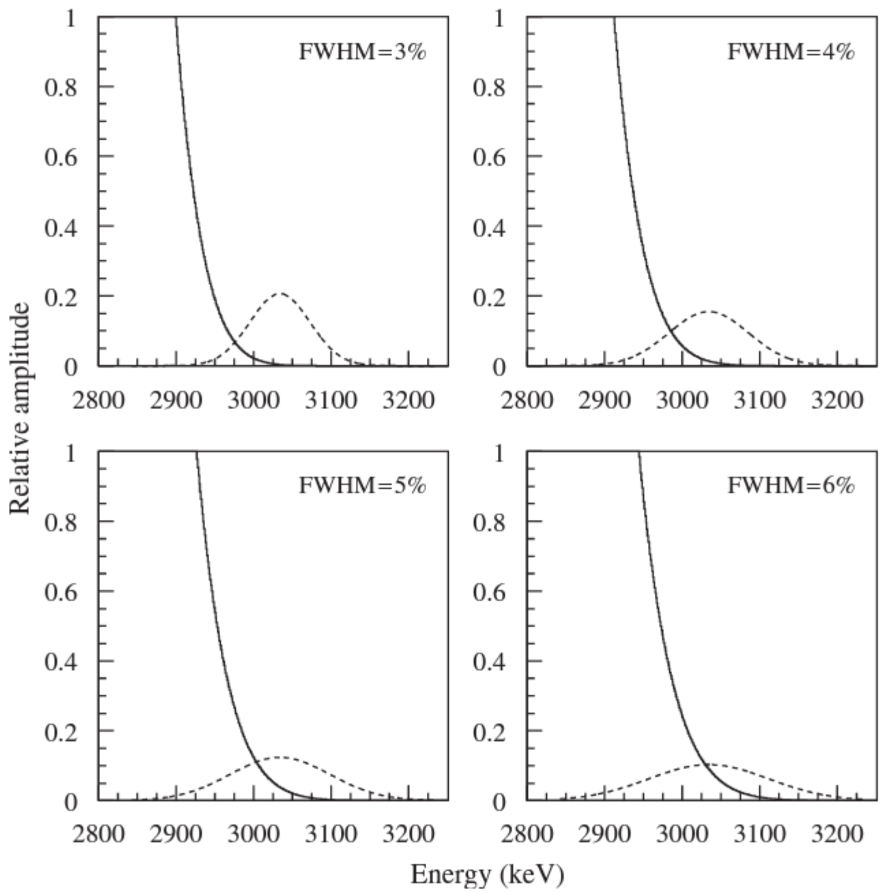
Nucl.	Q (keV)	Abun. (%)	$T_{1/2}^{2\nu}$ (10^{20} Y)	Exp	$T_{1/2}^{0\nu}$ (10^{24} Y)	M (meV)	Ref.
^{48}Ca	4270.0	0.187	0.53(0.1)	CANDLES	> 0.058	<3100-15400	PRC 78 058501 (2008)
^{76}Ge	2039.1	7.8	18.8(0.8)	GERDA-II	>180	<79-180	PRL125, 252502 (2020)
^{82}Se	2997.9	9.2	0.93(0.05)	CUPID-0	> 4.6	<263-545	PRL129, 111801 (2022)
^{100}Mo	3034.4	9.6	0.0688(0.0025)	CUPID-Mo	>1.8	<280-490	EPJC82, 1033 (2022)
^{116}Cd	2813.4	7.6	0.269(0.009)	AURORA	> 0.22	<1000-1700	PRD 98 092007 (2018)
^{130}Te	2527.5	34.5	7.91(0.21)	CUORE	> 22	<90-305	Nature 605, 53 (2020)
^{136}Xe	2458.0	8.9	21.8(0.5)	KamLAND-Zen	> 230	<36-156	PRL130, 051801 (2023)
^{150}Nd	3371.4	5.6	0.0934(0.0065)	NEMO-3	> 0.02	<1600-5300	PRD 94 072003 (2016)

Bolometer, Scintillation, Ionization

Motivation – Energy resolution

- **2ν2β spectrum and 0ν2β**

  - The response functions of a $Ca^{100}MoO_4$ detector for 2β decays of ^{100}Mo for different energy resolutions of the detector at the energy of ^{100}Mo 0νββ decay. This plot is from (A.N. Annenkov, et al. (2007))



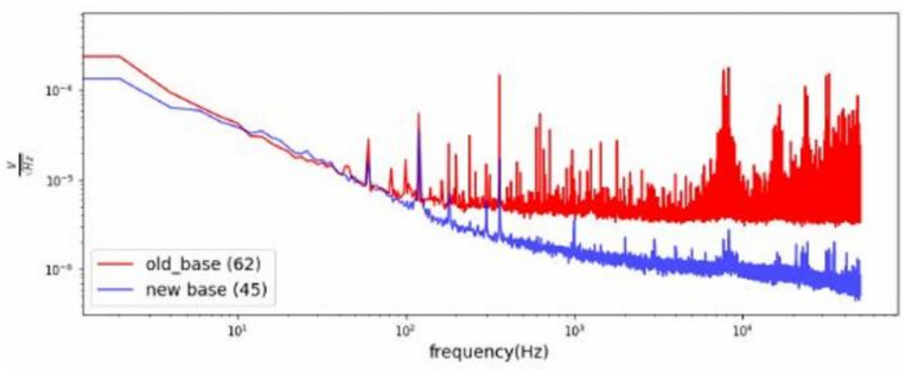
Motivation – Crystal R&D

- **LMO crystal**

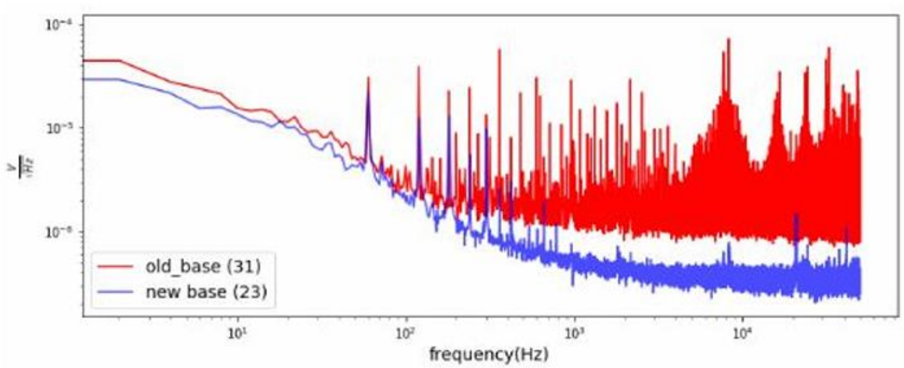
  - Previous studies did not investigate the effect of crystal surface condition on athermal phonon signals.
  - CMO studies were conducted using well-polished crystals. (AMoRE-Pilot, I)
  - The previous studies with LMO indicated the moisture damage on the surface is very important and we must minimize the damage by humidity.

  - No study the surface roughness effect on the phonon signal.
  - Surface polishing is a time-consuming process, and the need for polishing must be justified.
  - Additionally, the surface condition of phonon collector evaporation needs to be established.
  - AMoRE-1 crystals were sanded on the phonon collector surface.

