Development of a GAGG-based low-background neutron detector

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Low Radioactivity Techniques 2024

Goals of the project

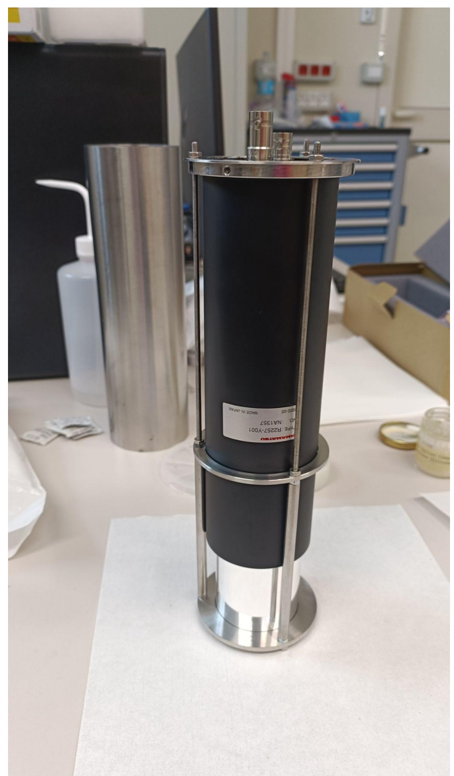
1. Develop a new neutron-detector technology alternative to ^3He counters capable of measuring the neutron flux <10 MeV in underground environment
2. Characterize the detector background and neutron detection efficiency
3. Realize a compact and portable setup with ~10 detectors operated with Bonner spheres
4. Measure the neutron spectrum inside the CUORE/CUPID radiation shielding
5. Measurement campaign in various locations @LNGS

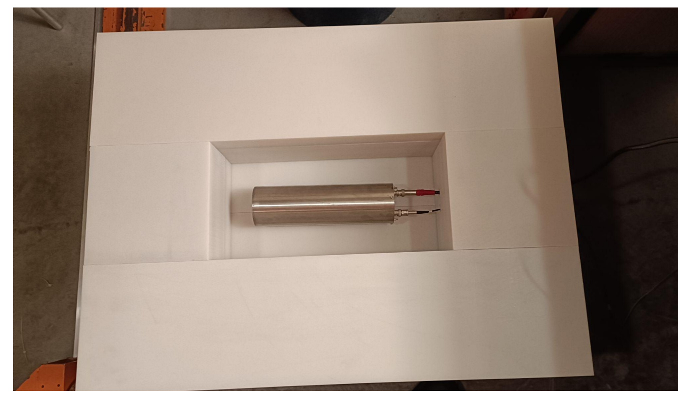
Why GAGG?

- GAGG(Ce) = $Gd_3Al_2Ga_3O_{12}$ scintillating crystal
  - High gadolinium content → High neutron cross section
  - High light-yield (45000 photons/MeV)
  - Capable of α vs β/γ discrimination
- Large size commercially available: up to 6 cm diameter and ~10 cm height
- High density: 6.6 g/cm^3
  → Can reach ~50% containment efficiency for γ's above 3 MeV
- Excellent pulse-shape discrimination
  → Fully reject α background

Detector prototype

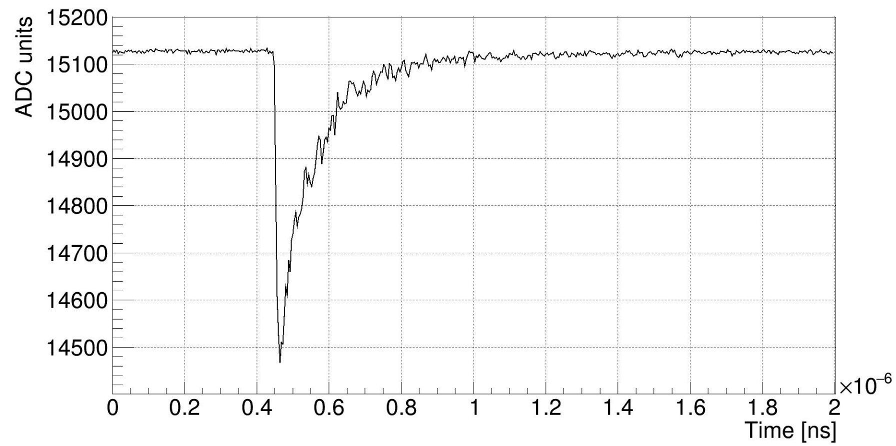
- ⌀ 5cm, h 5cm crystal
- Hamamatsu R2257 PMT
- CAEN electronics
  → VME crate read-out via V3718 bridge
  → V6533 HV module
  → V1725 digitizer
- Borated Polyethylene shielding for underground measurements

