Neutron detection and potential for rare decay searches with low-background GAGG detectors

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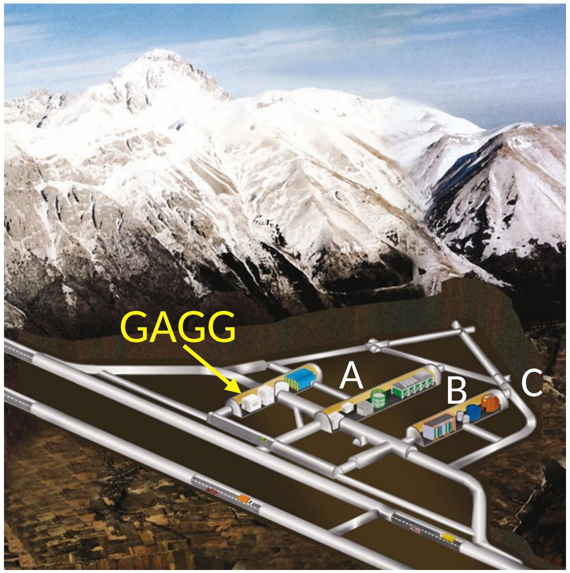
Low-background GAGG neutron detector

- Lack of coherent neutron spectrum measurements at LNGS
- A new technique as an alternative to ^{3}He detectors
- **$Gd_3Al_2Ga_3O_{12}$:Ce** scintillating crystals:
  → $^{155/157}$Gd (n, γ) with the highest σ_n
  → high light yield (45000/MeV)

  → particle identification with β/γ and α

Isotope	Natural Abundance (%)	Reaction	σ_n (b)
^{6}Li	7.5	$^{6}Li + n \rightarrow {}^{3}H + \alpha$	940
^{10}B	19.8	$^{10}B + n \rightarrow {}^{7}Li + \alpha + \gamma$ (0.477 MeV) (93.7%)	3840
^{113}Cd	12.2	$^{113}Cd + n \rightarrow {}^{114}Cd + \gamma$-rays (9.04 MeV)	20600
^{155}Gd	14.8	$^{155}Gd + n \rightarrow {}^{156}Gd + \gamma$-rays (8.53 MeV)	60900
^{157}Gd	15.6	$^{157}Gd + n \rightarrow {}^{158}Gd + \gamma$-rays (7.95 MeV)	254000