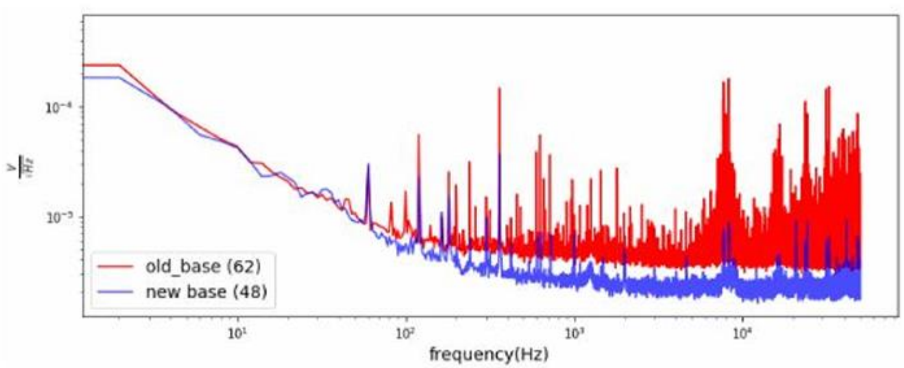
Optical link noise spectrum



SB29

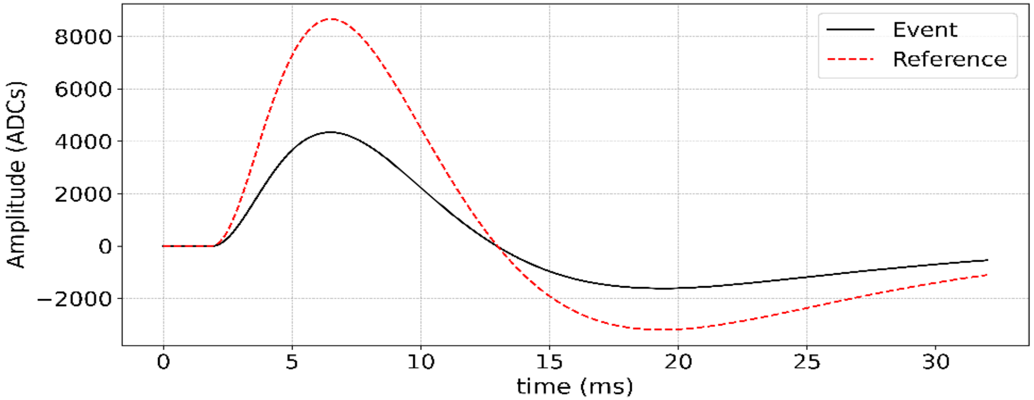


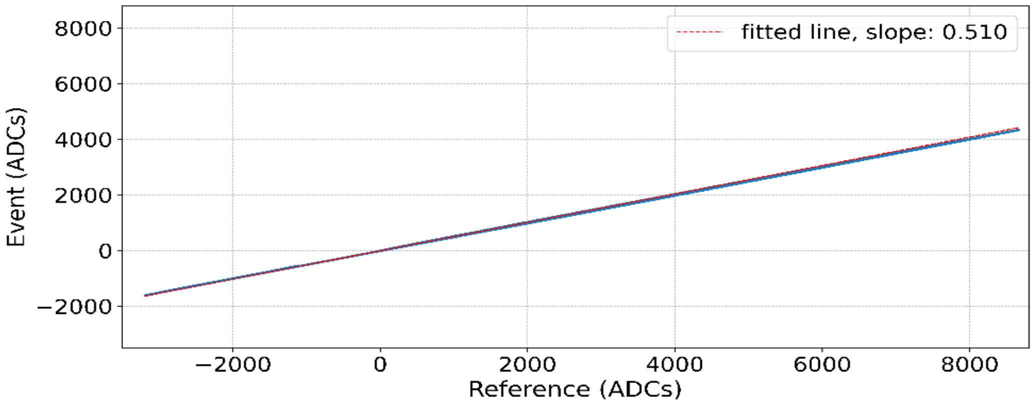
SE01



SS68

Templet Fit

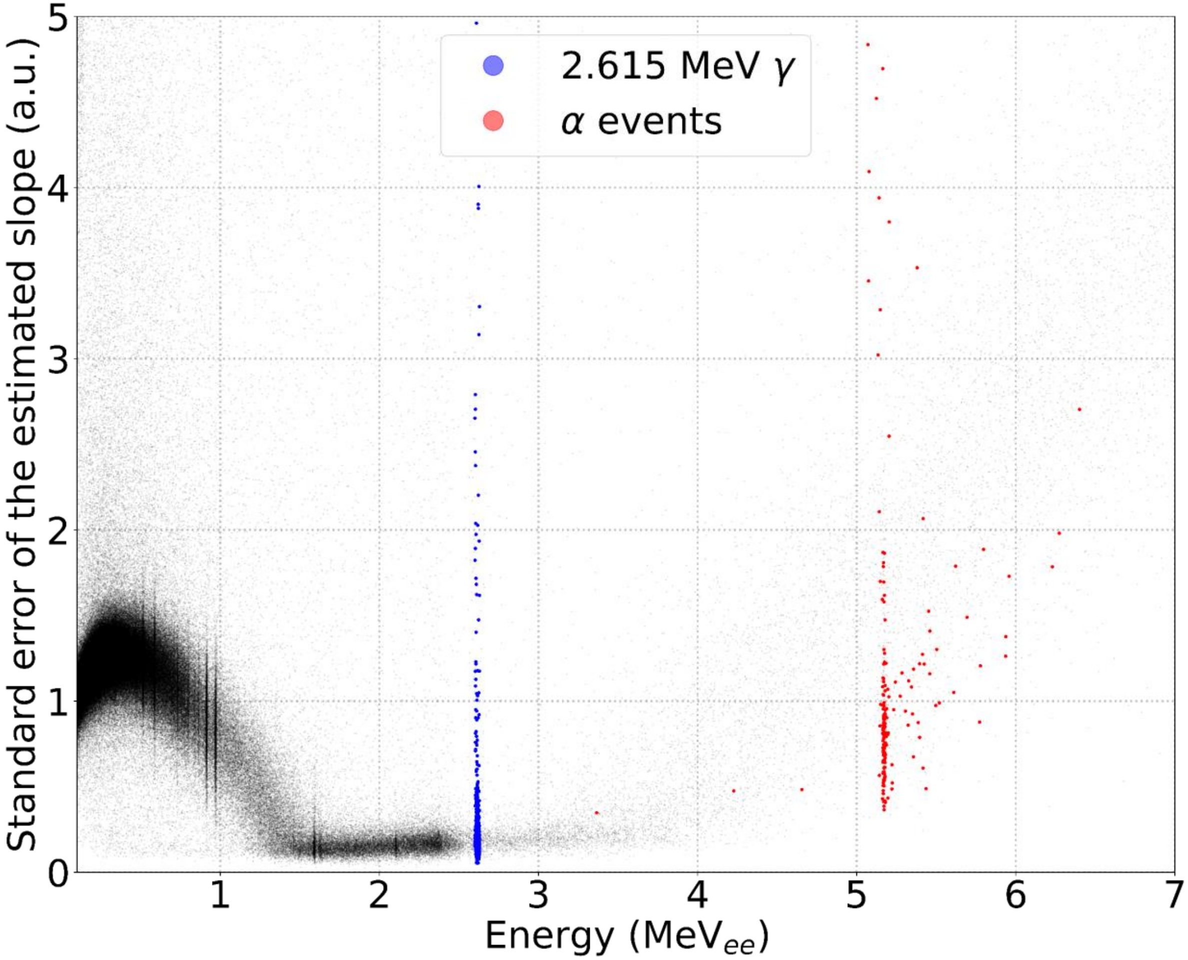




< scipy.stats.linregress (x, y=None, alternative='two-sided')[source]
Calculate a linear least-squares regression for two sets of measurements. >

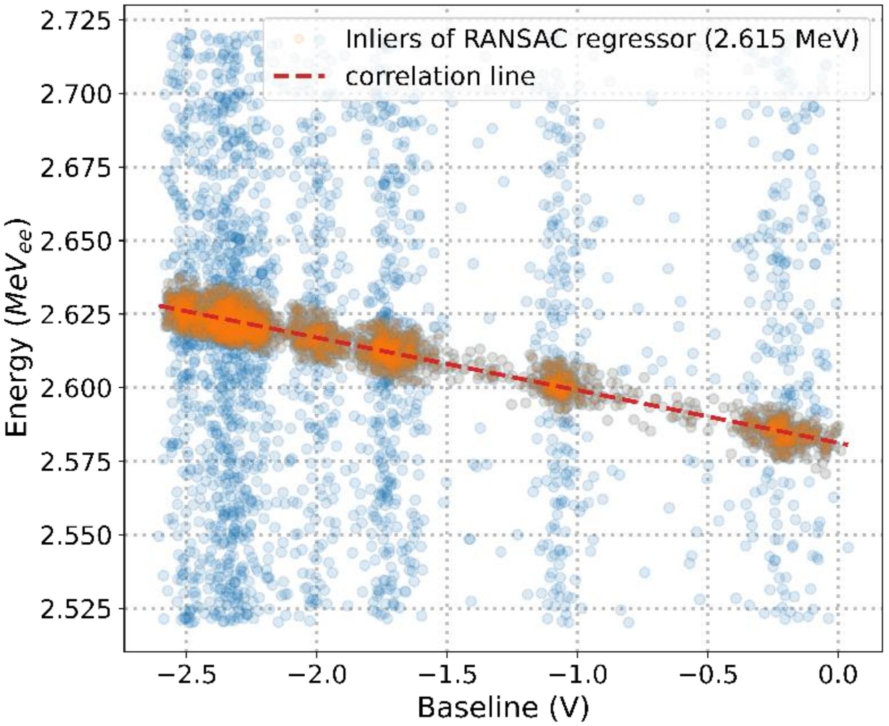
An example of the template fit using a Butterworth bandpass filter with a reference waveform of 2.615 MeV gamma for a 1.334 MeV gamma. The result of the template fit is 0.51, where a value of 1 indicates a perfect match to the reference waveform of 2.615 MeV gamma.

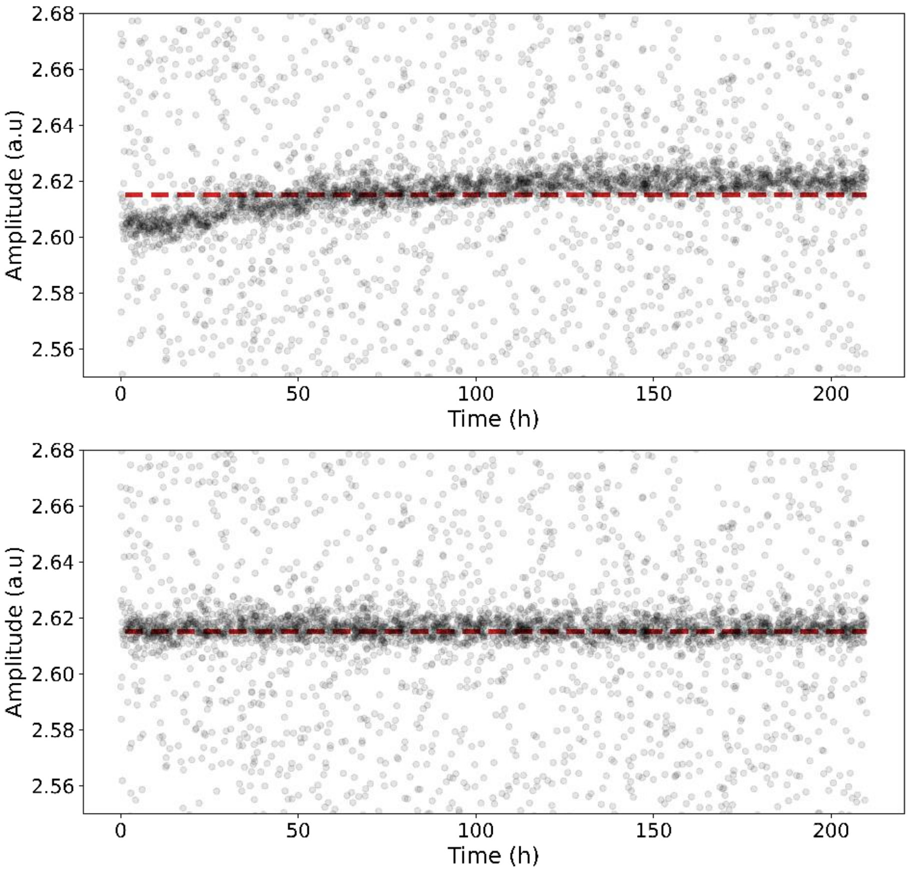
Templet Fit



2.615 MeV γ
α events
Standard error of the estimated slope (a.u.)
Energy (MeV_ee)
0
1
2
3
4
5
6
7

Baseline correction

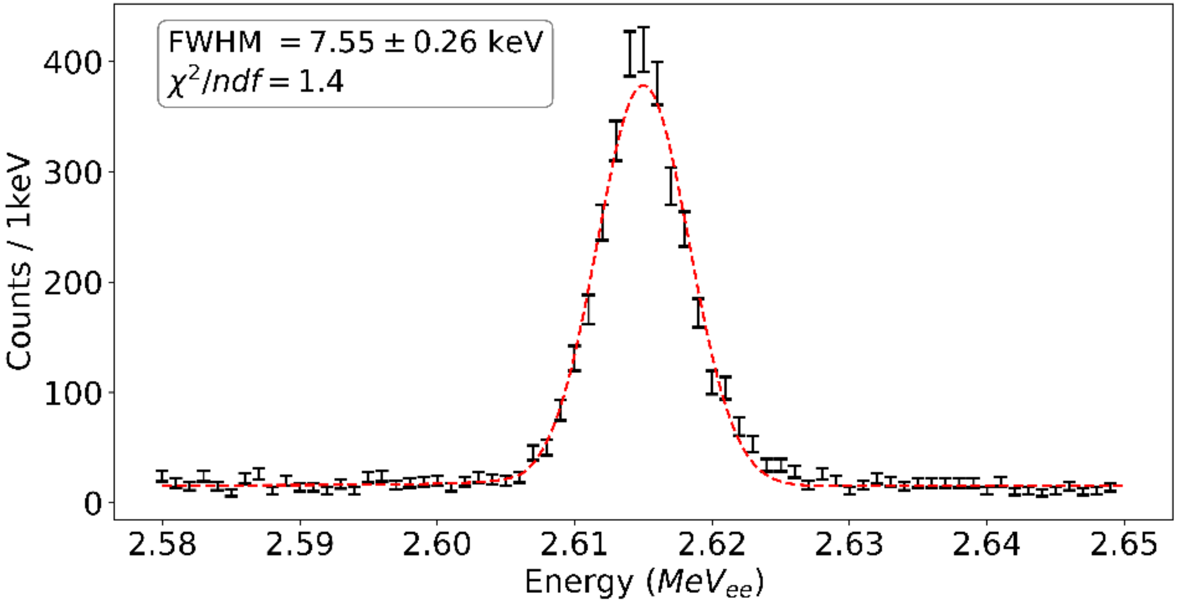




Fit function (Crystal ball function)