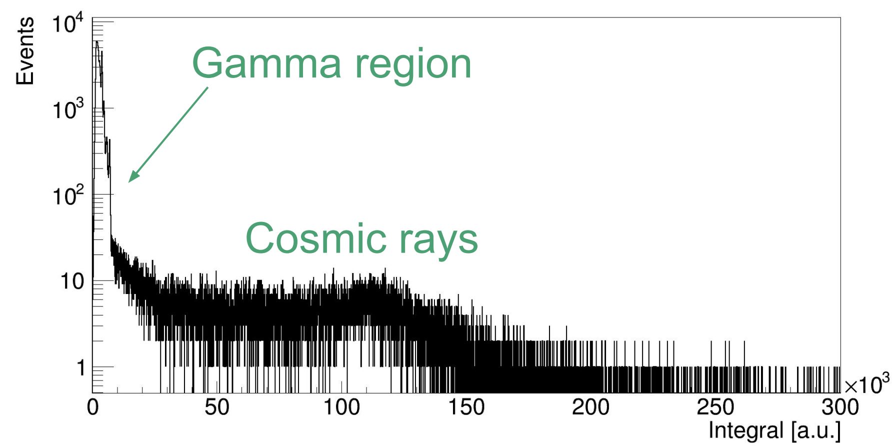




First data (above ground)

- Very first data!
- About 1 day of data taking
- No shielding
- Underbiased PMT to be able to record the full μ spectrum
- Low-energy events due to environmental radioactivity
- Energy threshold ~200-300 keV
- Muon events indistinguishable from β/γ events
  → Cannot use on the surface