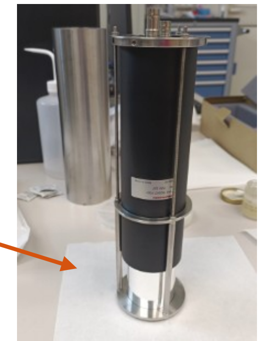
The first prototype at LNGS



$\phi = 5$ cm

$h = 5$ cm

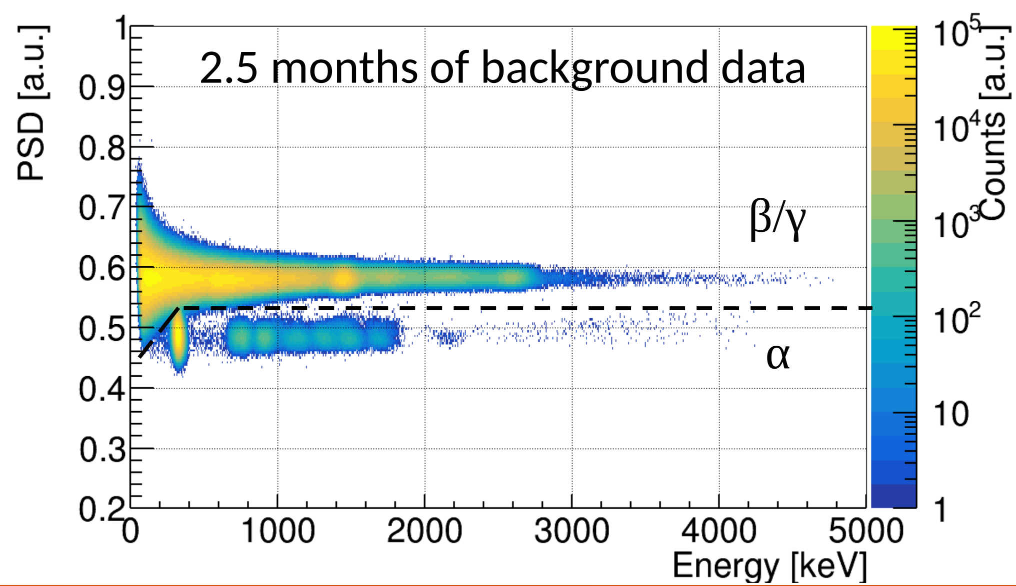
$\rho = 6.6\ \mathrm{g/cm^3}$



R2257 PMT

20 cm thick borated polyethylene (PE)

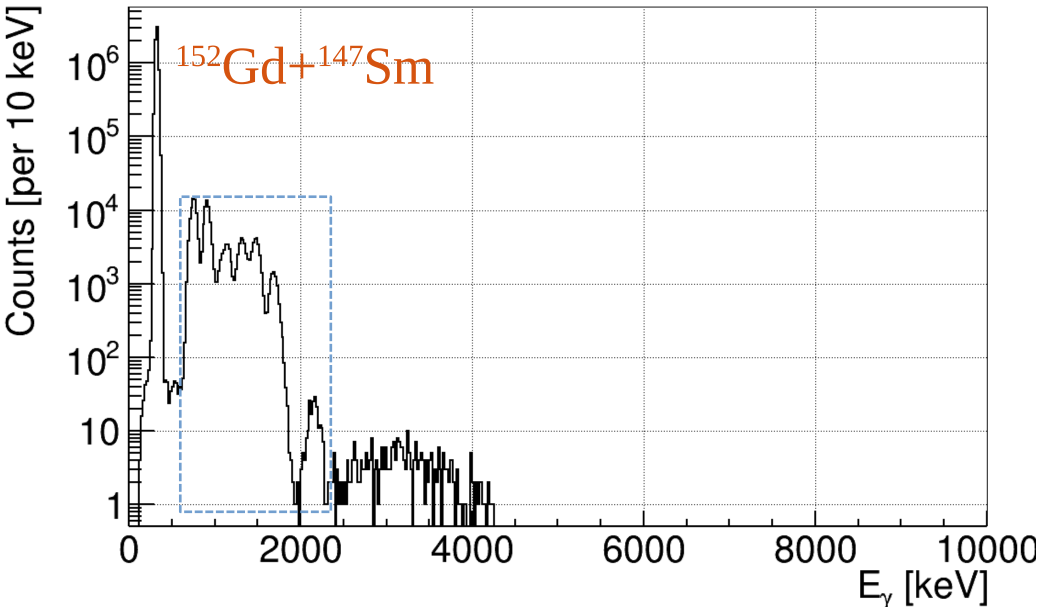
- Clean neutron signature above the 2614 keV γ-line
- α rejection using pulse shape discrimination (*PSD*) (decay times of β/γ and α)



