Spectrum-shape method for studying the forbidden beta decay of ^{210}Bi using $PbMoO_4$ cryogenic detectors

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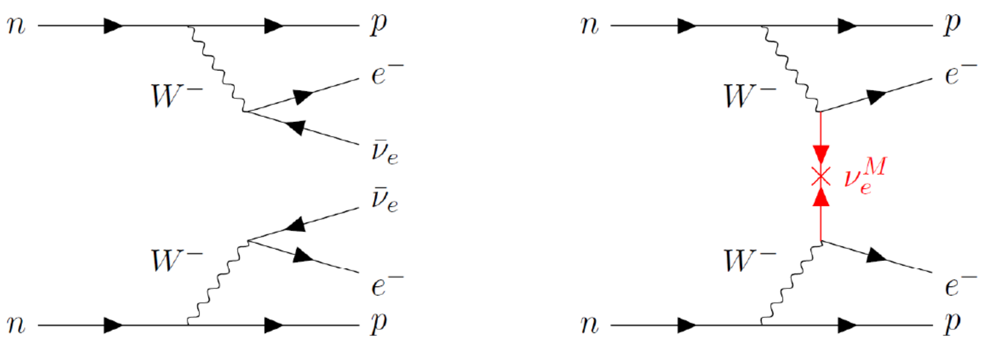
Motivation



(Z, A) → (Z+2, A) + 2e⁻ + 2anti-ν_e (ΔL = 0, conserved)
(Z, A) → (Z+2, A) + 2e⁻ (ΔL = 2, violated)

- 0*n bb* is forbidden by Standard Model for lepton number violation.
- Majorana *n* can be confirmed (unique experimental approach)
- Absolute mass of *n*

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}\left(Q_{\beta\beta}, Z\right)|M_{0\nu}|^2 < m_{\beta\beta} >^2$$

$$M_{0\nu} = (g_{A,0\nu})^2\,(M_{GT,0\nu} - (\frac{g_V}{g_{A,0\nu}})^2 M_{F,0\nu} + M_{T,0\nu})$$

Spectrum-shape method (SSM)
Forbidden non-unique β decay

Decomposition of the shape factor

$$C(w_e) = g_A^2\left[C_A(w_e) + \frac{g_V}{g_A} C_{VA}(w_e) + \left(\frac{g_V}{g_A}\right)^2 C_V(w_e)\right]$$

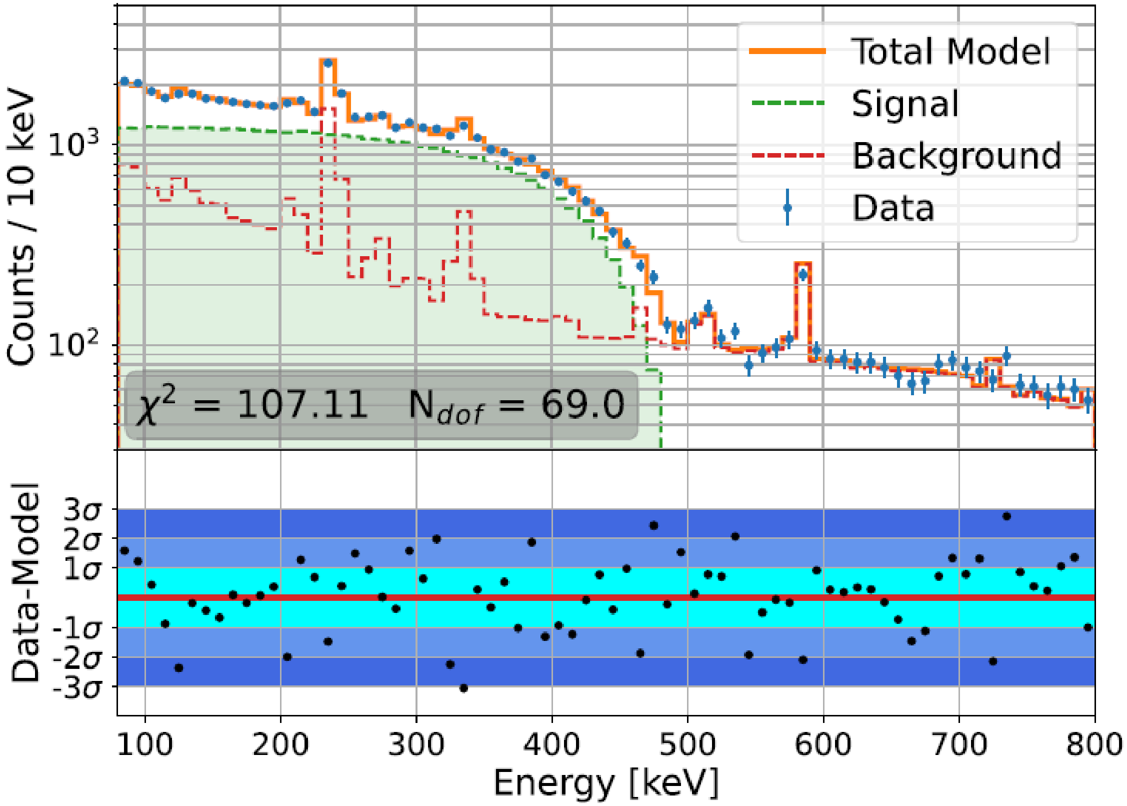
- Forbidden nonunique β-decays are crucial for investigating the quenching of g_A, as their spectral shape strongly depends on the g_A/g_V ratio.
- The spectrum-shape method (SSM) has been used to study these decays, achieving a high level of agreement between experimental data and theoretical predictions for spectral shapes.
- This approach enables more precise simultaneous predictions of the spectral shape and half-life.

ref: **J. Suhonen, et al., Front. Phys.** 7, **00029 (2019),**
M. Haaranen, et al., Phys. Rev. C 93, 034308 (2016).

Recent SSM study of ^{115}In and ^{113}Cd

ref: L. Pagnanini, et. al., Phys. Rev. Lett. 133, 122501 (2024)

Model	g_A	sNME [fm^3]	$T_{1/2}/10^{14}$	χ^2_{red}
Best fit ISM	$0.964^{+0.010}_{-0.006}$	$1.75^{+0.13}_{-0.08}$	5.26 ± 0.06	1.55

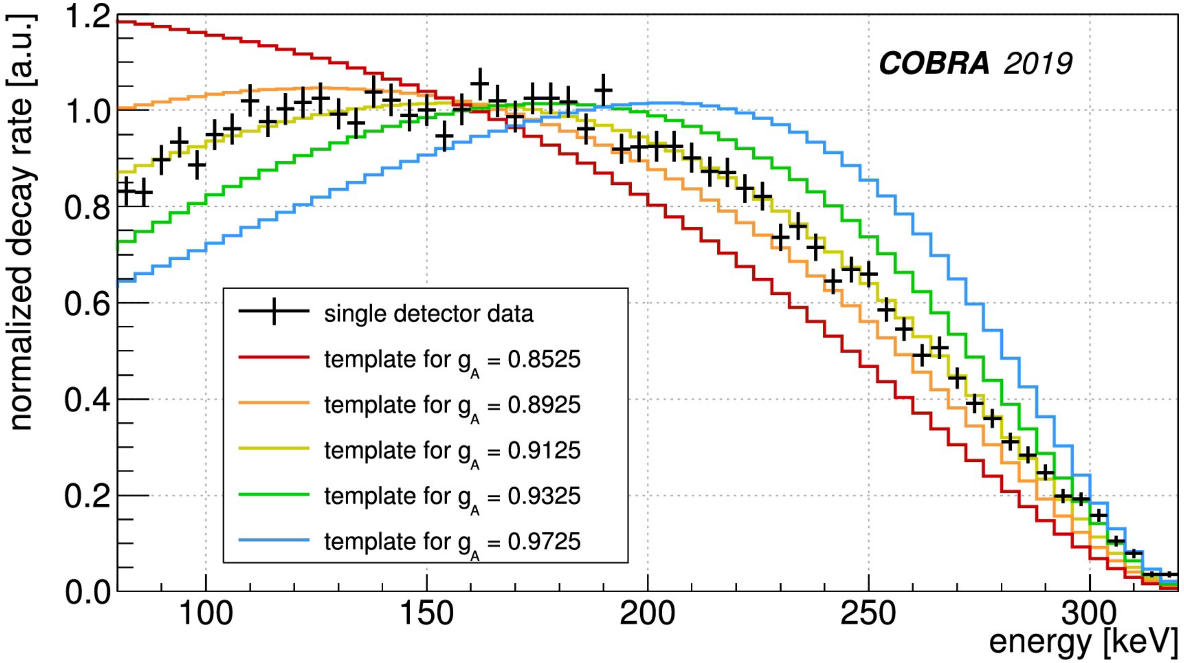


ref: L. Bodenstein-Dresler, et. al., Phys. Lett. B 800, 135092 (2020)

4th forbidden non-unique β decay

^{113}Cd(1/2$^+$) → ^{113}In(9/2$^+$) $(\Delta J^\pi = 4^+)$

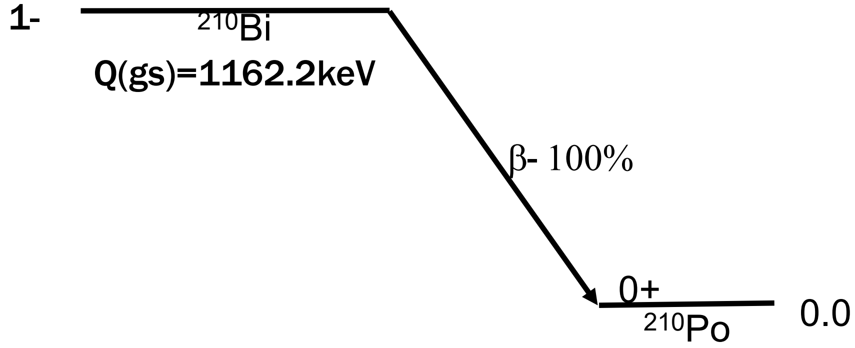
- $\bar{g}_A$(ISM) = 0.915 ± 0.007
- $\bar{g}_A$(MQPM) = 0.911 ± 0.013
- $\bar{g}_A$(IBFM-2) = 0.955 ± 0.022