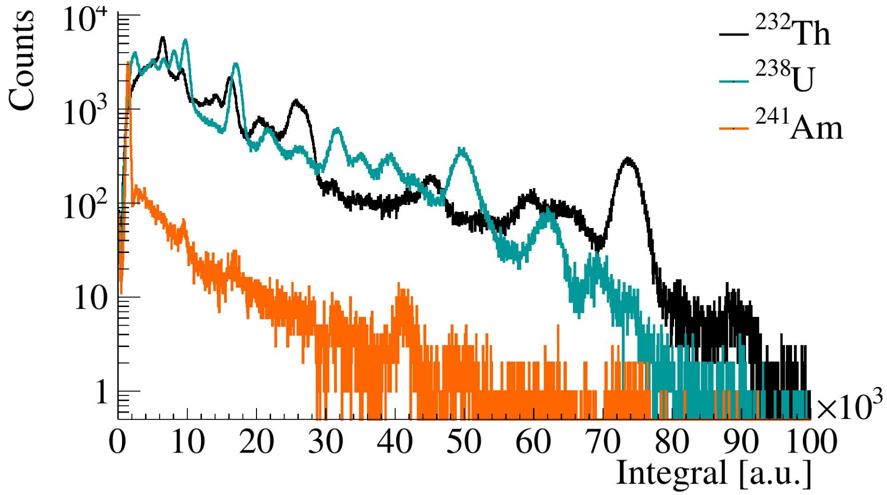


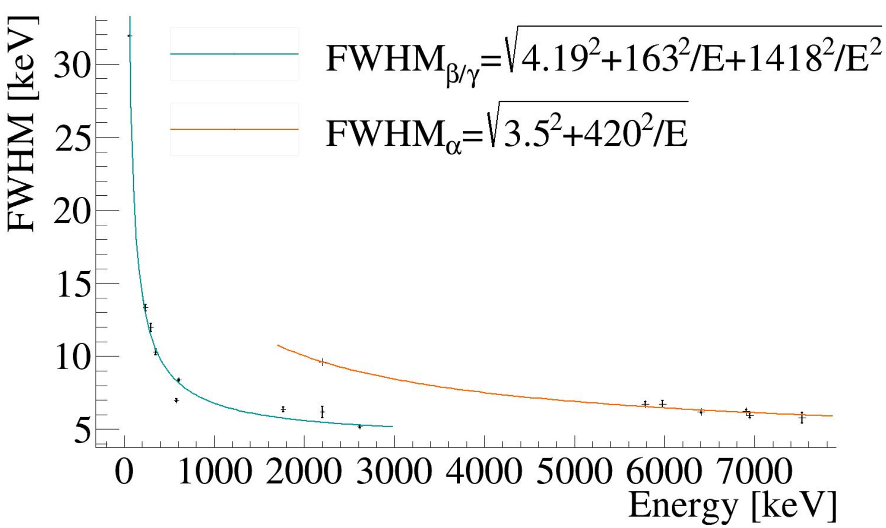


Underground measurement campaign

- Calibration data with ^{232}Th, ^{238}U and ^{241}Am γ sources
- Background data inside borated polyethylene (PE) shielding of 20 cm thickness
  → 2.5 months of data
- AmBe calibration inside shielding
  → 4 days of data with different configurations
- Environmental data without shielding
  → 1 month of data

Event reconstruction and detector performance





Event reconstruction

- Energy ∝ pulse integral
- Quality cuts on:
  - Baseline slope → pre-window pileup
  - Trigger position → in-window pileup
  - Decay time → noise spikes

Detector performance

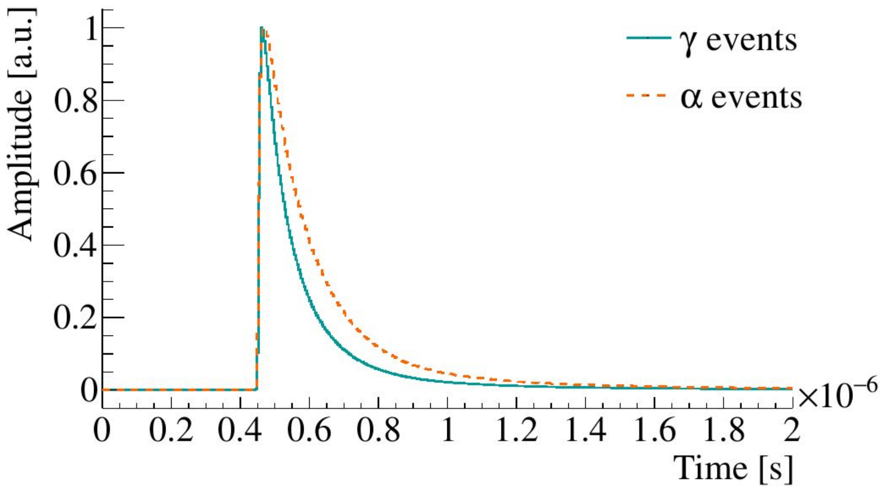
- Energy scale for β/γ linear to ~0.1%
- Energy resolution asymptotically approaching ~4% FWHM on both α and β/γ energy scales