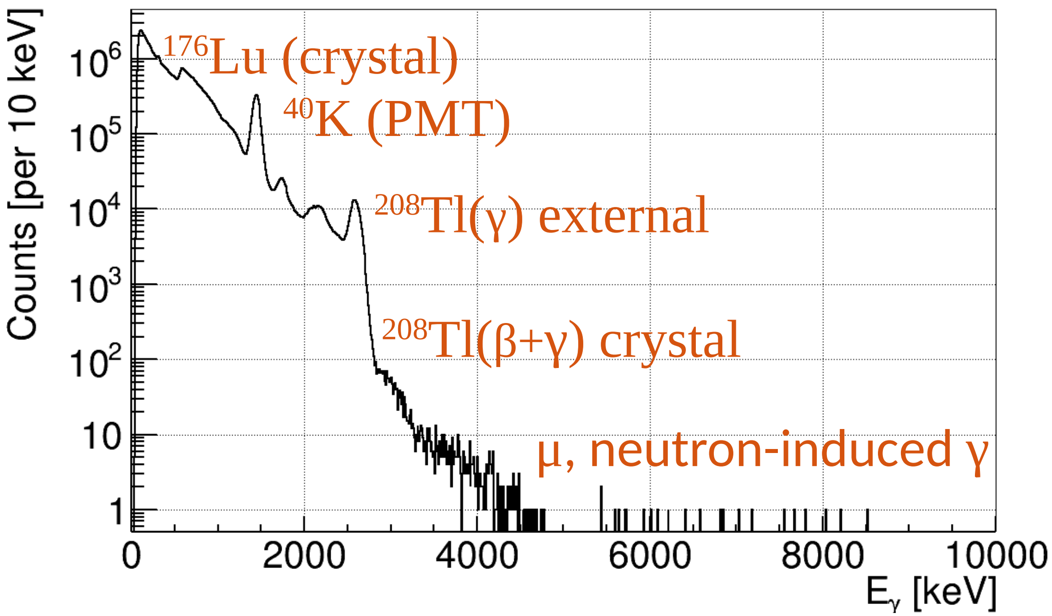
Background characterization

- α peaks identified with delayed coincidence analysis
  → sensitive to decays with $T_{1/2} \sim 30$ s in $^{235}U/^{238}U$ and ^{232}Th decay chains
- Radiopure crystal beneficial to extend ROI to lower energies