SSM study of ^{210}Bi with $PbMoO_4$

$$^{210}\mathrm{Pb}(\beta, 22.3\ \mathrm{y}) \rightarrow {}^{210}\mathrm{Bi}(\beta, 5.0\ \mathrm{d}) \rightarrow {}^{210}Po(\alpha, 115\ \mathrm{d})$$

Q-value: 63.5 keV   Q-value: 1162 keV   Q-value: 5304 keV

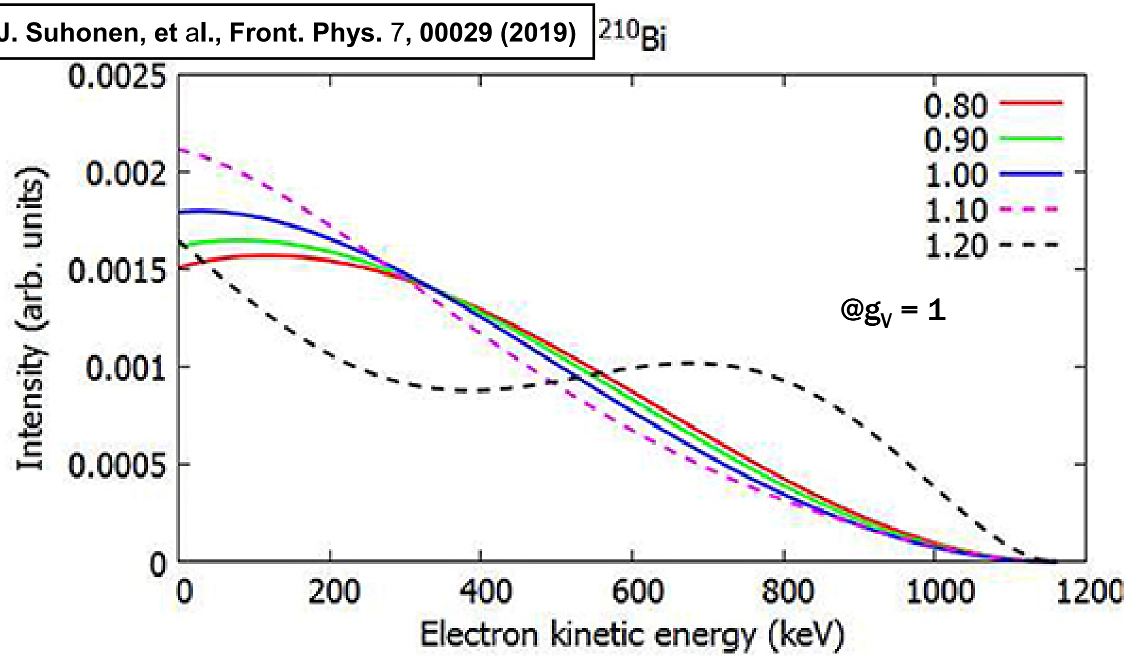


1[st] forbidden non-unique β decay

$^{210}Bi(1^-) \rightarrow {}^{210}Po(0^+)$ $(\Delta J^{\pi} = 1^-)$

Normalized ISM-computed spectrum

ref: J. Suhonen, et al., Front. Phys. 7, 00029 (2019)



g_A-EXPERT collaboration

gA-EXPERiment and Theory collaboration

KYUNGPOOK NATIONAL UNIVERSITY 경북대학교

ibs Institute for Basic Science

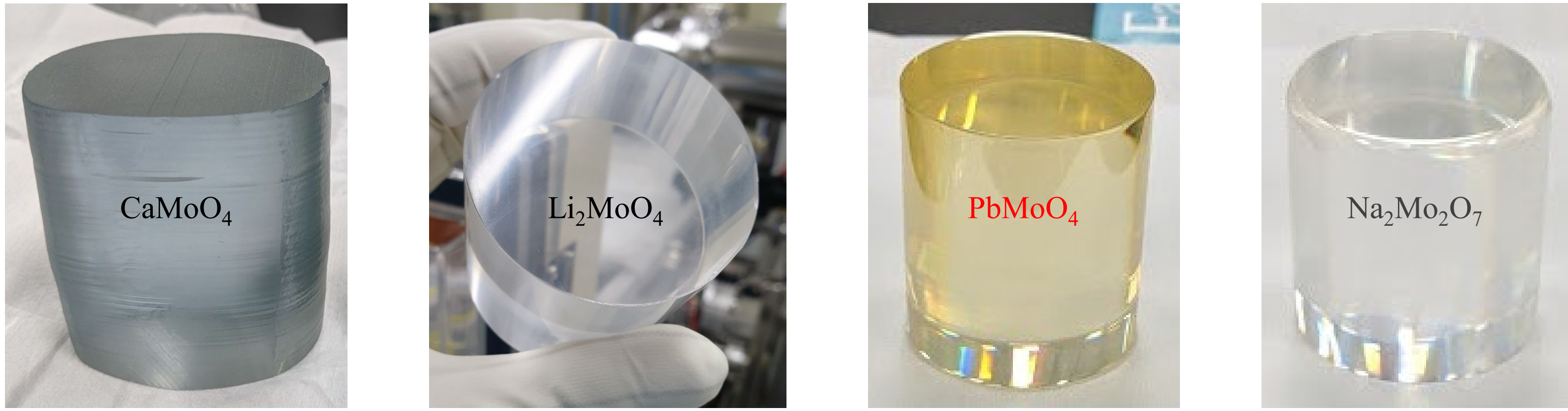
KRISS

UNIVERSITY OF JYVÄSKYLÄ

Luke NATURAL RESOURCES INSTITUTE FINLAND

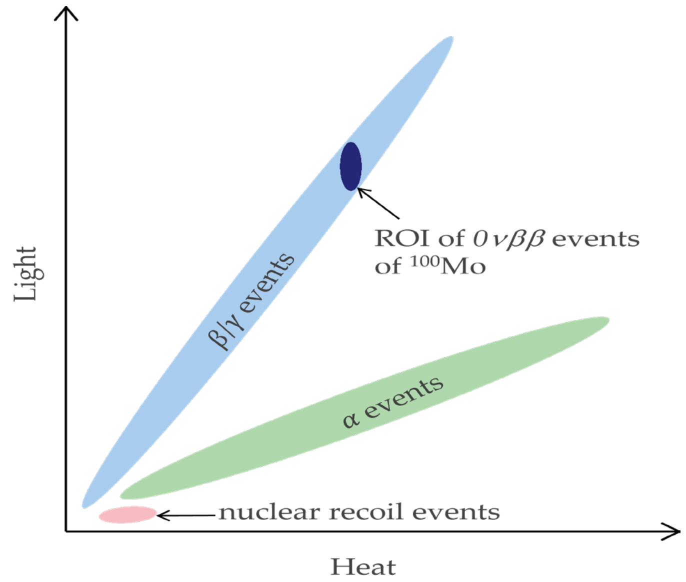
MoO_x based Crystal Scintillators for AMoRE

	Inter. BG	LY at 10 K (%)	Density (g/cm^3)	Melt. Point (°C)	Hygroscopic
$CaMoO_4$	High (^{48}Ca)	100	4.2	~1450	No
Li_2MoO_4	Lower	5	3.0	~700	Middle
$PbMoO_4$	Under study (^{210}Pb)	105	6.8	~1065	No
$Na_2Mo_2O_7$	Under study	9	3.7	~600	Weak



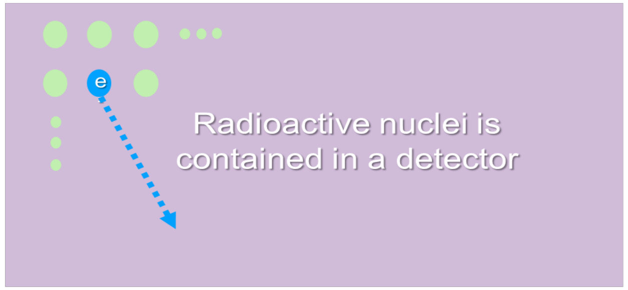
Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.268	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.998	8.8
$^{96}Zr \rightarrow ^{96}Mo$	3.356	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow ^{110}Cd$	2.017	11.7
$^{116}Cd \rightarrow ^{116}Sn$	2.813	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.293	5.8
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.1
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.371	5.6

Scintillation & cryogenic detector



*ROI : Region of Interest

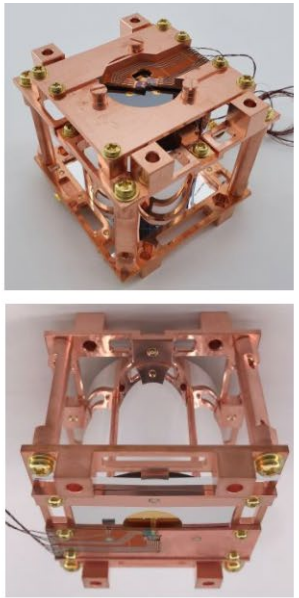
Detector = Source

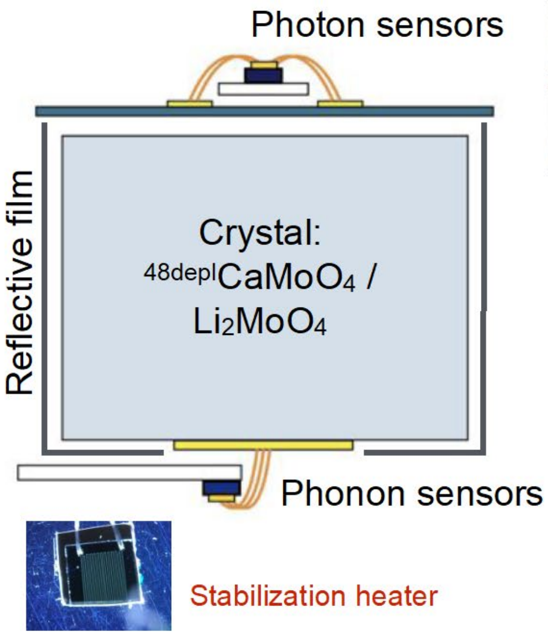


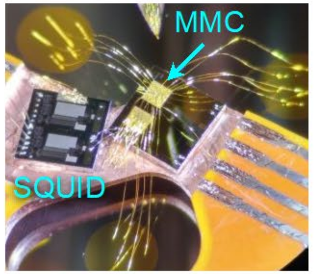
There is not the energy loss of beta particles

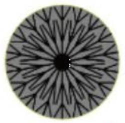
Calorimetric experiment using molybdate scintillator

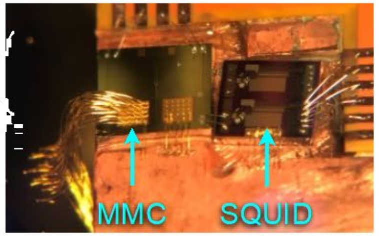
- Cylindrical CMO and LMO crystals, sizes vary 4 cm ≲ Φ / H ≲ 5 cm.
  - CMO: ^{48}Ca depleted, $Q_{\beta\beta}$ (^{48}Ca) = 4271 keV.
- Metallic magnetic calorimeter (MMC) + SQUID:
  - Fast signal timing: a few millisecond rise-time for phonon signals at mK.
  - Low random coincidence background.
  - Energy resolution ~ 10 keV FWHM at 2.6 MeV.