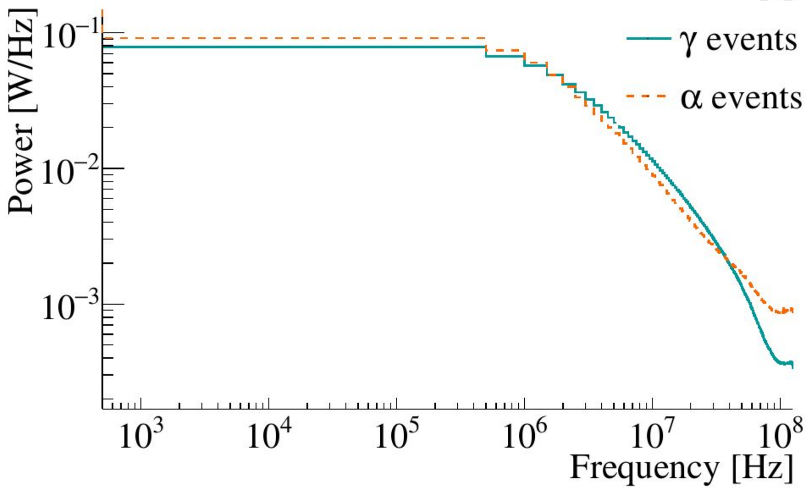
Pulse-shape discrimination

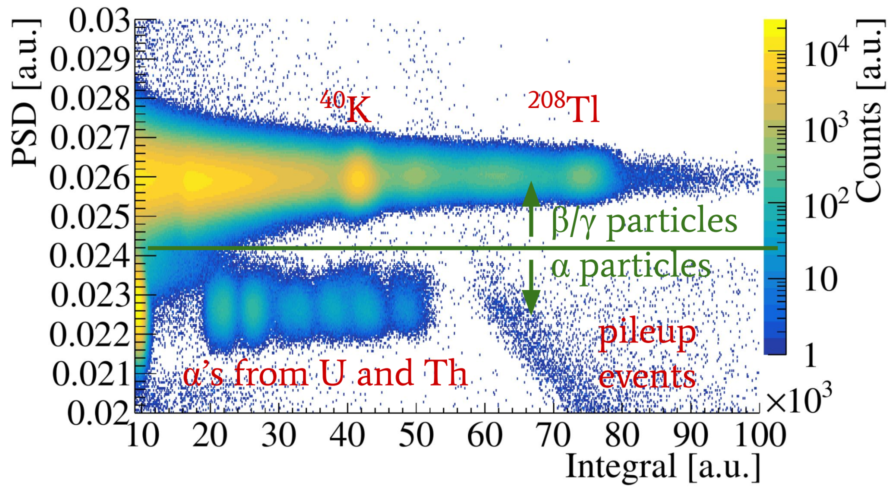
- Exploit different decay times for α vs β/γ events
- Bypass trigger time fluctuations by computing χ^2 w.r.t. average pulse power spectrum

$$\chi^2 = \sum_{f=0}^{f_{max}} \left(w_f - A_{\chi^2} \cdot \bar{w}_f\right)^2$$

$$PSD = \frac{A_{\chi^2}}{I}$$



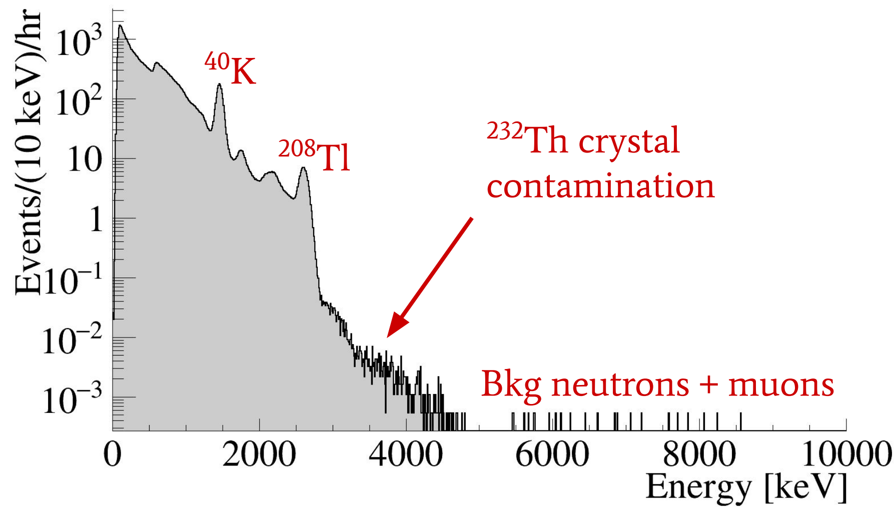




Background characterization

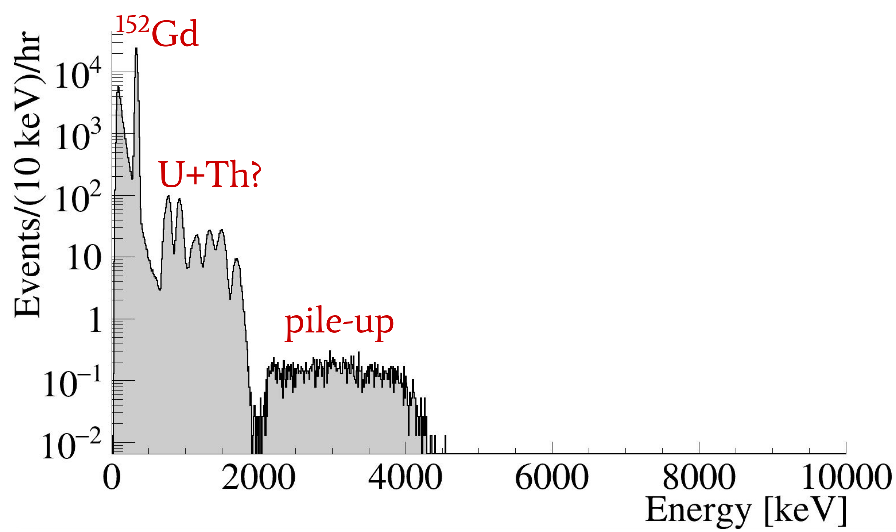
β/γ spectrum

- ^{40}K peak from crystal?
  → Doesn't matter, useful for self-calibration
- ^{208}Tl peak from surrounding material
- Continuum between 2.8 and 5 MeV
  → ^{232}Th crystal contamination
  → Limiting factor for neutron measurement