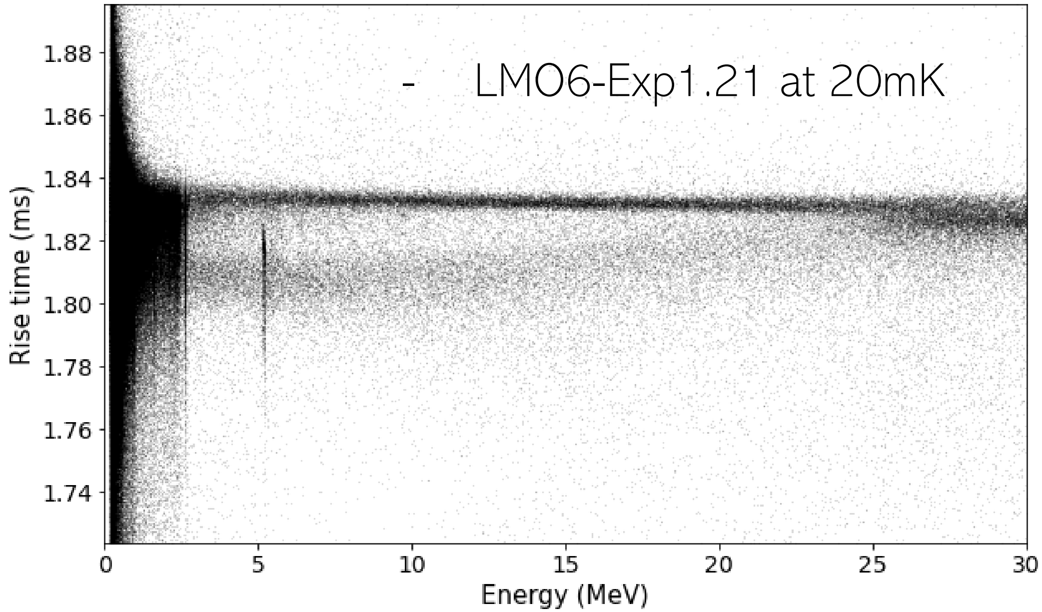
$$f(E; A, \alpha, n, \mu, \sigma, B) = \mathrm{A} \cdot f_{CBF}(E; \alpha, n, \mu, \sigma) + \mathrm{B}$$

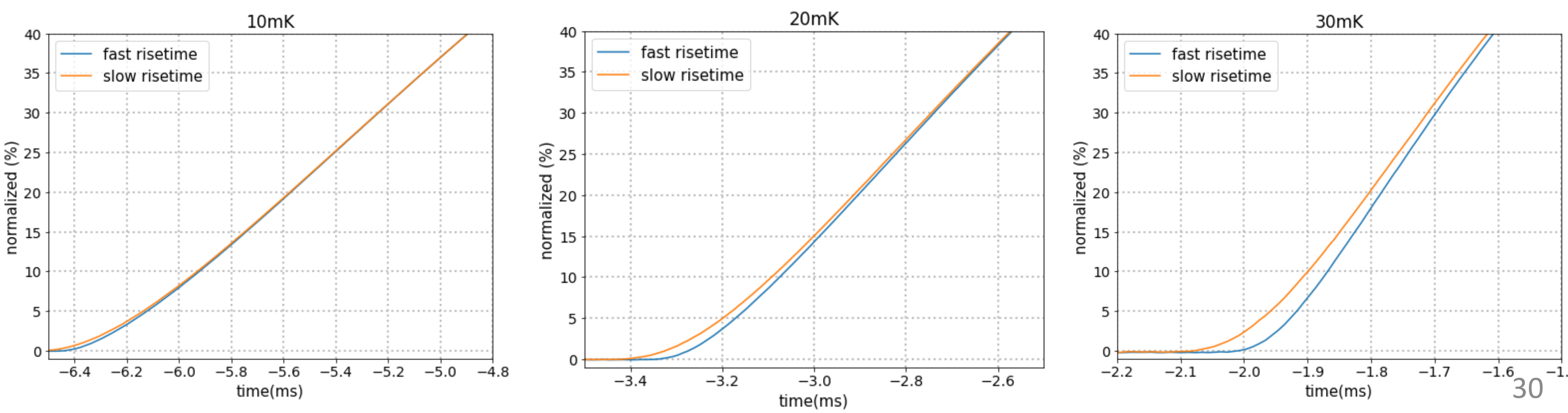
$$\mathrm{f_{CBF}}(\mathrm{E}; \alpha, \mathrm{n}, \mu, \sigma) = \begin{cases} N\, e^{-E^2/2}, & for\ x > \alpha \\ N\, A\, (B - \mathrm{E})^{-n}, & for\ x \le -\alpha \end{cases}$$



Crystal volume

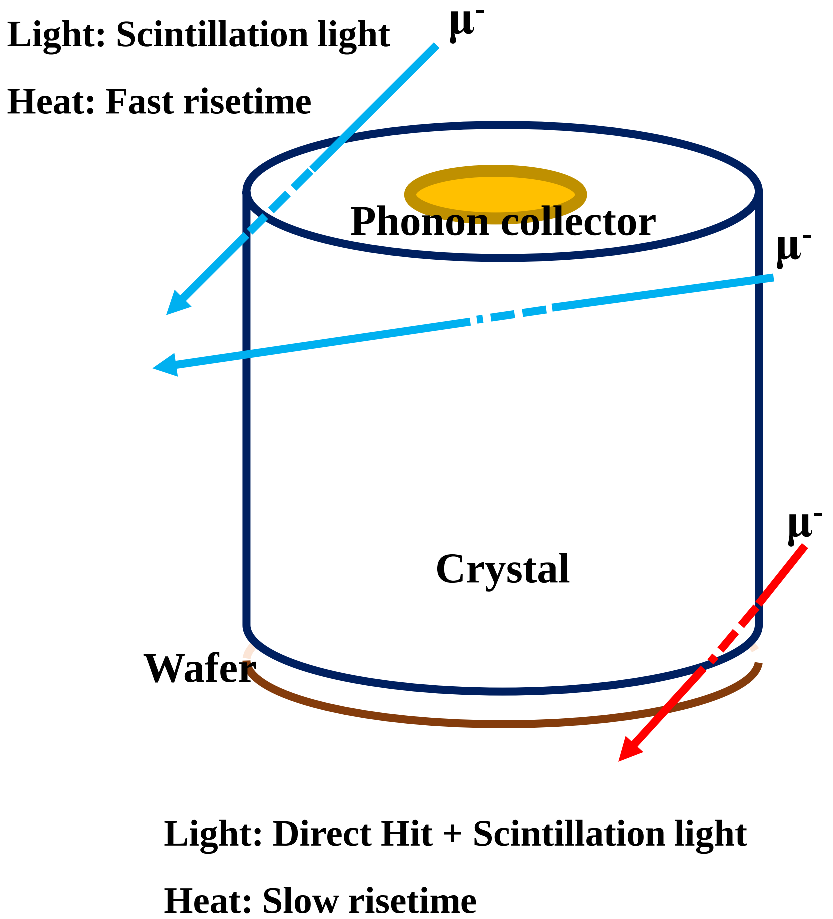
- **Issue on large crystal volume: muons**