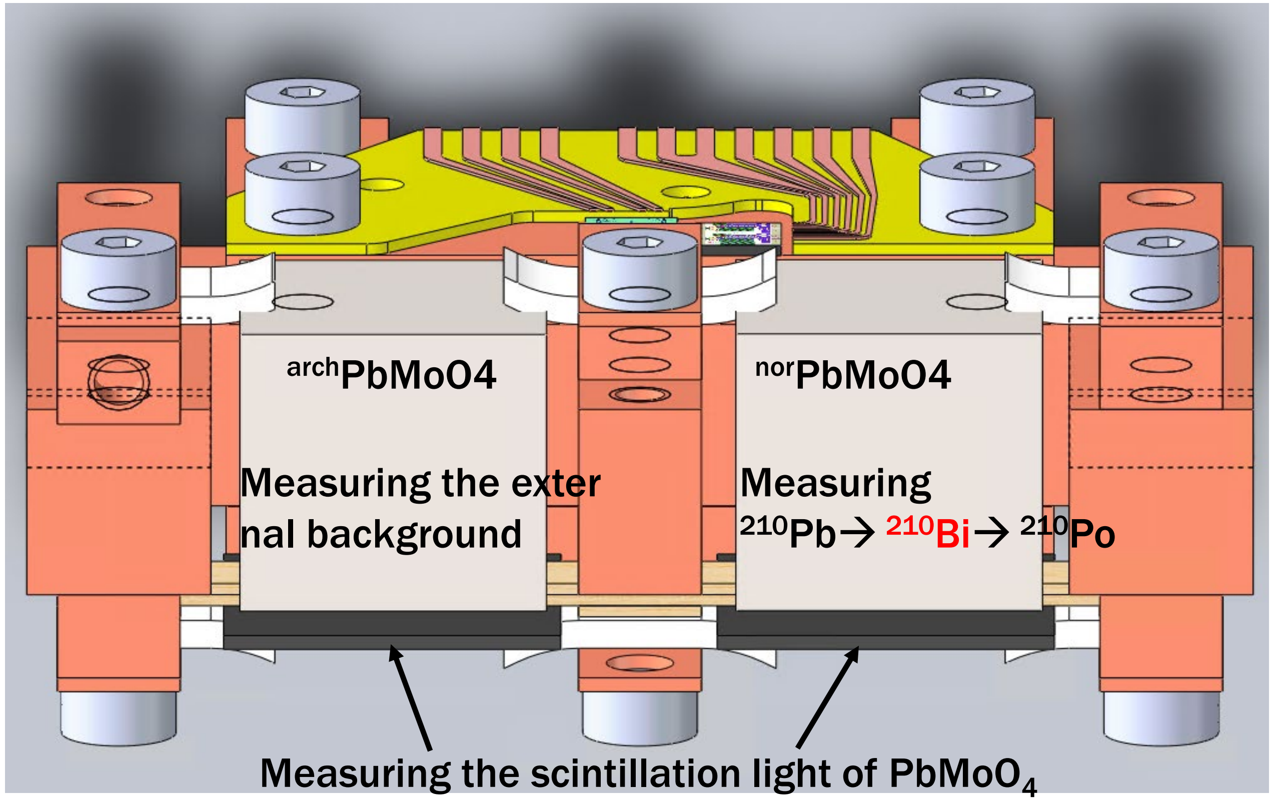


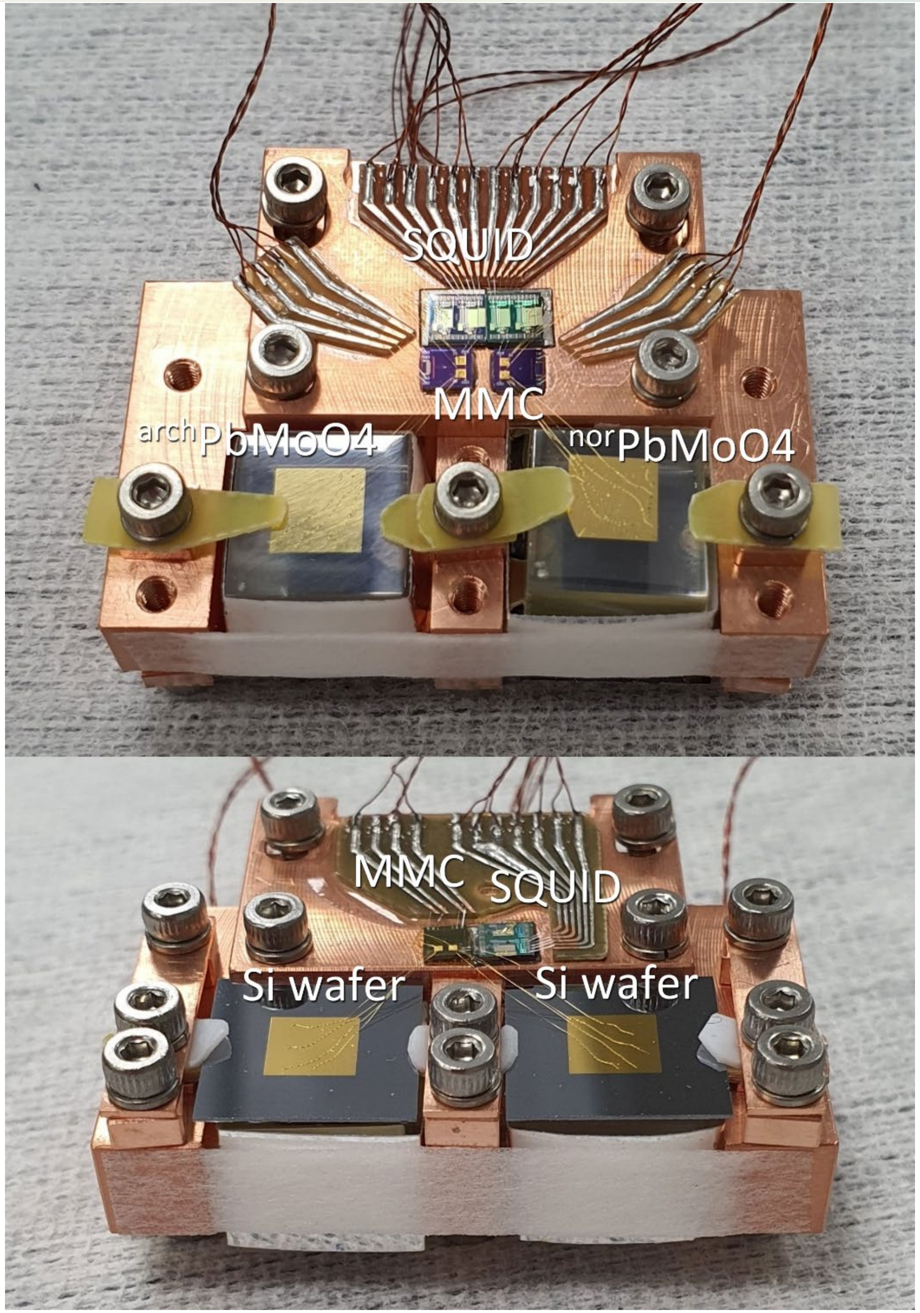






Detector Set-up



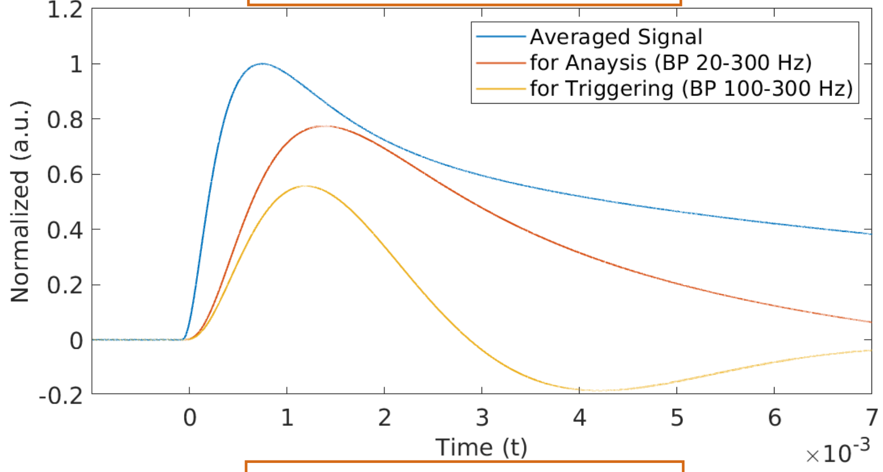


- Refrigerator: CF-DR
- Crystal: Archeological & Normal $PbMoO_4$ (10 x 10 x 10 mm^3)
- Scintillation light absorber: Si wafer (15 x 15 x 0.5 mm)
- Vikuiti for light reflector
- Radioactive calibration source: Thoriated welding rod