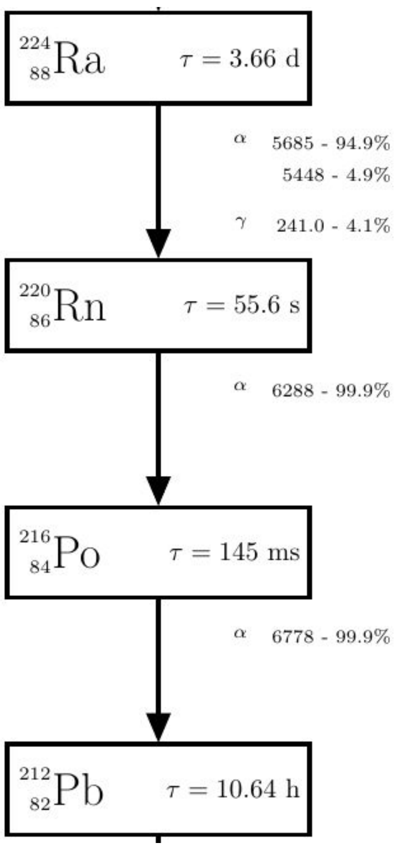
α spectrum

- Non-linear quenching ~15%
- ^{152}Gd peak at 2.2 MeV
- Several peaks from ^{232}Th and ^{227}Ac
  → **Delayed coincidence (DC)** analysis for peak identification
- Residual pile-up events removed with updated analysis