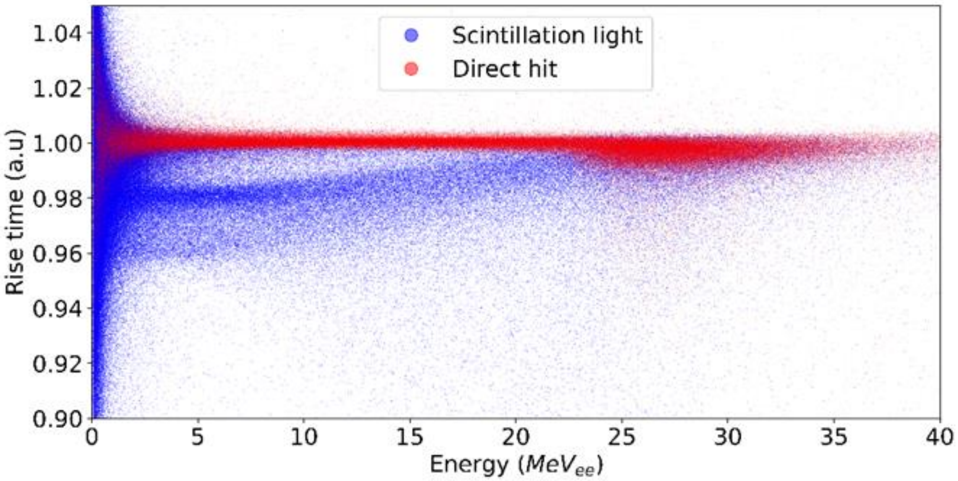


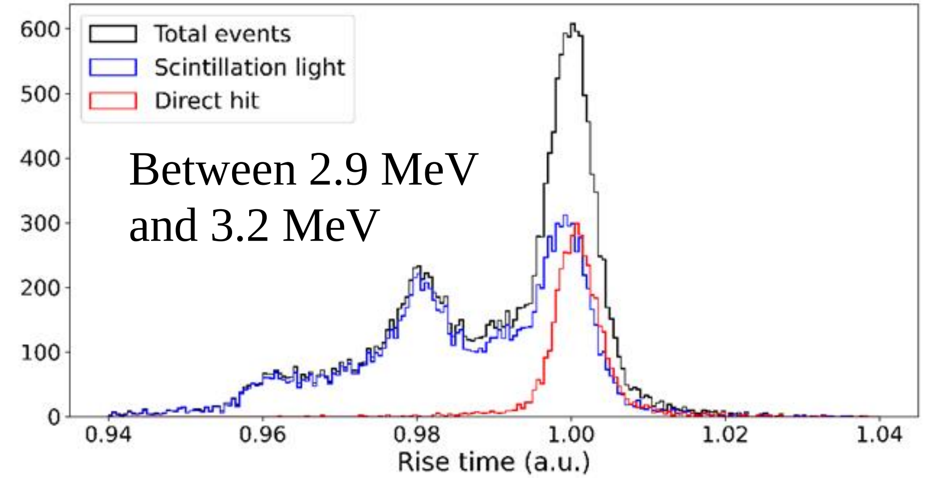


Crystal volume – Position dependence issue

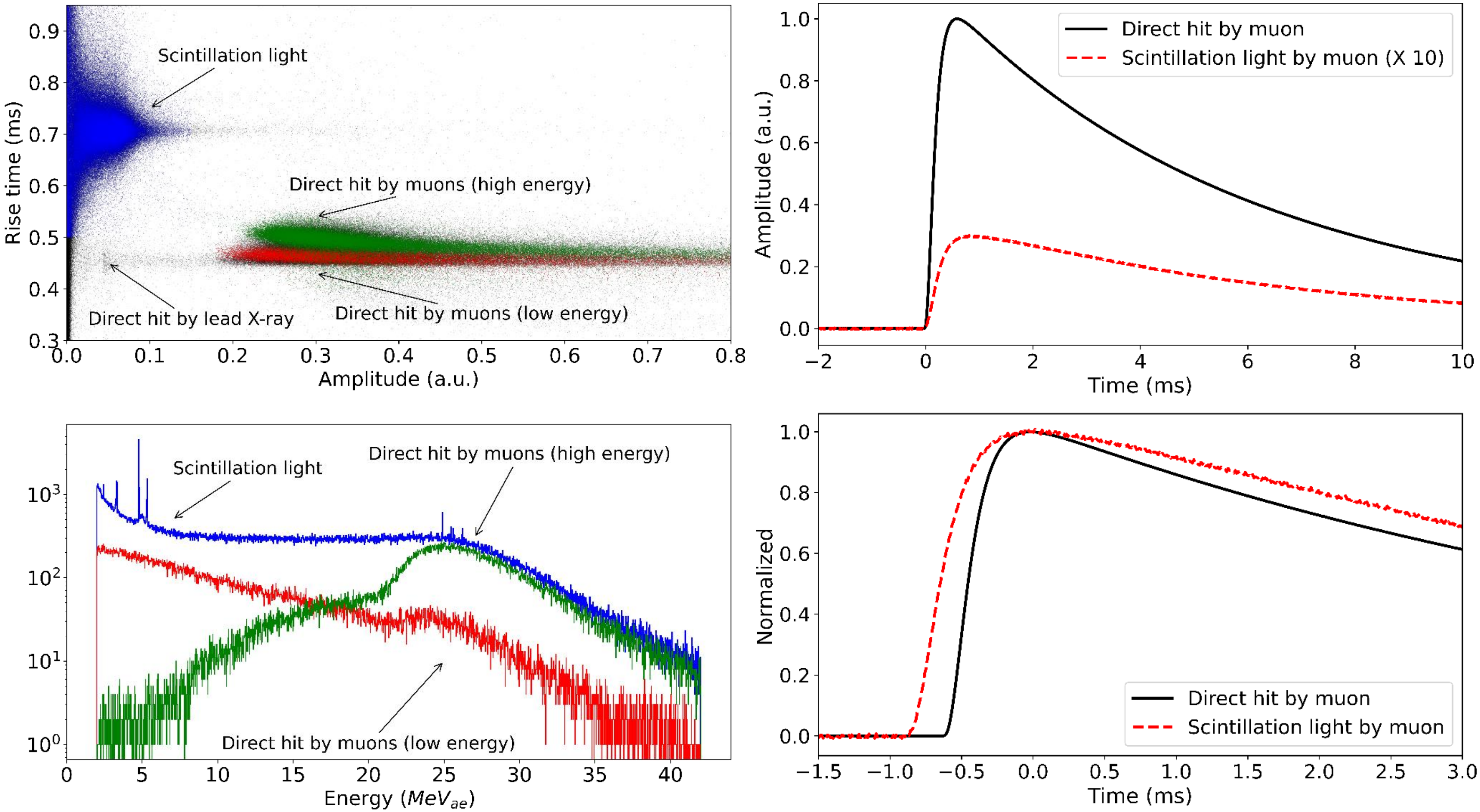
- **Issue on large crystal volume (muons)**



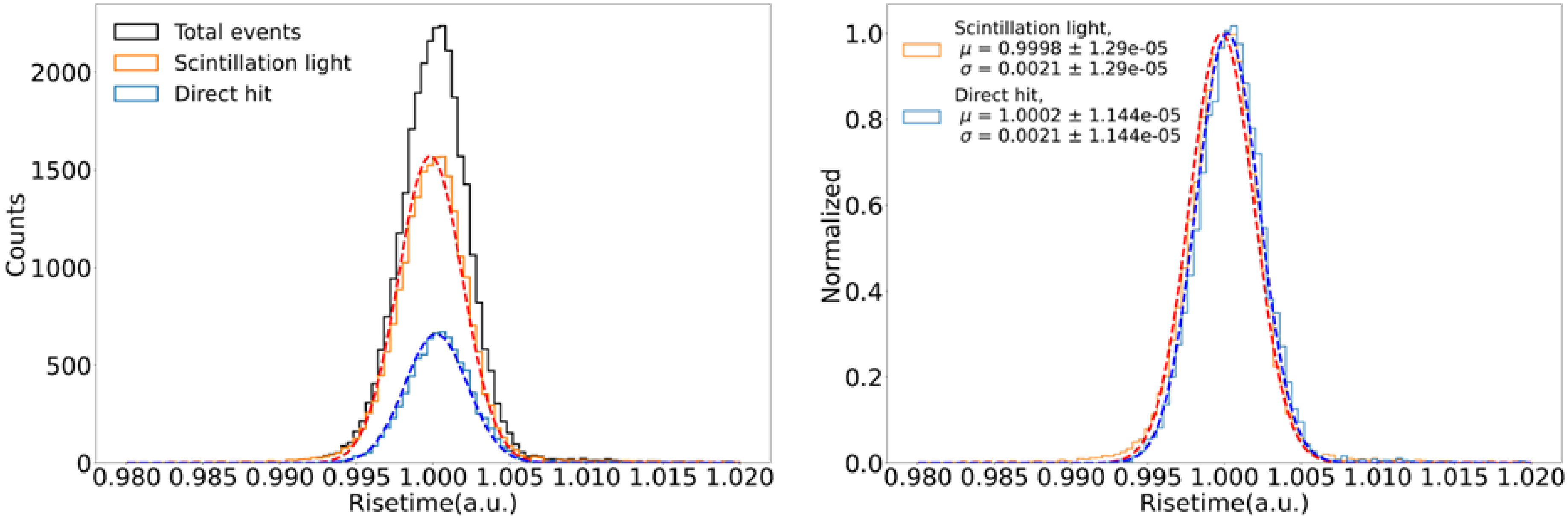




Light detector (Muon)

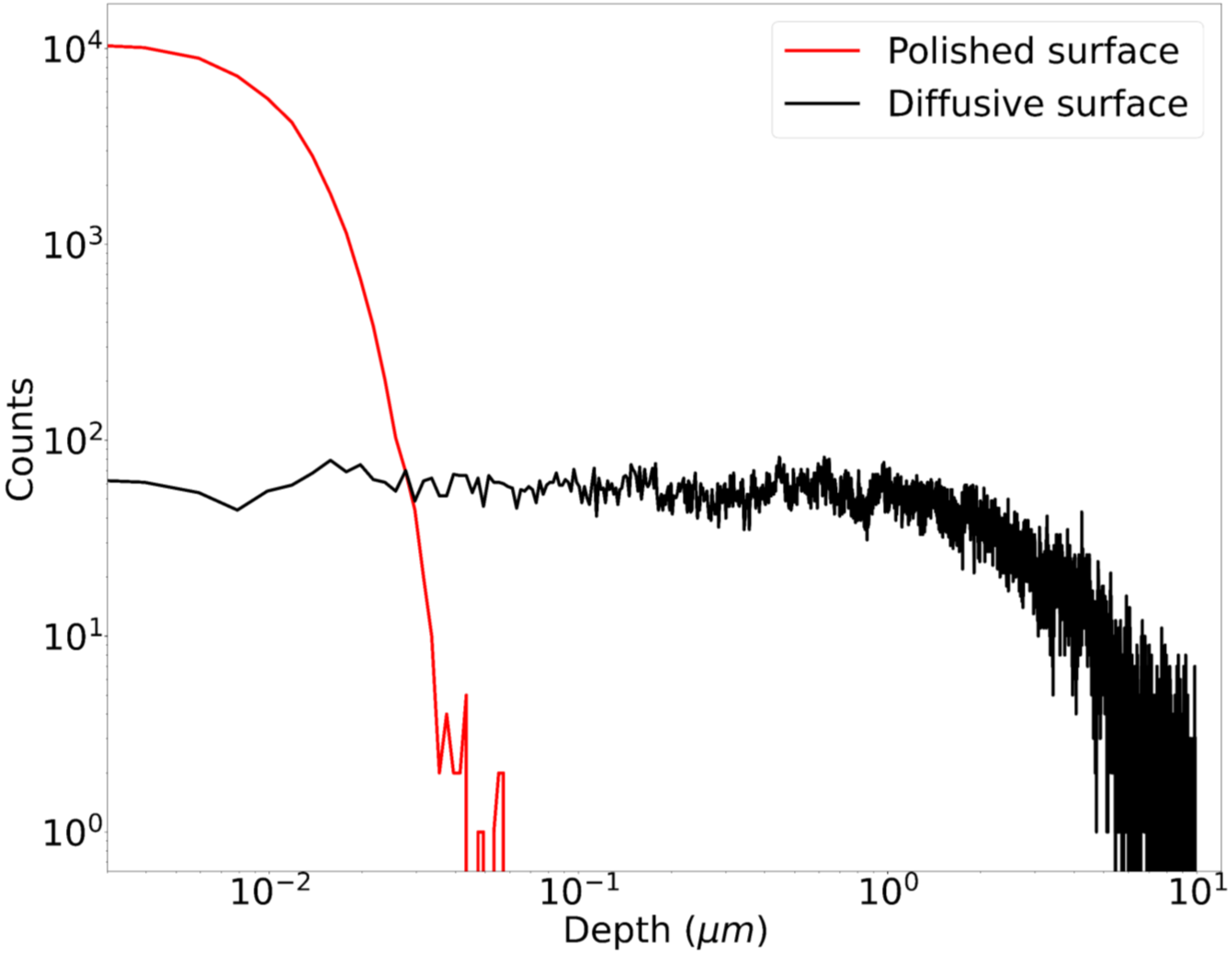


Light detector (Muon)