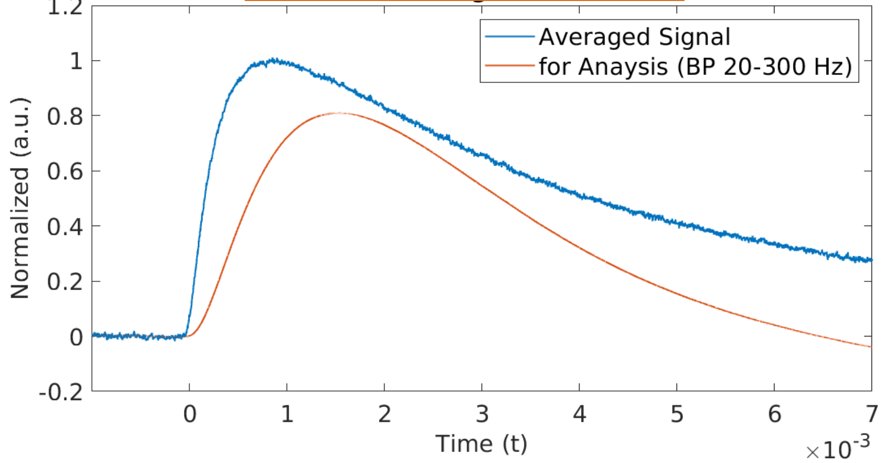
Signal trigger

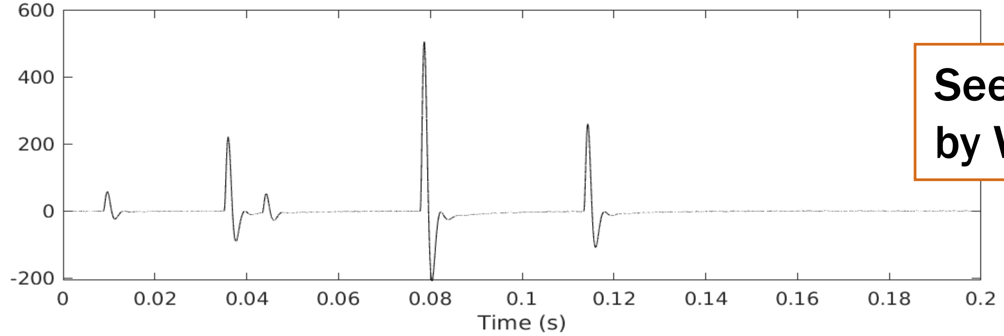
$$\mathrm{Rvalue} = \frac{\sum_{i=1}^{n}\left(\mathrm{RefSig}_i - \overline{\mathrm{RefSig}}\right)\left(\mathrm{Data}_i - \overline{\mathrm{Data}}\right)}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{RefSig}_i - \overline{\mathrm{RefSig}}\right)^2}\sqrt{\sum_{i=1}^{n}\left(\mathrm{Data}_i - \overline{\mathrm{Data}}\right)^2}}$$

Crystal Heat Signal



Crystal Light Signal





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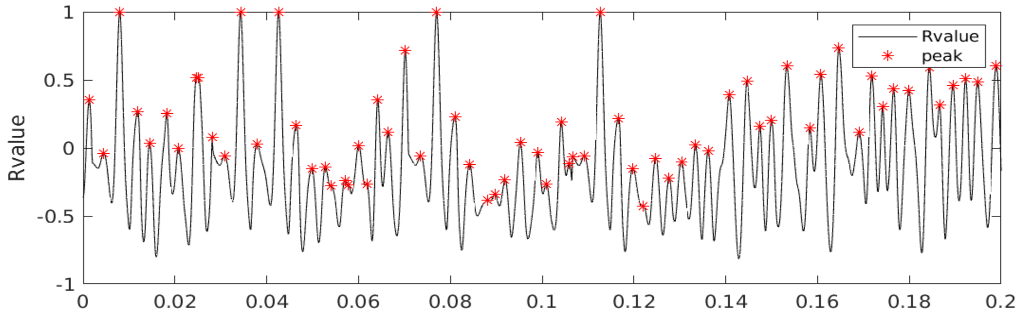
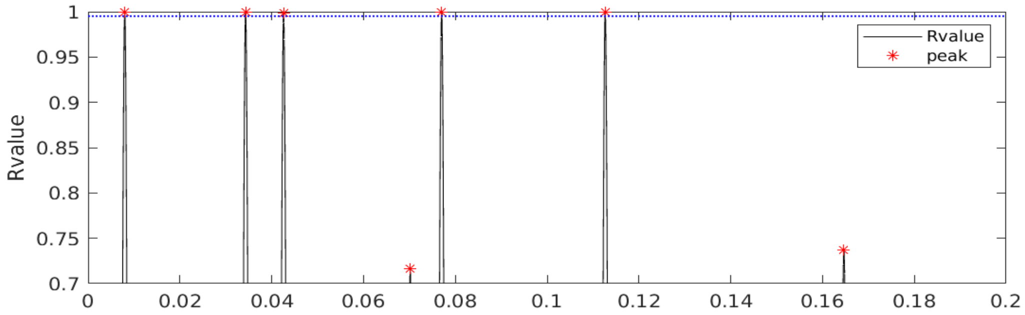
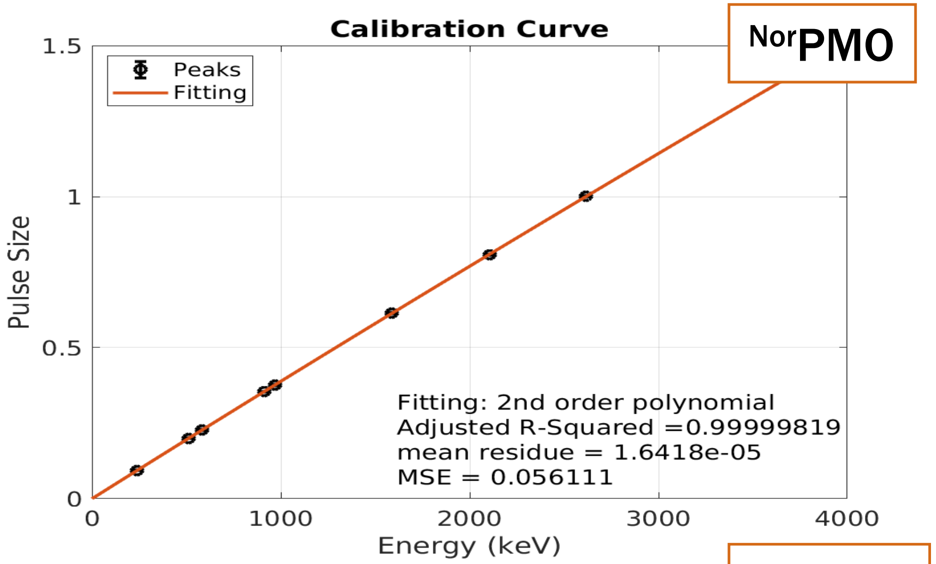
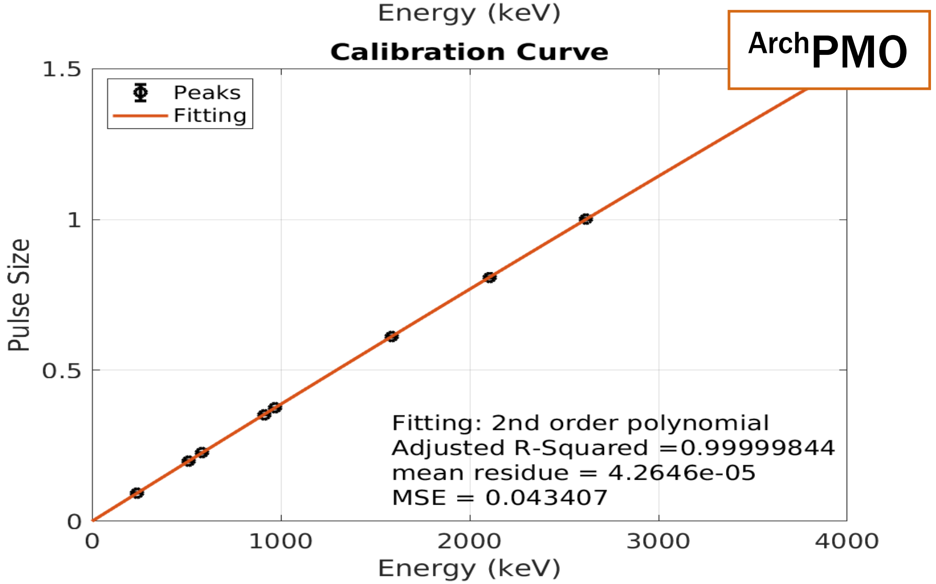
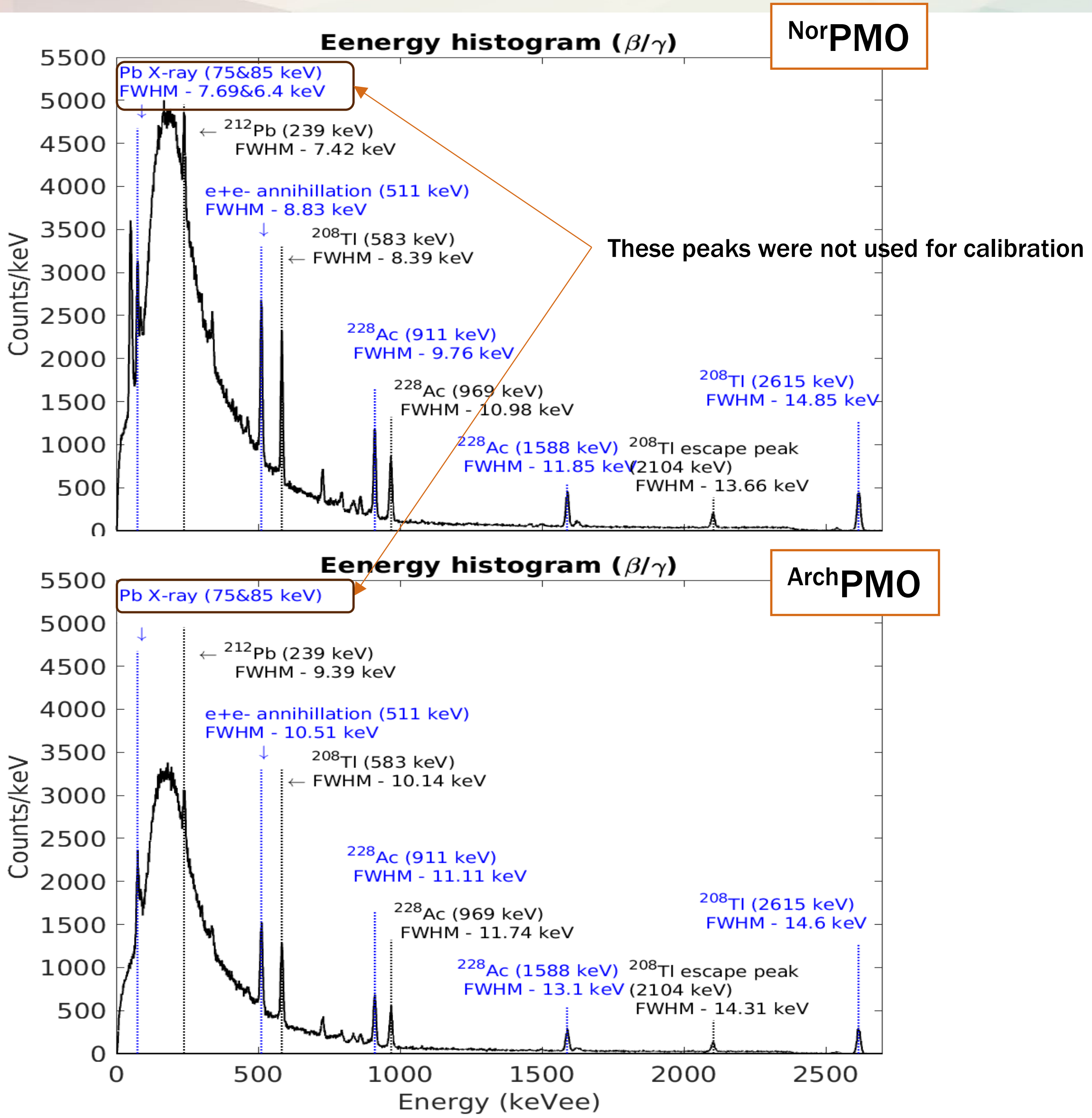