α spectrum

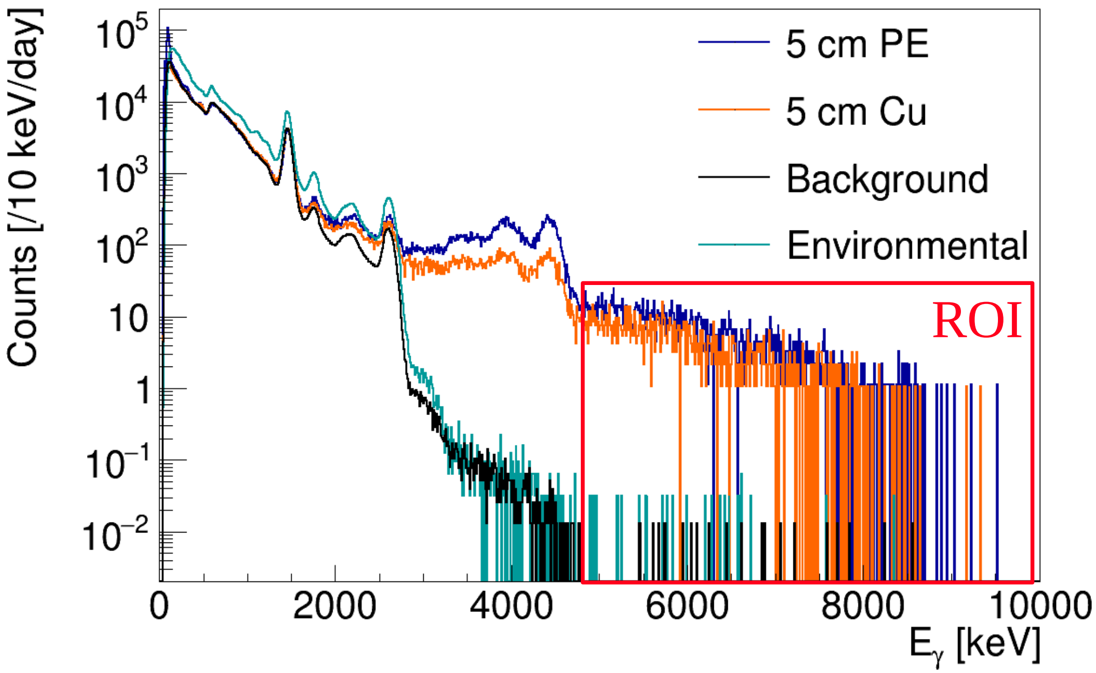


β/γ spectrum



Detection of neutron-induced high-energy γs

https://doi.org/10.1140/epjc/s10052-025-148075



Standard PE moderator

Copper brick

AmBe calibration neutron source

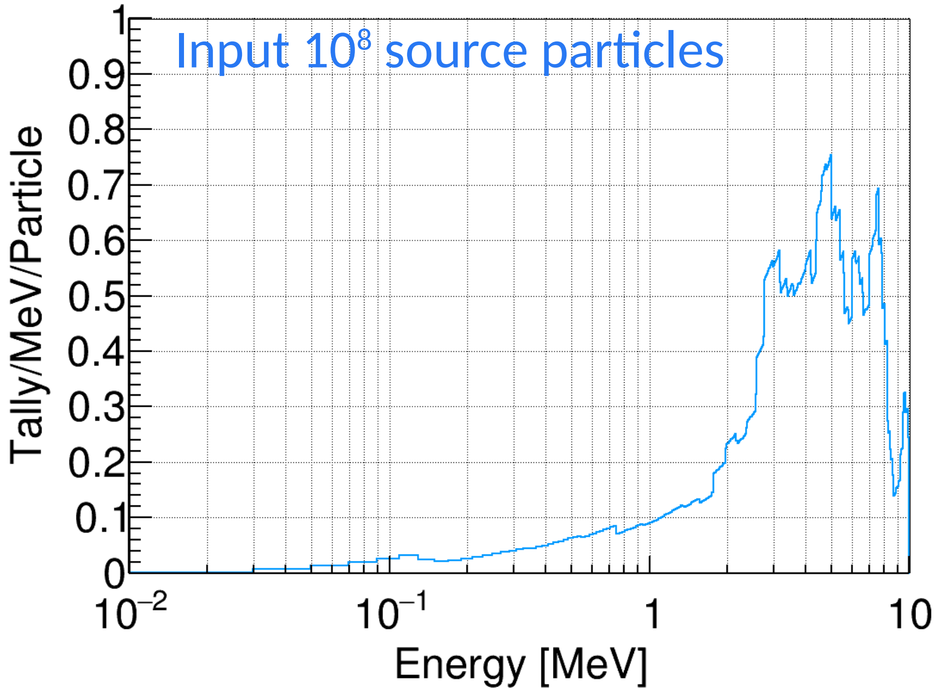
$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n + \gamma$ (4.4 MeV)

Neutron flux, ~1×10^{-6} $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, comparable with other studies

Detector verification with MCNP simulations

- Compare with data measured using 5 cm PE and 5 cm Cu
- Add Pb into another setup configuration