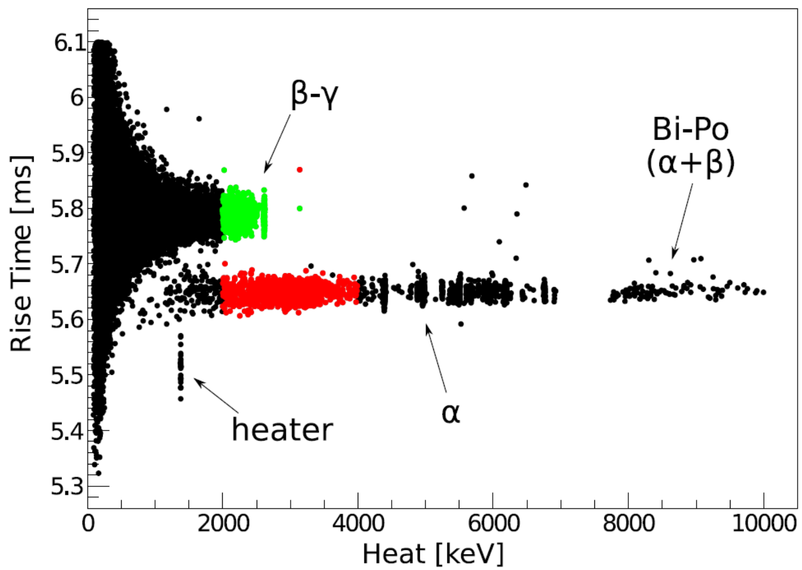
Diffusive surface

- **Measurement of crystal surface**



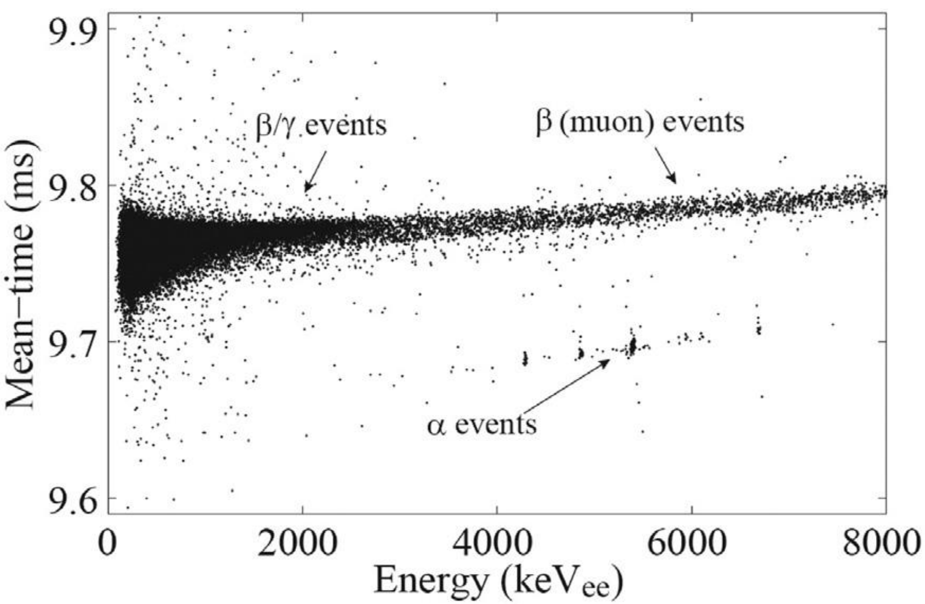
NTD-Ge, MMC with $CaMoO_4$ crystal

Fig. 1 (Color online) Scatter plot of τ_{rise} vs. Heat in $CaMoO_4$ crystal. In *green* (*light in the upper curve*) events in the 2–4 MeV region due to β/γ particles and in *red* α events. The energy calibration is performed on the γ peaks. The total live time of this measurement was ~43 h. In order to have a high number of α counts in the 2–4 MeV region in these measurements a degraded ^{238}U source [8–11] was placed in front of the crystal



NTD, DP_{RISE} : $6.5\ \sigma$

L. Gironi (2012), 'Pulse Shape Analysis with Scintillating Bolometers', J Low Temp Phys (2012) 167:504–509



MMC,

DP_{RISE} : $20.1\ \sigma$

$DP_{meantime}$: $19.0\ \sigma$

G.B. Kim (2017), 'Novel measurement method of heat and light detection for neutrinoless double beta decay', Astroparticle Physics 91 (2017) 105–112

Luminescence spectra

$CaMoO_4$ **Li_2MoO_4**

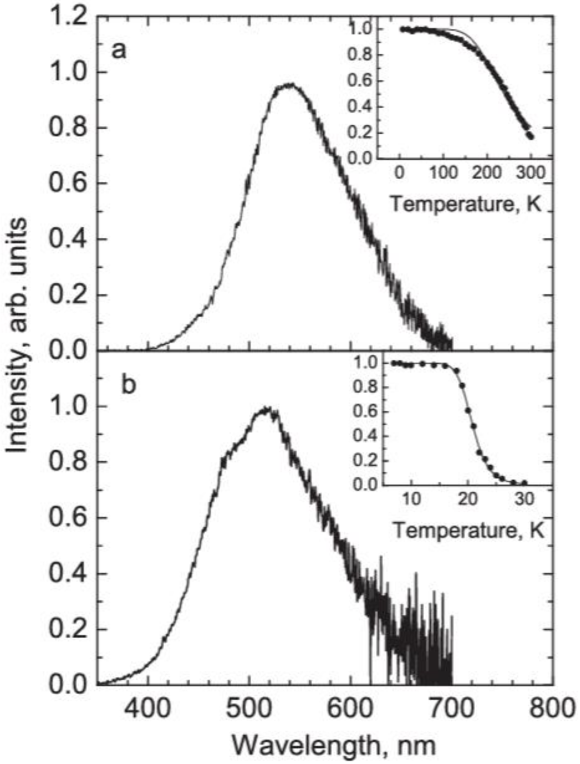
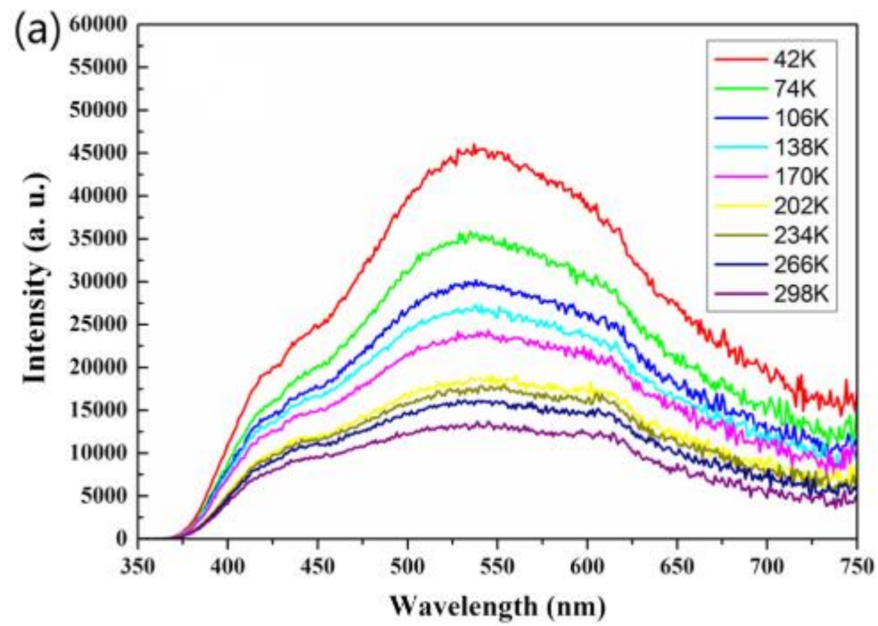


Figure 1. Luminescence spectra of $CaMoO_4$ (a) and $MgMoO_4$ (b) measured under excitation with 7.7 eV photons at 8 K. Insets show the variation of the integrated light yield as a function of temperature. Lines are the best fit of the Mott formulae to the data points.



CUPID-Mo experiment

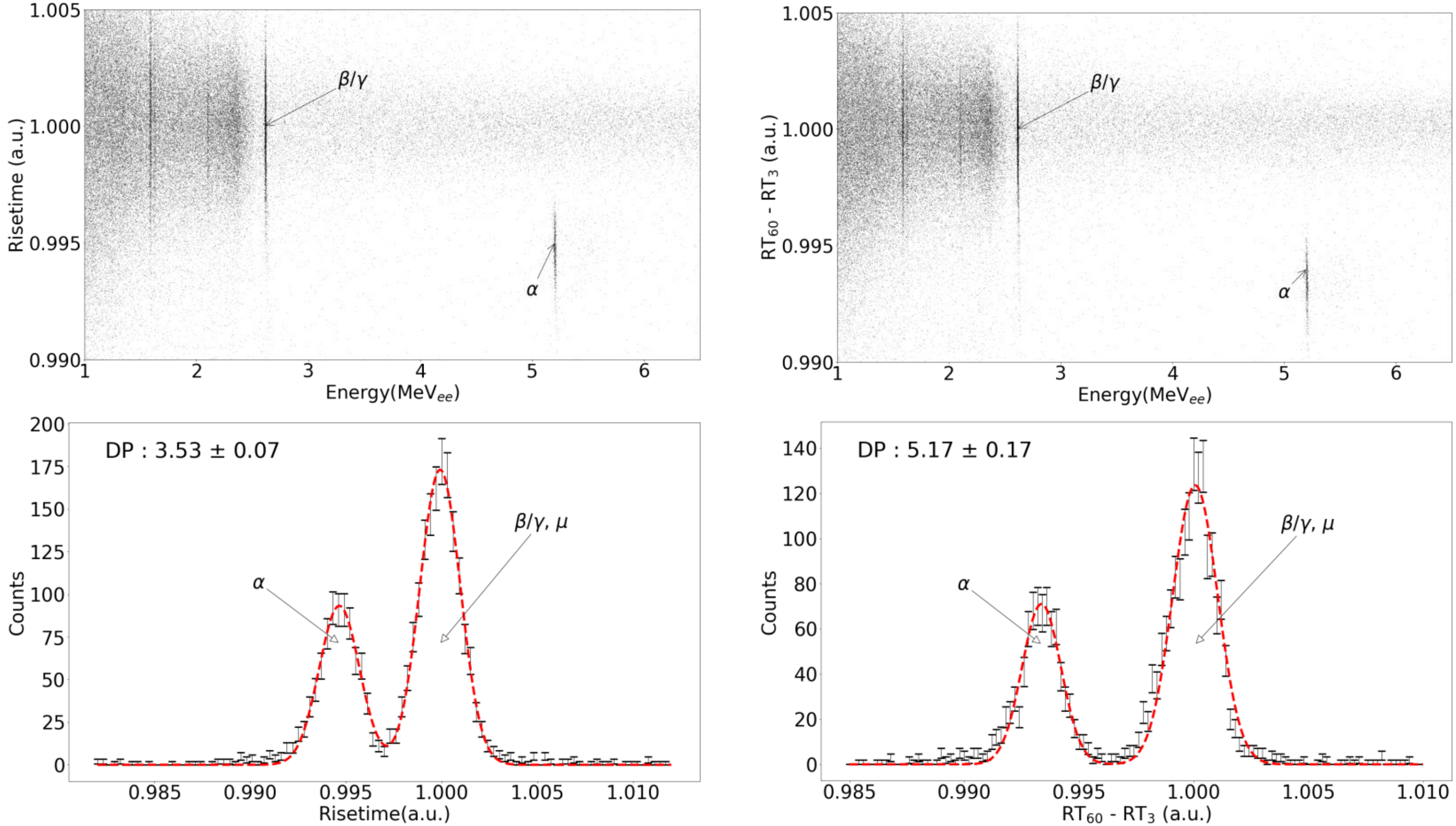
- 20 enriched Li2MoO4 crystals
- NTD-Ge thermometer
- Temperature : 20mK
- Fitting function : Normalized linear function + Smeared step function + Gaussian function (signal)
- Resolution : 6.6 ± 0.1 keV at 2.615 MeV, 7.4 ± 0.4 keV at $Q_{\beta\beta}$ (extrapolate with model $\sqrt{p_0^2 + p_1 E}$)
- PSD → Remove pile-up events using Principal Component Analysis (PCA)
- DP with light detector
- using 2 light detectors: 7.3 ~ 8.2
- Assuming single light detector: 3.9 ~ 6.2
- Light yield quenching of alpha particle : 17 ~ 21

E.Armengaud et al. (2019), The CUPID-Mo experiment for neutrinoless double-beta decay: performance and prospects

A.Armatol et al. (2022), 'Optimization of the first CUPID detector module'

C. Augier et al. (2022), Final results on the $0\nu\beta\beta$ decay half-life limit of ^{100}Mo from the CUPID-Mo experiment