Energy calibration



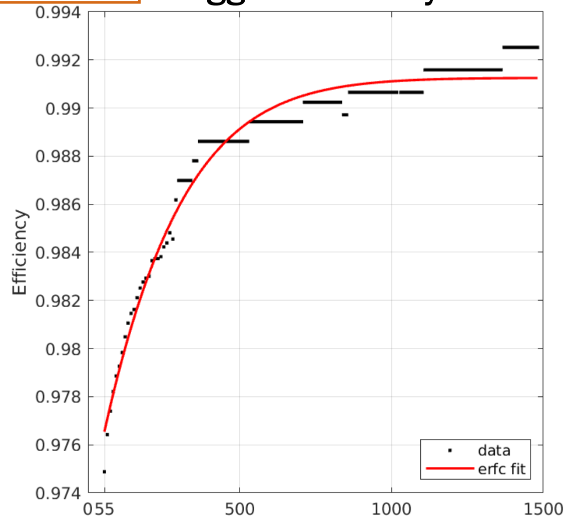




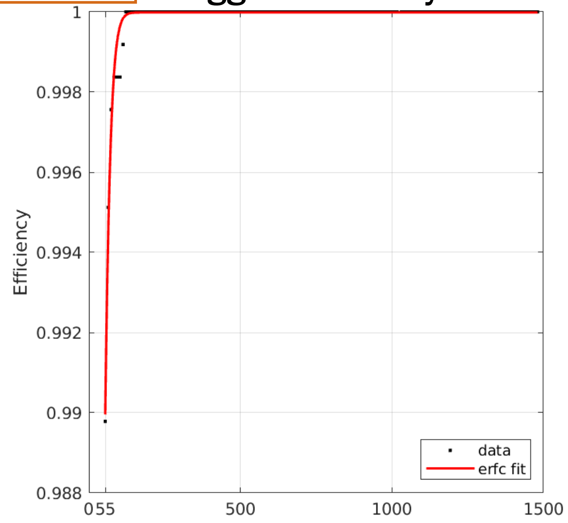
Pseudo Data Simulation (preliminary)