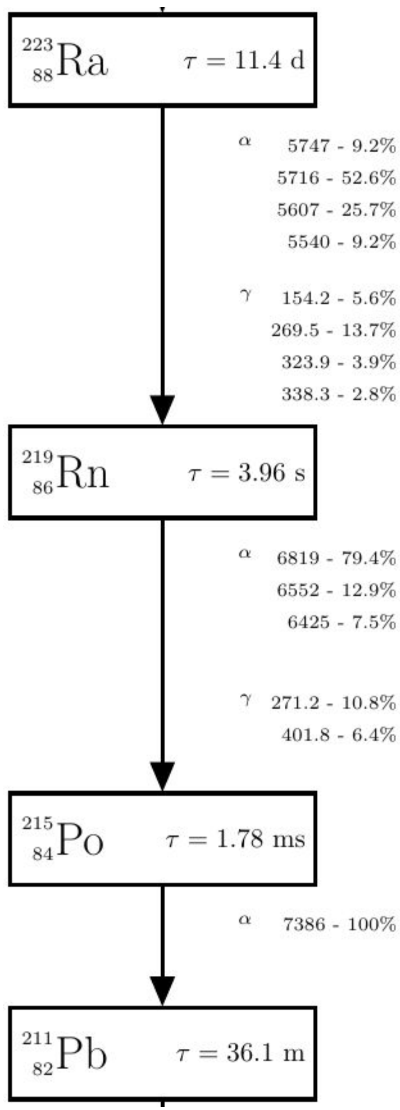


Delayed coincidence analysis

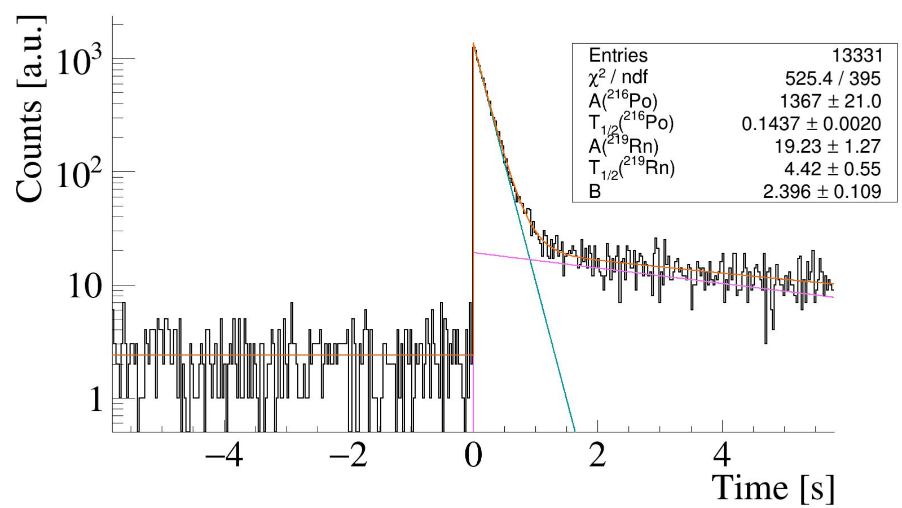
^{232}Th chain



^{235}U chain



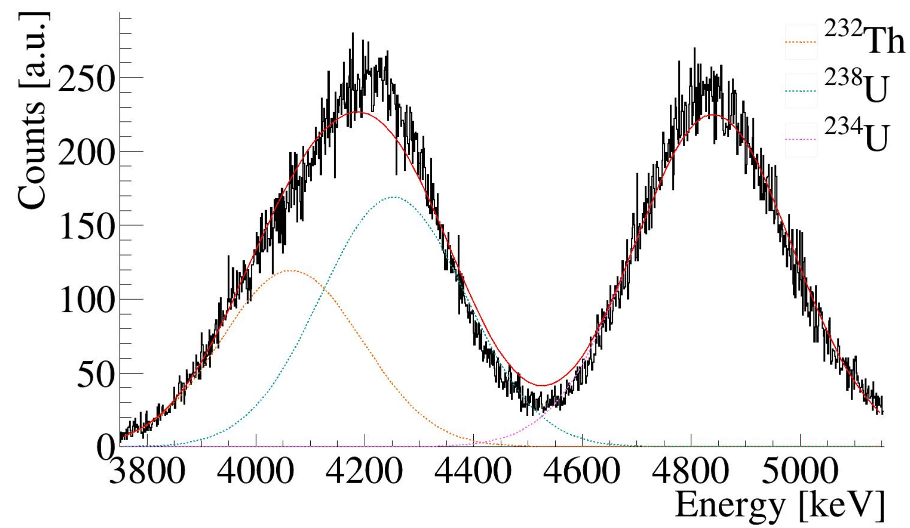
- Search for delayed α-α events from subsequent decays with short half-life values in ^{232}Th, ^{235}U and ^{238}U decay chains
  → Allows to identify events from lower part of decay chains
- Fit Δt with flat background + exponential signal
- Include events with inverse order to better constrain the background



Measurement of early parts of decay chains

- Early parts of ^{232}Th, ^{235}U and ^{238}U decay chains feature only isotopes with very long half life values energies in [4,5] MeV range
  →Fit calibrated α spectrum with a combination of Gaussian with fixed μ and σ
- Early part of ^{235}U chain not visible
  → Crystal contamination must be from ^{227}Ac
- Early part of ^{238}U chain visible, lower part not visible (with delayed coincidence)
- ^{238}U and ^{234}U activity not compatible