Pulse Shape Discrimination

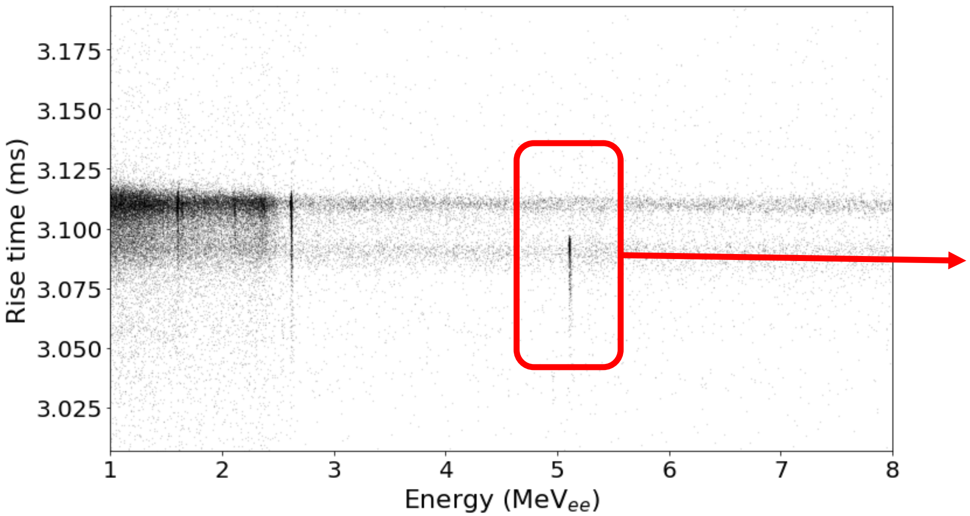


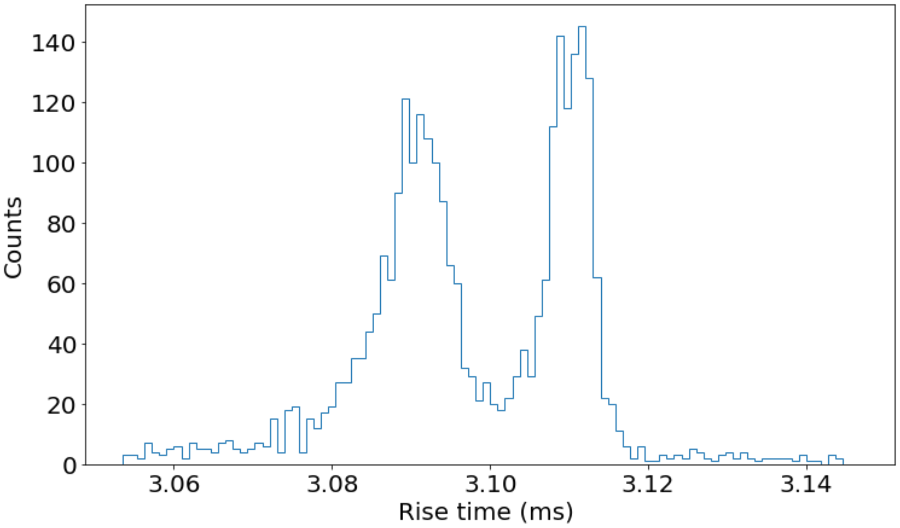
- Risetime distribution of crystal with polished surface is non-Gaussian shape, because of muon position dependence.

- Crystals with diffusive surfaces exhibited better discrimination between alpha and beta/gamma by PSD analysis, due to the mitigated position dependence, although their signal was slower than polished crystals.

* Discrimination power (DP) = $|\mu_\alpha - \mu_\beta| / \sqrt{\sigma_\alpha^2 + \sigma_\beta^2}$

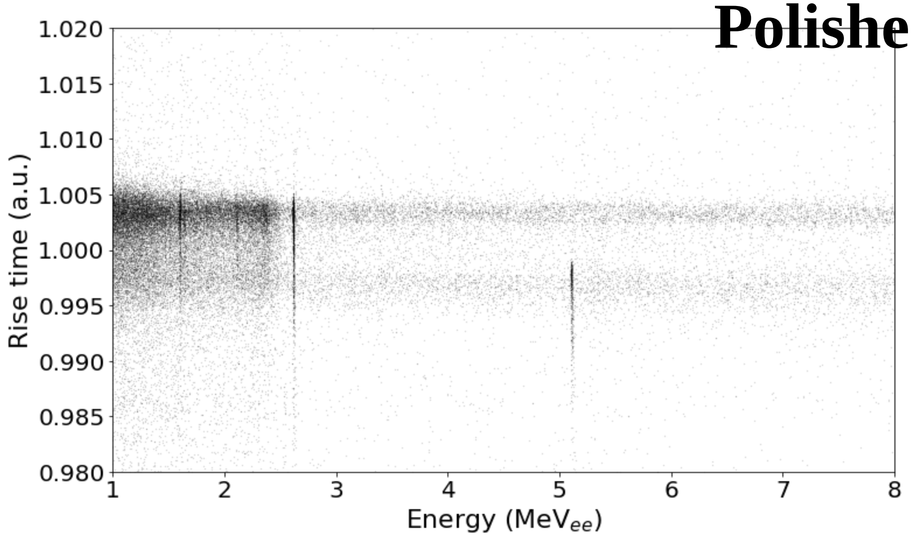
Pulse Shape Discrimination (Polished 6cm)