^{210}Pb Q-value : 63.5 keV
^{210}Bi Q-value : 1162 keV

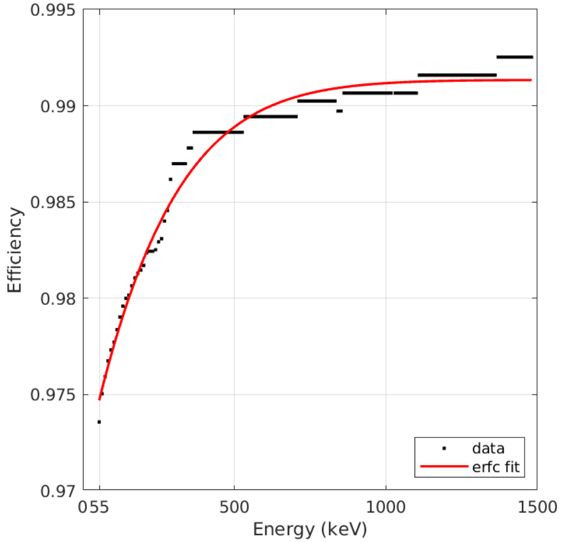
^{Nor}PMO Trigger Efficiency



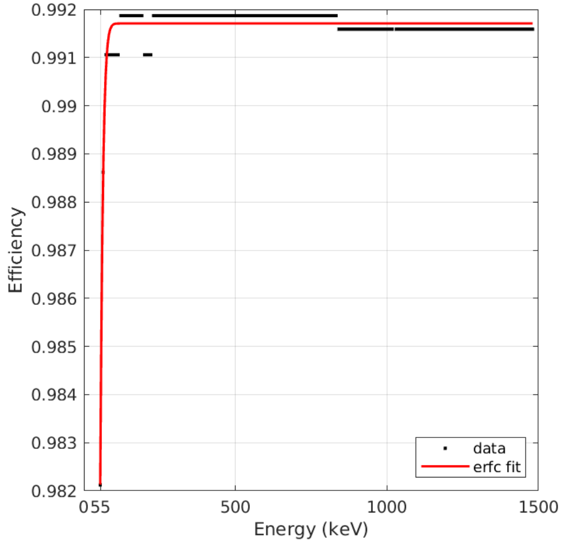
^{Arch}PMO Trigger Efficiency

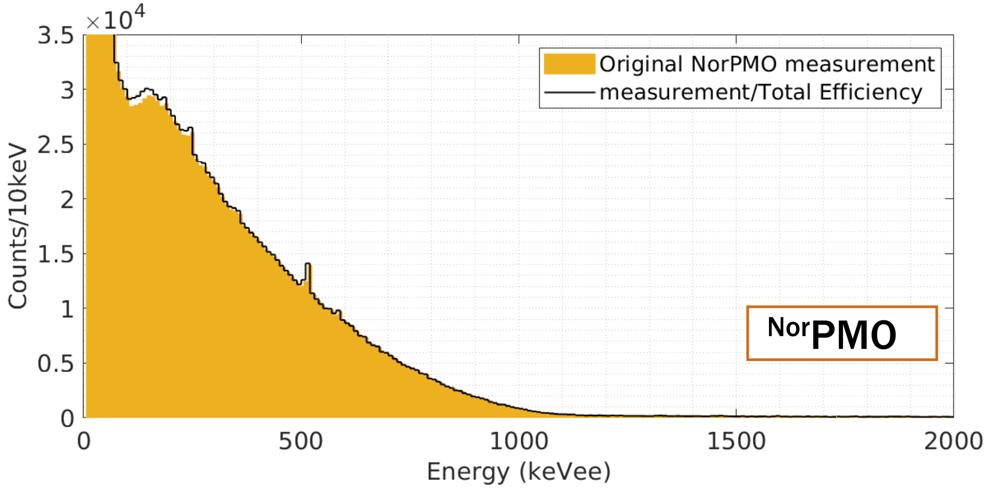


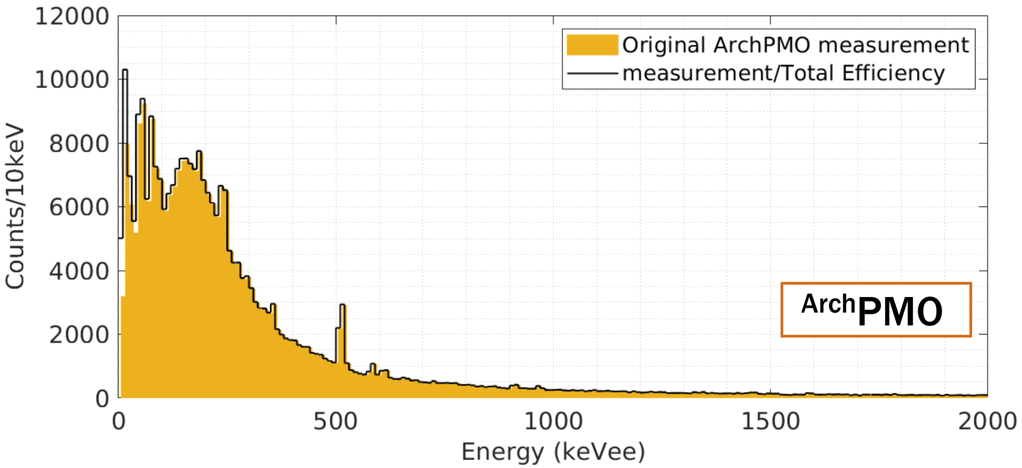
Total (+analysis cut) Efficiency



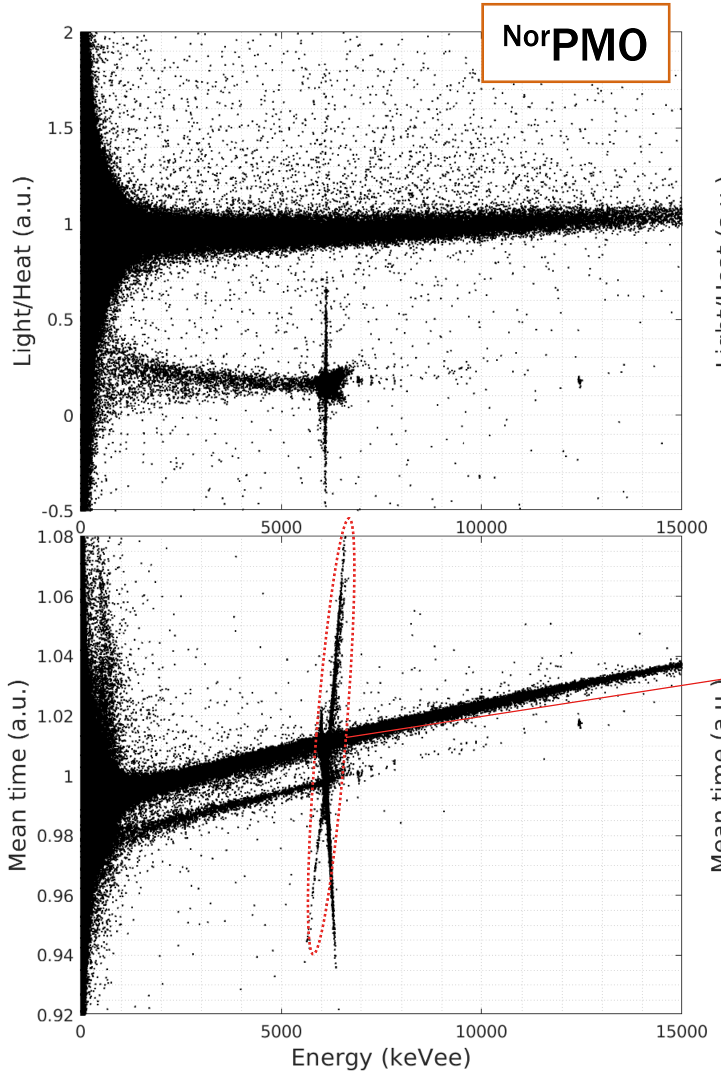
Total (+analysis cut) Efficiency

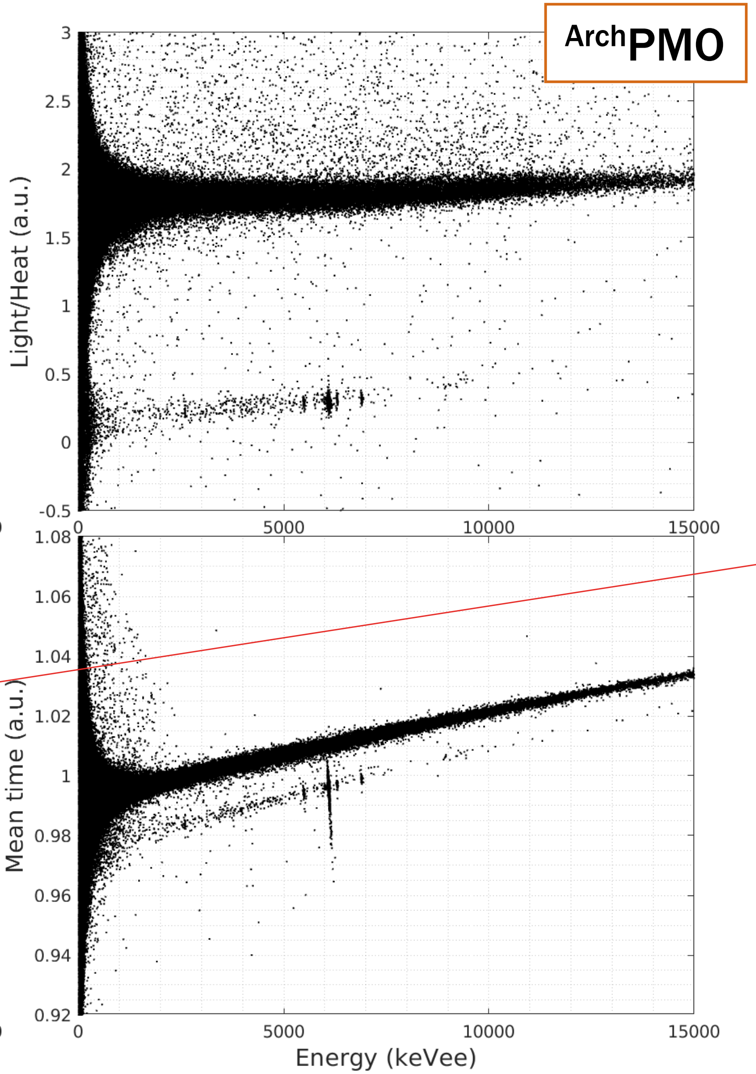


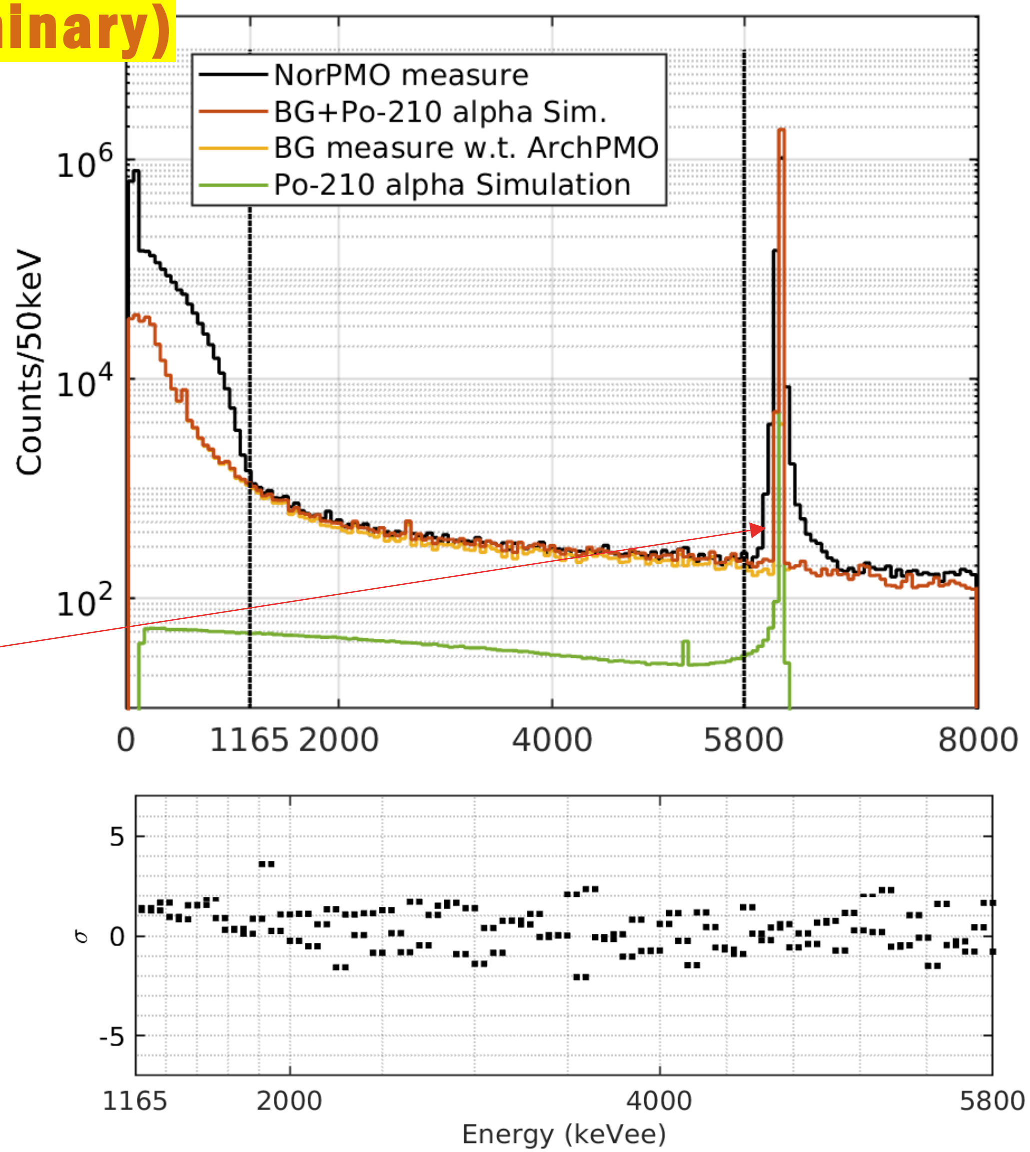




^{210}Po Alpha background (preliminary)