⇨ Further refinement of the analysis is required



Crystal contamination values

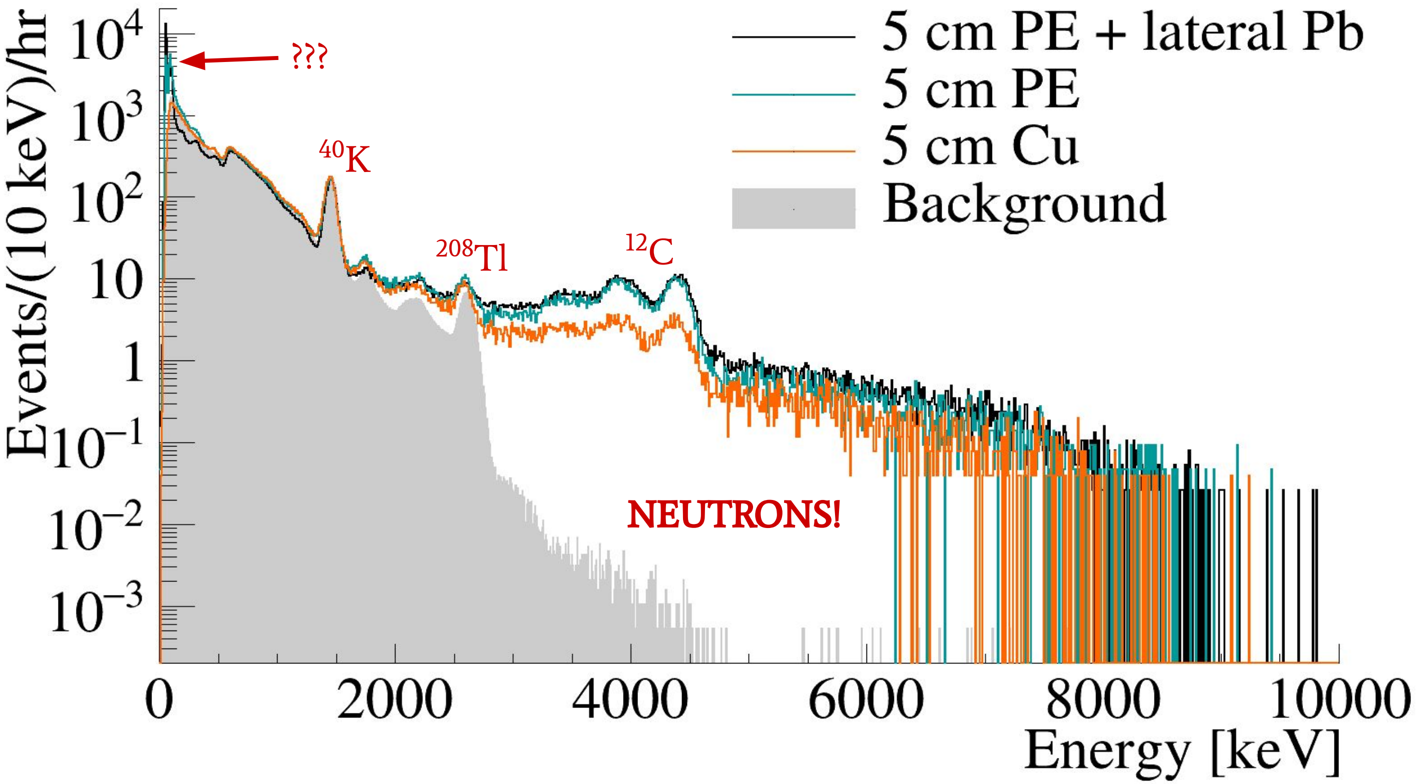
Chain	Method	Contamination [mBq/kg]	
		This work	PIKACHU PTEP 2024 033D01
^{232}Th high	^{232}Th peak	TBD	
^{232}Th low	^{220}Rn – ^{216}Po DC	2.50±0.06	10.3±0.8
	^{224}Ra – ^{220}Rn DC	2.33±0.08	
^{235}U high	^{235}U peak	TBD (limit?)	4.1±1.9
^{235}U low	^{215}Po – ^{211}Pb DC	0.90±0.03	3.07±0
	^{223}Rn – ^{215}Po DC	0.77±0.03	
^{238}U high	^{238}U peak	~13	125.2±1.6
	^{234}U peak	~19	154.6±2.4
^{238}U mid	^{222}Rn – ^{128}Po DC	TBD	<0.28
^{238}U low	^{210}Po peak	TBD	5.93±0.44

- Overall α count rate ~20 times lower than for PIKACHU high-purity GAGG
- Lower part of ^{232}Th most worrisome background for neutron measurement
  → Delayed coincidence of ^{212}Bi – ^{208}Tl seems to induce a too high dead time
- All numbers to be considered as **preliminary!**

Neutron calibration

- AmBe neutron source with ~200 n/s activity in front of GAGG (inside shielding)
- Three measurements with different configurations:
  - 5 cm PE moderator + 5 cm Pb on sides and top to shield from external γ's
  - 5 cm PE moderator to compare with background measurement
  - 5 cm Cu to suppress 4.4 MeV γ from ^{12}C de-excitation

Neutron calibration



- Neutron signature: continuum reaching up to ~9 MeV
- Peaks at ~80 keV appearing when AmBe source is used to be understood
- Neutron detection efficiency to be computed via comparison with MC simulations

Next steps

- Refined evaluation of crystal contamination values
- Development of MC simulations and validation against AmBe measurements
- Measurement with mono-energetic neutron source/generator for further validation of MC
- Design of a full-scale setup with ~10 detectors for measuring the neutron spectrum underground @LNGS
- Purification of starting materials for crystal growth?

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