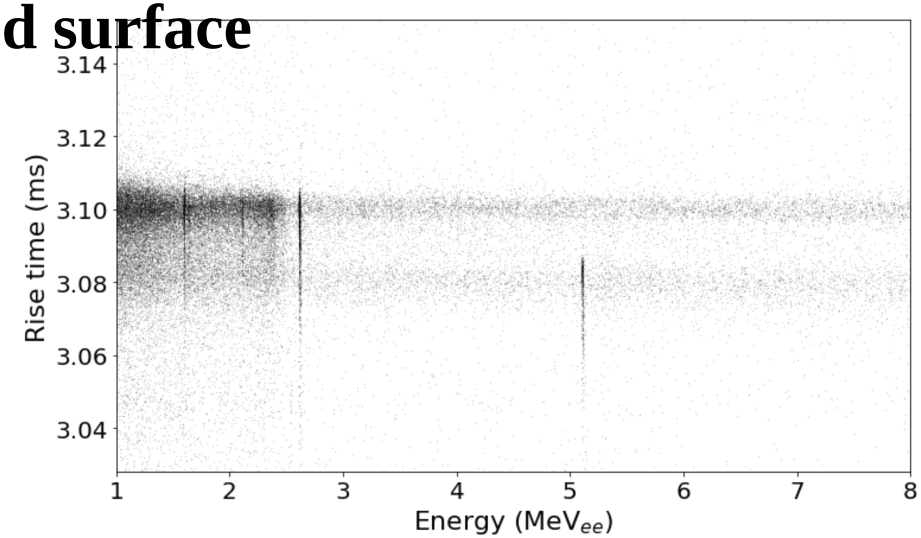




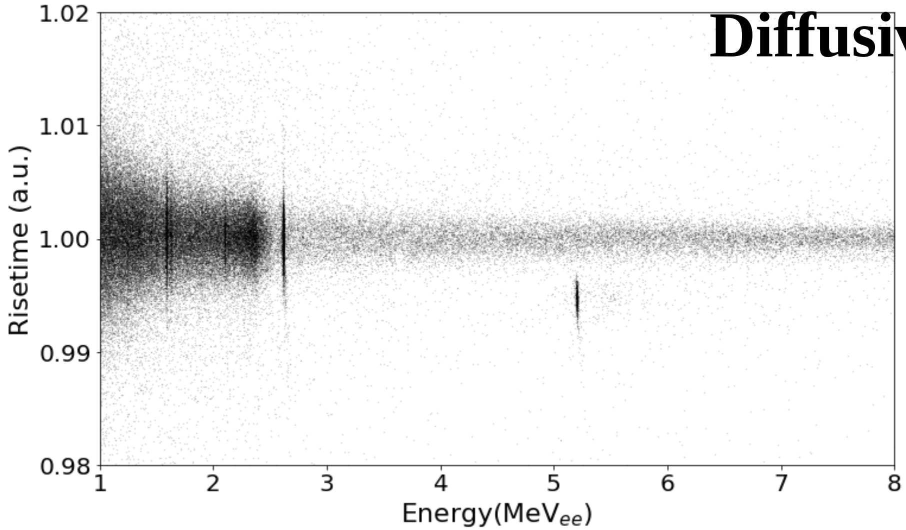
Pulse Shape Discrimination

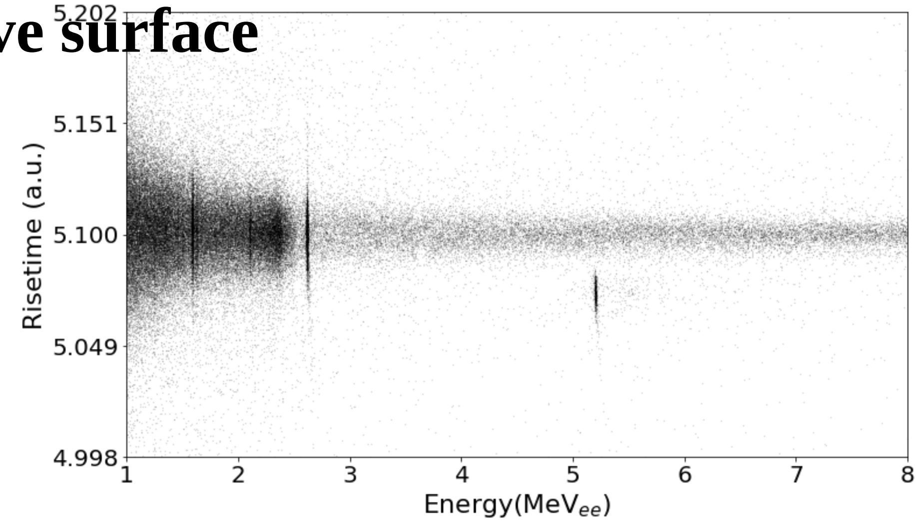
Polished surface





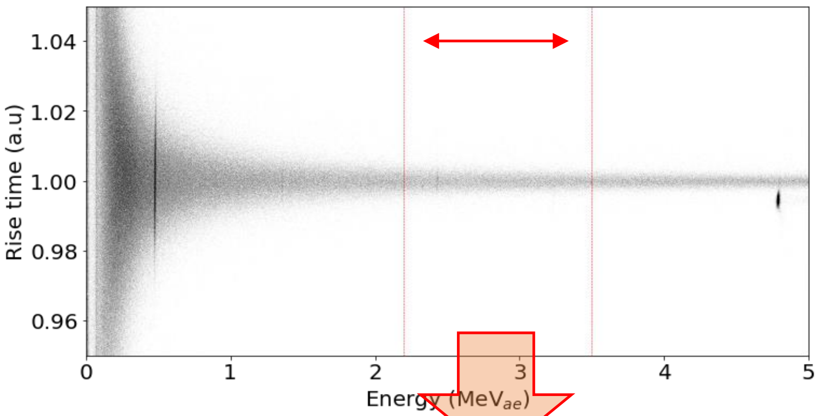
Diffusive surface



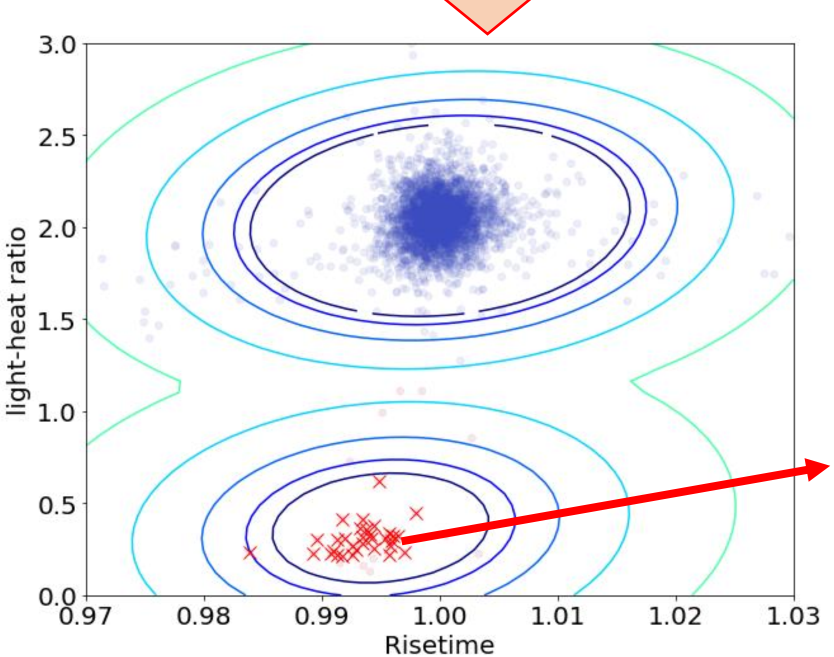


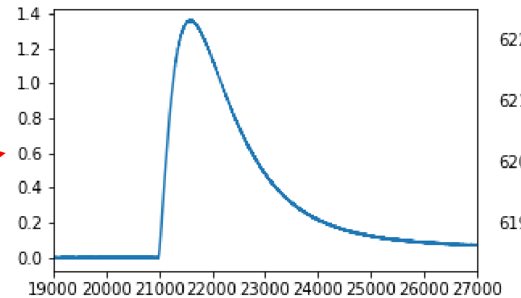
Particle Identification

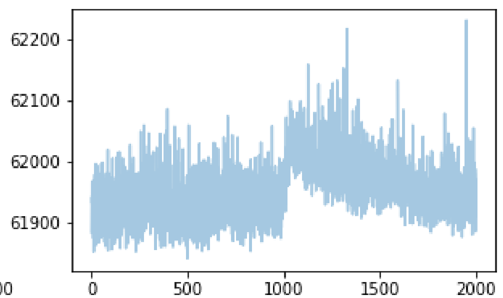
2.2 ~ 3.5 MeV_{ae} (LMOCUPEII-Exp2.22 at 20mK)



→ **The lowest vibration noise among all detector**

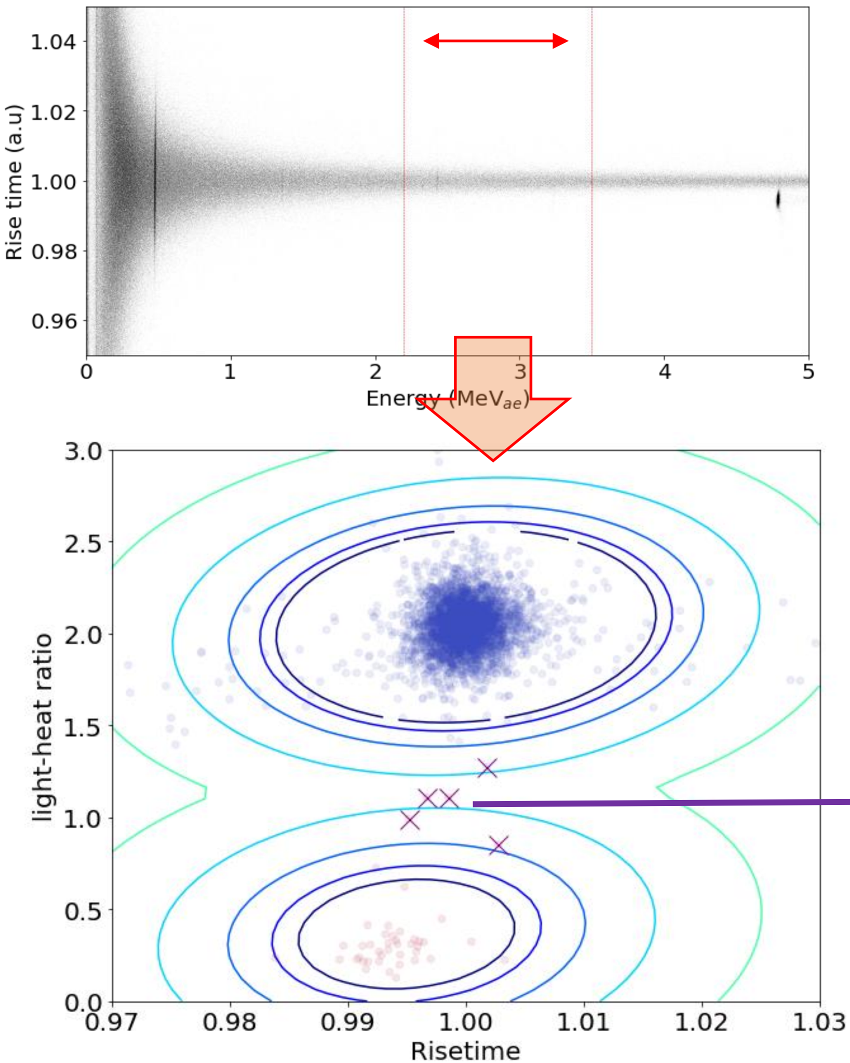




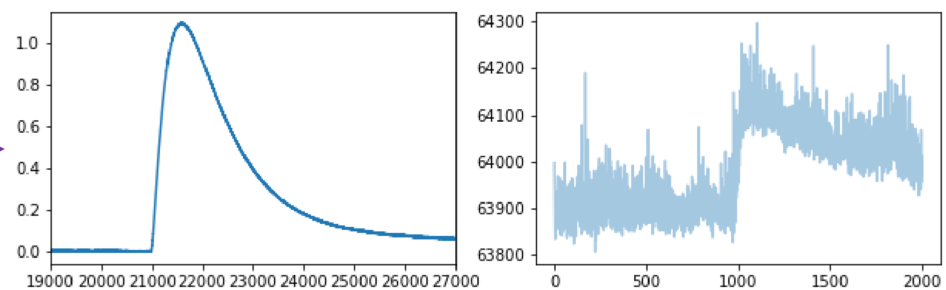


Particle Identification

2.2 ~ 3.5 MeV_{ae} (LMOCUPEII-Exp2.22 at 20mK)

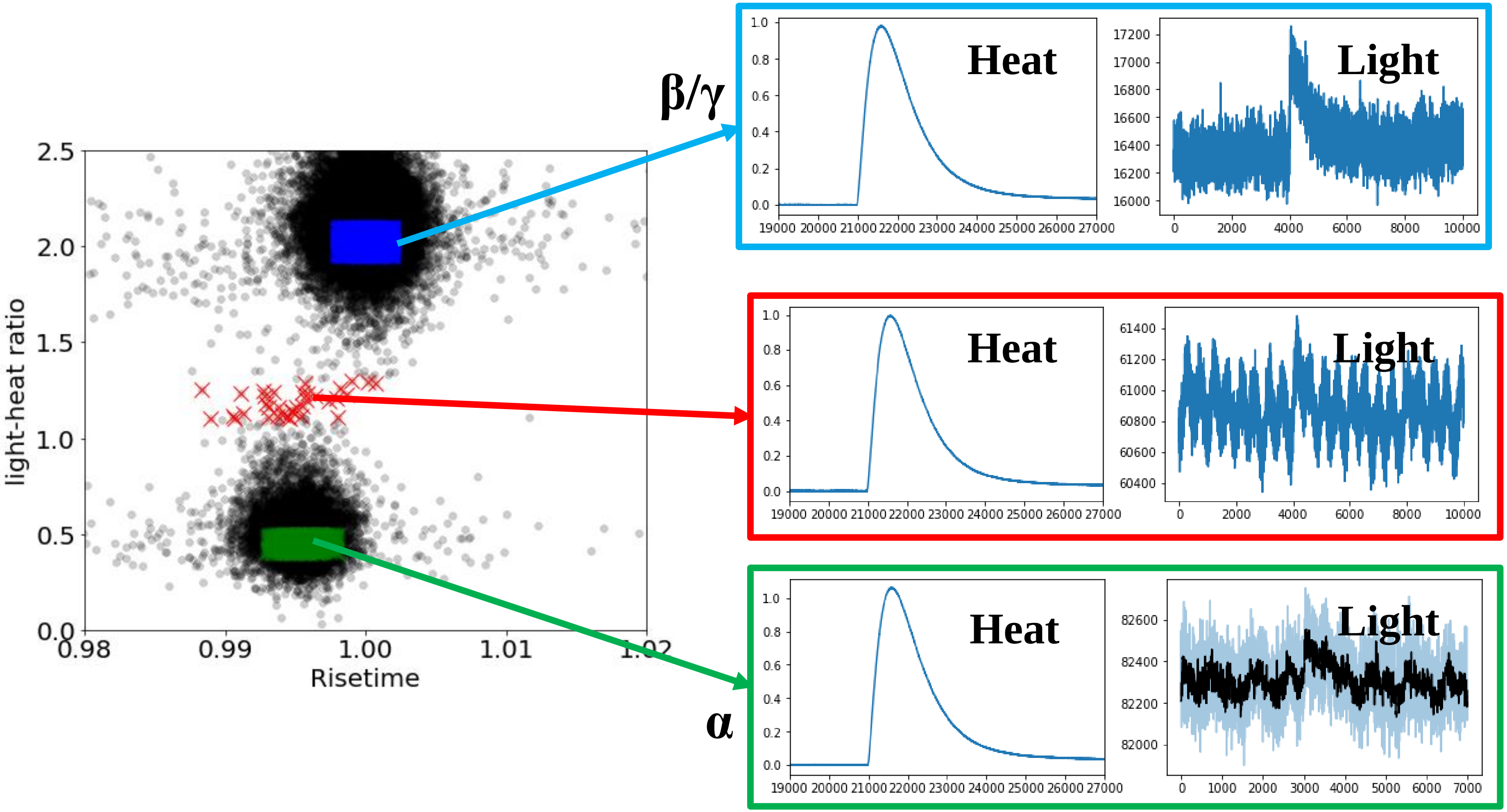


In this scatterplot, the events that fall in the middle range are not noise, but rather exhibit an intermediate value in terms of the signal amplitude of gamma and alpha.