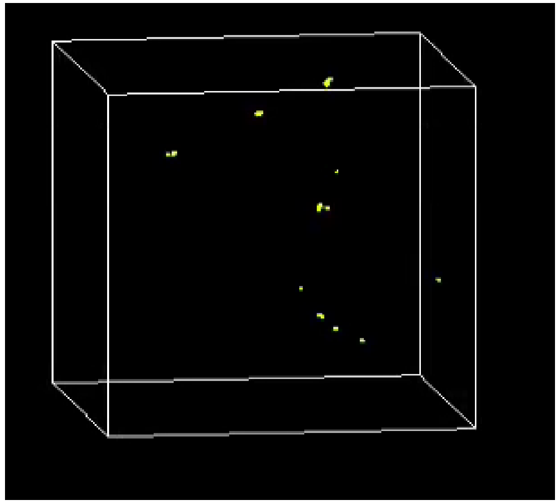


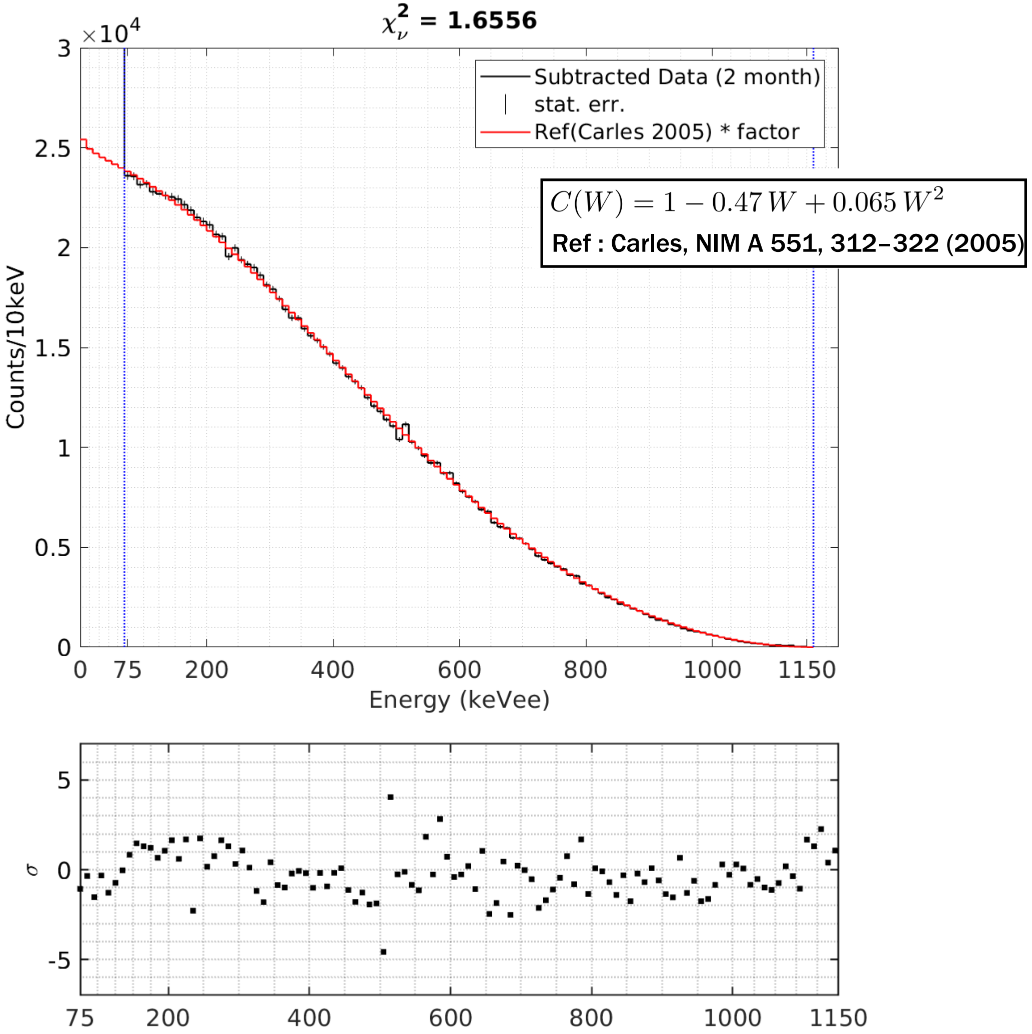


Detection Efficiency Matrix using G4 simulation

(preliminary)

Generation Energy
: 0 – 1170 keV (over Q-value)
Binning : 5 keV

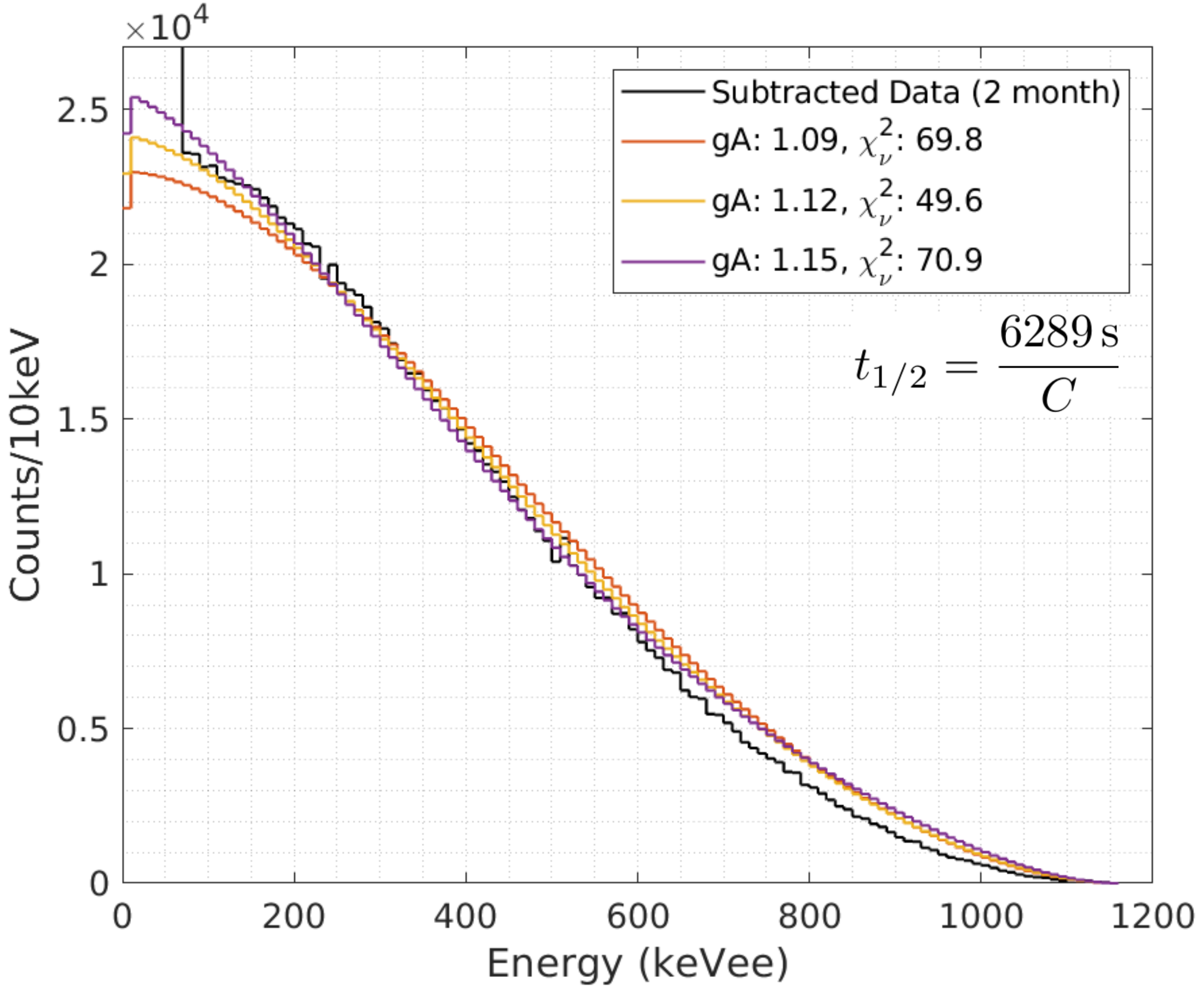


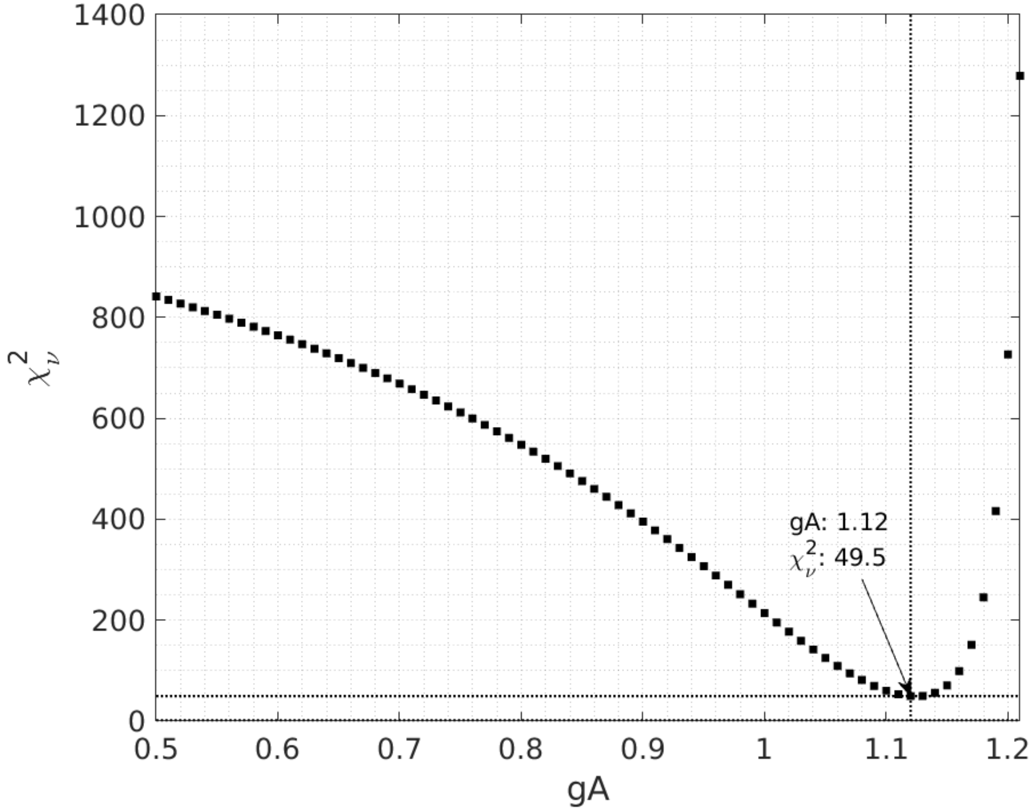


$$\begin{bmatrix} \mathrm{Data}_1 \\ \mathrm{Data}_2 \\ \vdots \\ \mathrm{Data}_N \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & \cdots & M_{1N} \\ M_{21} & M_{22} & \cdots & M_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ M_{N1} & \cdots & \cdots & M_{NN} \end{bmatrix} \cdot \begin{bmatrix} \mathrm{Ref}_1 \\ \mathrm{Ref}_2 \\ \vdots \\ \mathrm{Ref}_N \end{bmatrix}$$

$$\mathrm{Data}_i = \sum_j M_{ij} \cdot \mathrm{Ref}_j$$

Beta spectrum shape (preliminary)