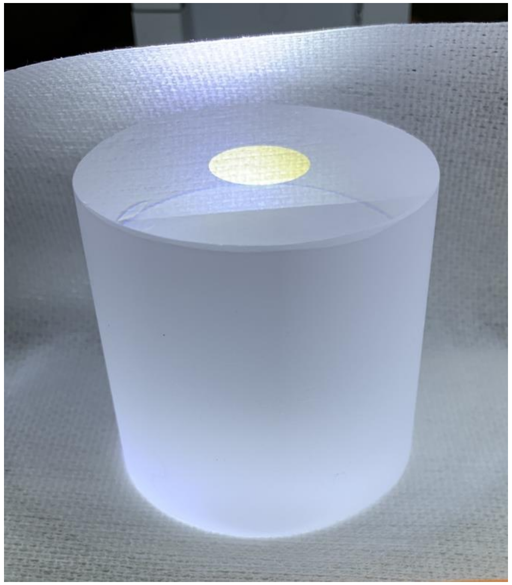
Particle Identification

4 ~ 5 MeV$_{ae}$ (LMO6E-Exp2.22 at 20mK)

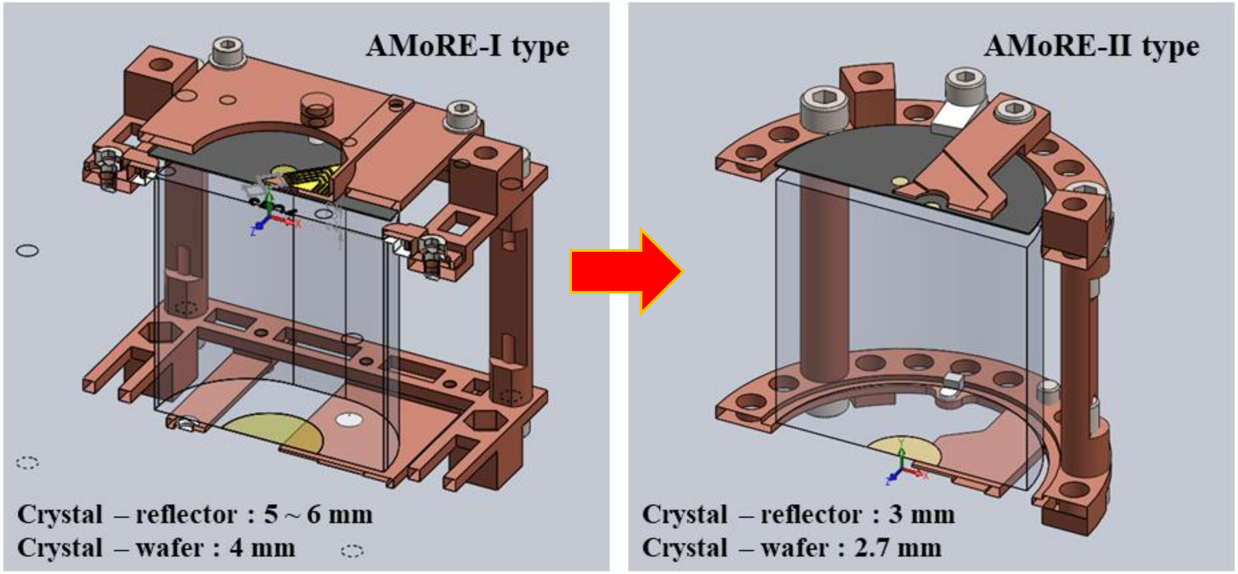


Particle Identification with light detector

1. Diffusive surface



2. Optimization of design

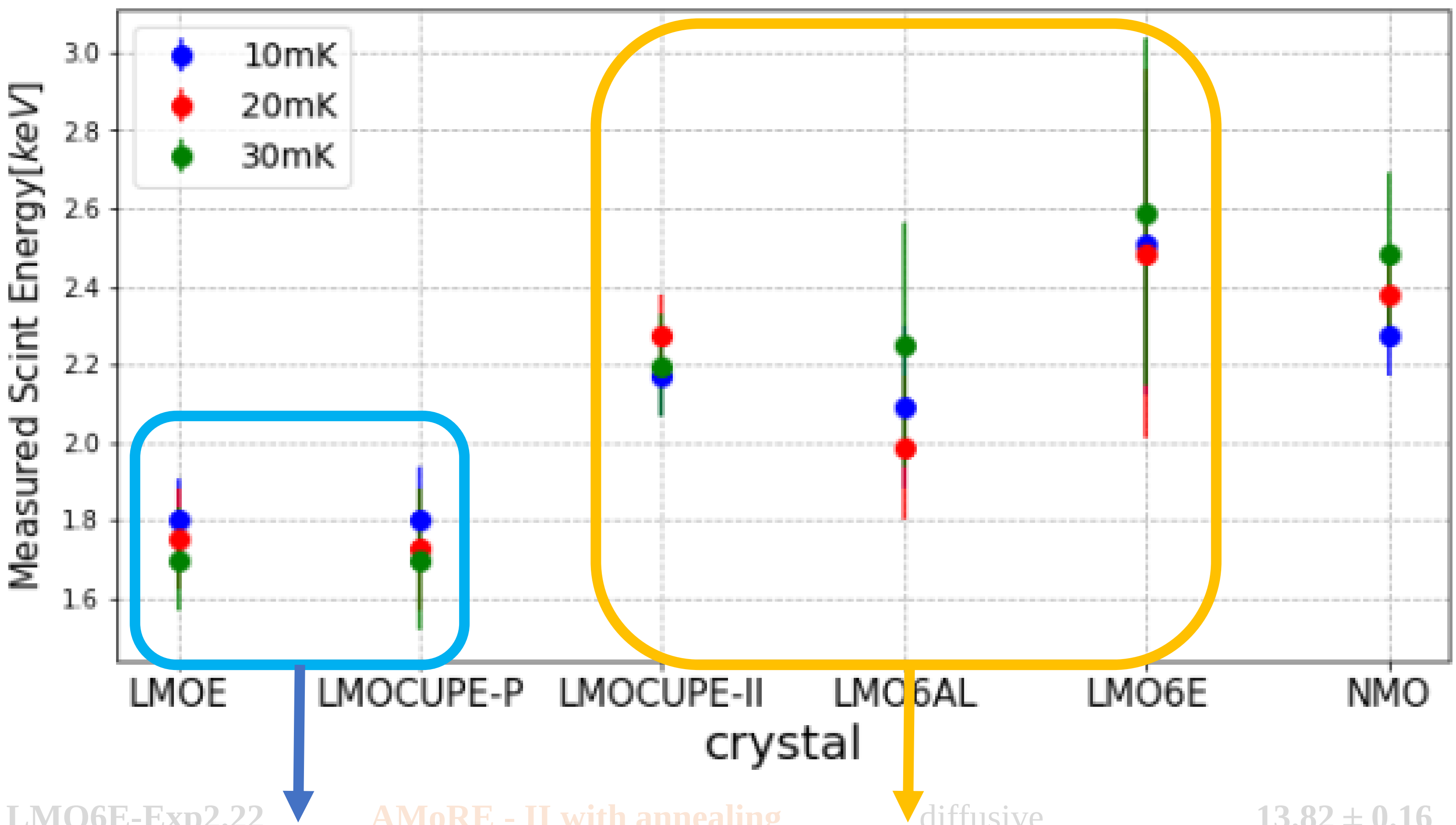


- To improve light absorption in the detector, two approaches have been taken:

  1. Using crystals with a diffusive surface (by Model for the Cherenkov light emission of TeO2 cryogenic calorimeters (2017))

  2. Reducing the distance between the crystal and the light detector wafer and reflector, which has been achieved through a new design. (by Characterization of cubic $Li_2{}^{100}MoO_4$ crystals for the CUPID experiment (2021))

Particle Identification with light detector - Result



LMO6E-Exp2.22 AMoRE - II with annealing diffusive 13.82 ± 0.16

AMoRE-Pilot/I type **AMoRE-II type**

- Reduction of gap is important role in light detector improvement .

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IEEE TASC 2023.3263333

- ...nant in the performance of the light detector.

Crystal volume - Result

Detector ID	LMOA – Exp1.21	LMO6 – Exp1.21	LMOCUPEII – Exp2.22	LMO6E – Exp2.22
Volume (D x H, cm)	**5 x 5**	**6 x 6**	**5 x 5**	**6 x 6**
Surface	Polished	Polished	Diffusive	Diffusive
Signal size (Φ_0)	1.06	1.07	0.49	0.30
Rise time (ms)	3.3	3.7	3.5	5.1
Baseline resolution (keV)	4.54 ± 0.05	3.23 ± 0.02	3.34 ± 0.02	3.39 ± 0.00
Energy resolution at 2.615 MeV (keV)	15.87 ± 0.77	11.67 ± 0.47	8.35 ± 0.19	7.55 ± 0.26
DP with light-heat ratio	6.97 ± 0.20	-	19.50 ± 0.09	13.82 ± 0.16
DP with PSD	3.08 ± 0.19	-	5.10 ± 0.15	5.27 ± 0.09

- The experimental results on crystal size show a slight increase in the signal risetime, but the performance in terms of energy resolution, signal amplitude, and scintillation light yields satisfactory results, as summarized in the following table.

- Position dependence issue can solve with correction and crystal surface treatment. (will discuses the crystal surface treatment)

* Discrimination power (DP) = $|\mu_\alpha - \mu_\beta| / \sqrt{\sigma_\alpha^2 + \sigma_\beta^2}$

Diffusive surface – Result

Detector ID	LMOA – Exp1.21	LMOE – Exp2.21	LMO6SL – Exp1.22	LMOCUPEII – Exp2.22	LMO6E – Exp2.22
Volume	5 x 5	5 x 5	6 x 6	5 x 5	6 x 6
Surface	Polished	Diffusive	Diffusive	Diffusive	Diffusive
Signal size (Φ_0)	1.06	1.07	1.65	0.49	0.30
Rise time (ms)	3.3	4.8	5.0	5.9	5.1
Energy resolution at 2.615 MeV (keV)	15.87 ± 0.77	7.74 ± 0.46	8.55 ± 0.22	8.35 ± 0.19	7.55 ± 0.26
DP with light-heat ratio	6.97 ± 0.20	14.25 ± 0.06	12.37 ± 0.09	19.50 ± 0.09	13.82 ± 0.16
DP with PSD	3.08 ± 0.19	5.18 ± 0.12	-	5.10 ± 0.15	5.27 ± 0.09

- First try to test about phonon signal of diffusive surface crystal
- Despite the slower risetime observed in the diffusive surface crystal compared to the polished one, we found that it exhibited improved energy resolution and discrimination power when analyzing the light-heat ratio and pulse shape. This is attributed to the diffusive surface, which helps to mitigate position dependence.

Further R&D experiments for AMoRE-II

1. To represent diffusive 6cm crystal result.
2. To study position dependence of diffusive crystal.
3. To study position dependence issue with beta source.
4. To optimize phonon collector size for 6cm LMO crystal.
    - Increase size of phonon collector
        - Heat capacity ↑, signal size ↓
        - Position dependence ↓, energy resolution ↑ (?)
    - Decrease size of phonon collector
        - Position dependence ↑, separate surface event (concept : BEGe detector (GERDA)) (?)
5. Improvement pulse shape discrimination to study possibility of reduction number of channel.