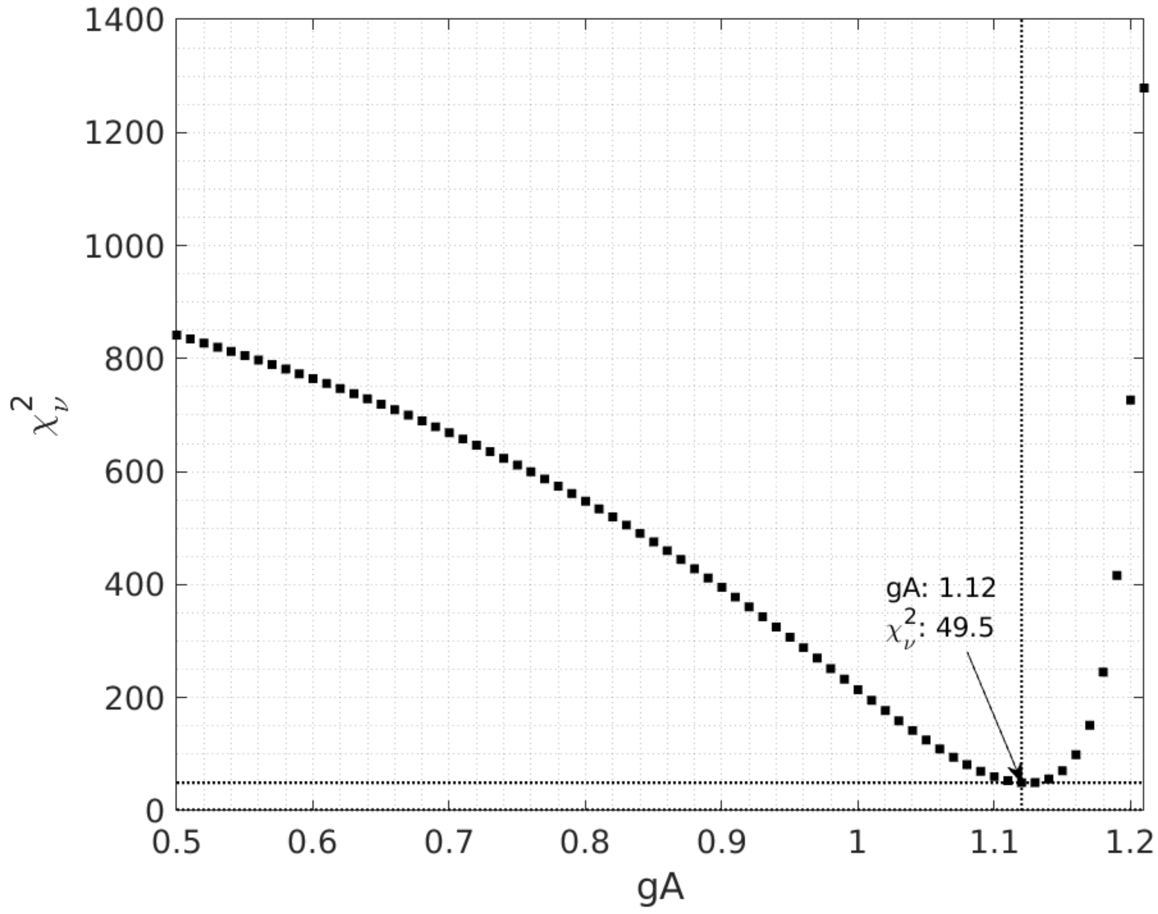


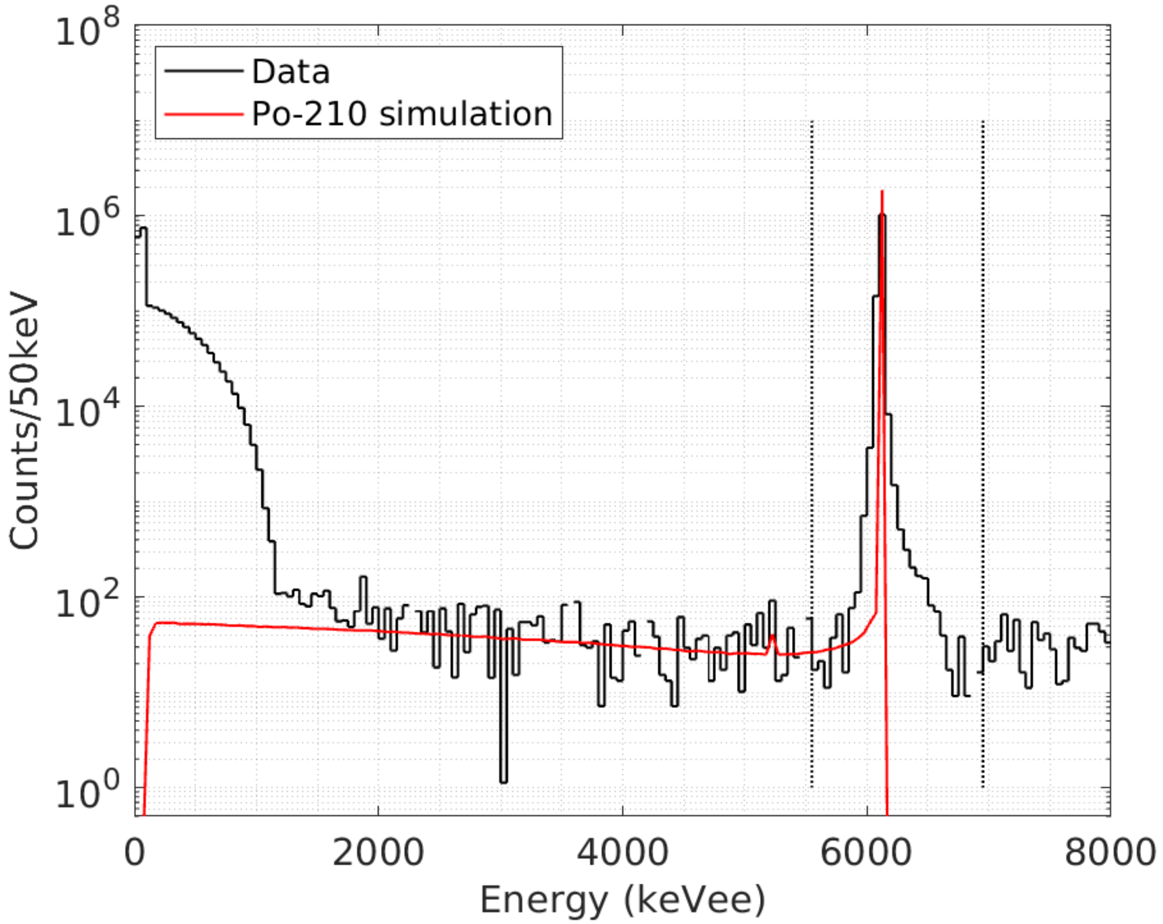
Conclusion

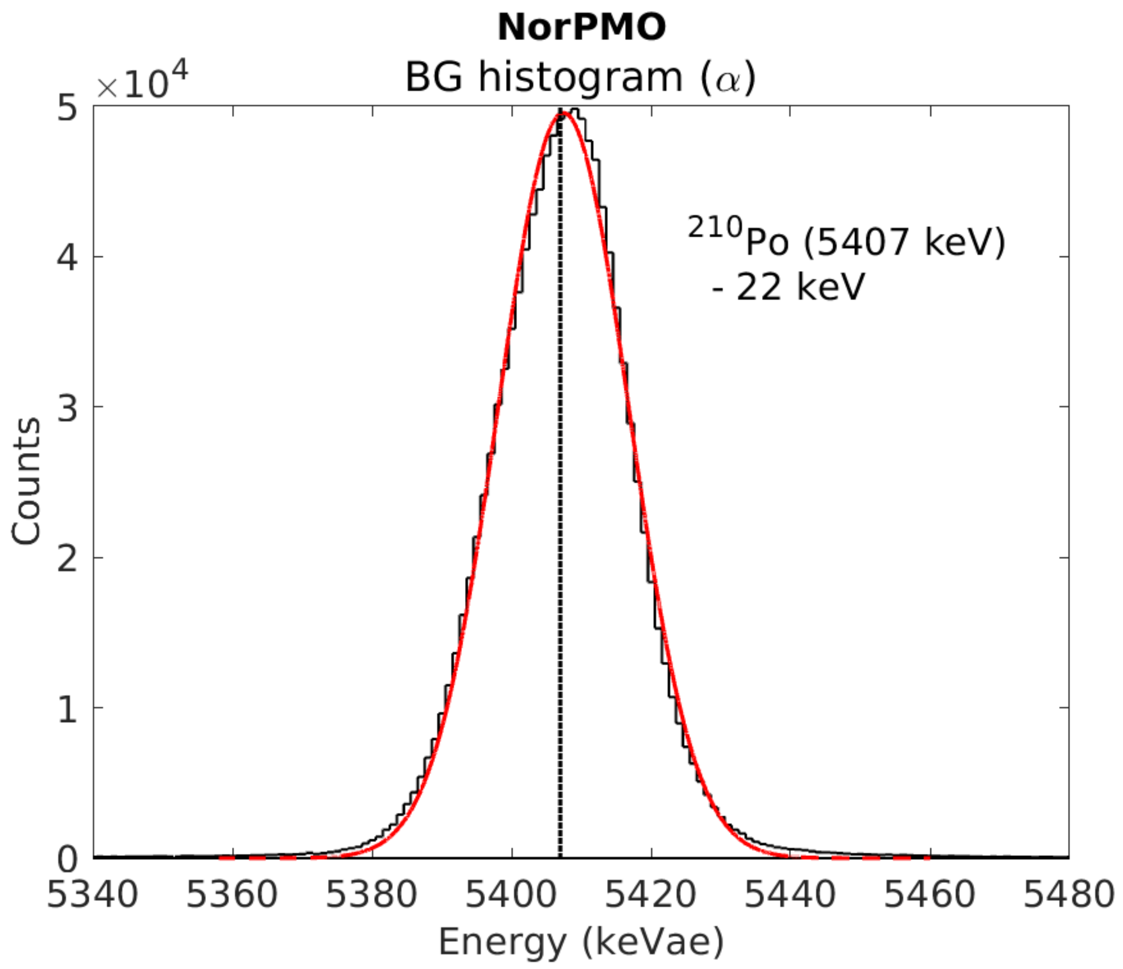
- ✓ The newly developed detector enabled the measurement of the beta spectrum shape for the shape study.
- ✓ Further studies of the trigger and analysis cut efficiency are needed, utilizing large-statistics pseudo data.
- ✓ Background subtraction in the total subtraction spectrum at high energies was confirmed to be effective.
- ✓ Compared to the theoretically calculated spectra based on g_A variation using the current SSM, the measured beta spectrum shape shows better agreement with the beta shape reported by Carles et al. (2005).
- ✓ The best agreement with the experimental data was found for g_A =1.12 (χ_ν^2=49.6), but this value is still much larger than that obtained for the reference data (χ_ν^2=1.65), indicating that further improvements to the modeling or experimental system may be required.

Thank you

Back up


1400
1200
1000
800
600
400
200
0
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
gA
χ^2_ν
gA: 1.12
χ^2_ν: 49.5


Data
Po-210 simulation
Counts/50keV
Energy (keVee)
10^8
10^6
10^4
10^2
10^0
0
2000
4000
6000
8000


NorPMO
BG histogram (α)
$\times 10^4$
Counts
Energy (keVae)
^{210}Po (5407 keV)
- 22 keV
5340
5360
5380
5400
5420
5440
5460
5480

Pseudo Data Simulation

NorPMO Pseudo Signals for 55 keVee