neutron spectra of AmBe source



Count γ events above 5 MeV

$$\left(\frac{Cu}{PE}\right)_{\text{data}} = 0.62 \pm 0.11$$

$$\left(\frac{Cu}{PE}\right)_{\text{sim}} = 0.50 \pm 0.01$$

$$\left(\frac{Pb+PE}{PE}\right)_{\text{data}} = 1.39 \pm 0.20$$

$$\left(\frac{Pb+PE}{PE}\right)_{\text{sim}} = 1.51 \pm 0.01$$

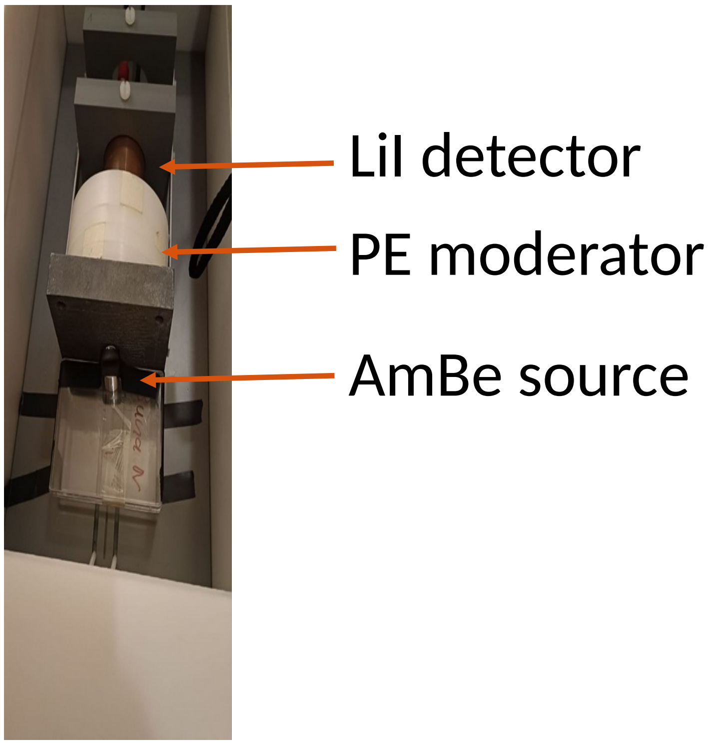
Simulation and data fit well

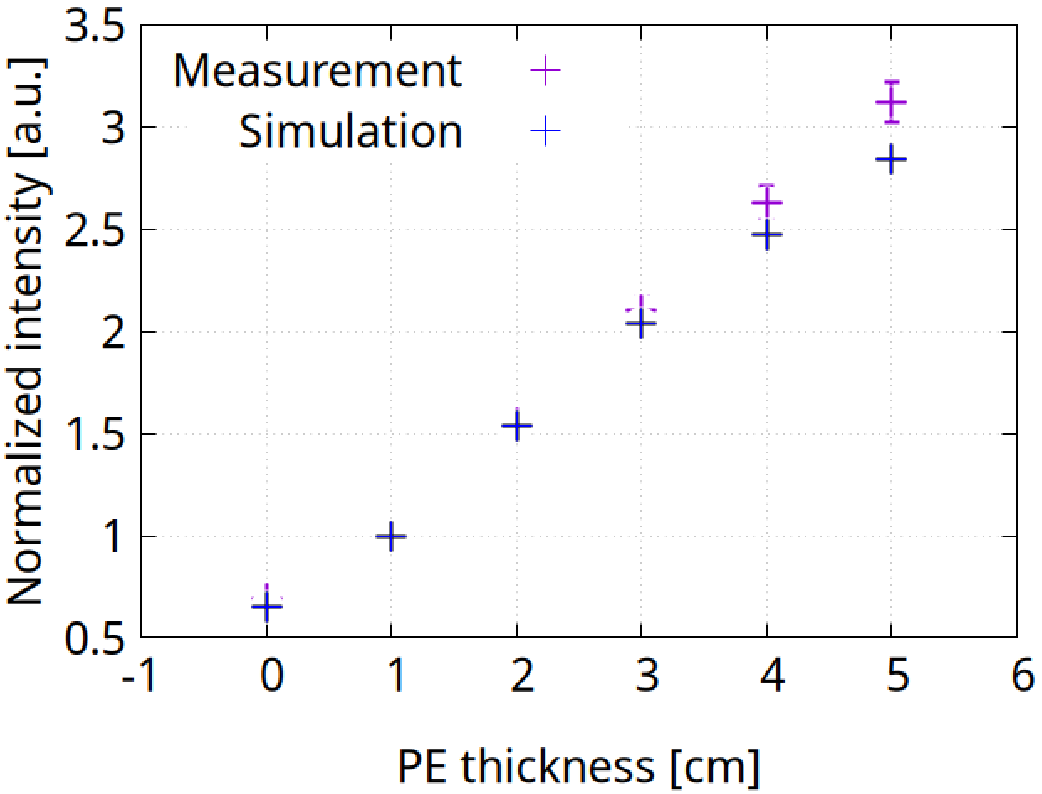
Detector verification with MCNP simulations

- Cross-check simulation with a low-background LiI detector

Credit: Laura Baudis

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H} + Q \ (Q = 4.78\ \mathrm{MeV})$$





Development of a novel neutron detector with GAGG wafer and high radiopurity NaI crystals

The detector concept – sandwich design

- Thermal neutrons being captured in the thin GAGG wafer
  doi: 10.1109/TNS.2019.2958065
- "NaI – GAGG - NaI" to improve the detection efficiency

PMT

High-purity NaI crystal (ϕ = 7.62 cm, h = 7.62 cm)

GAGG wafer (ϕ = 5 cm, h = 2 mm): neutron capture layer

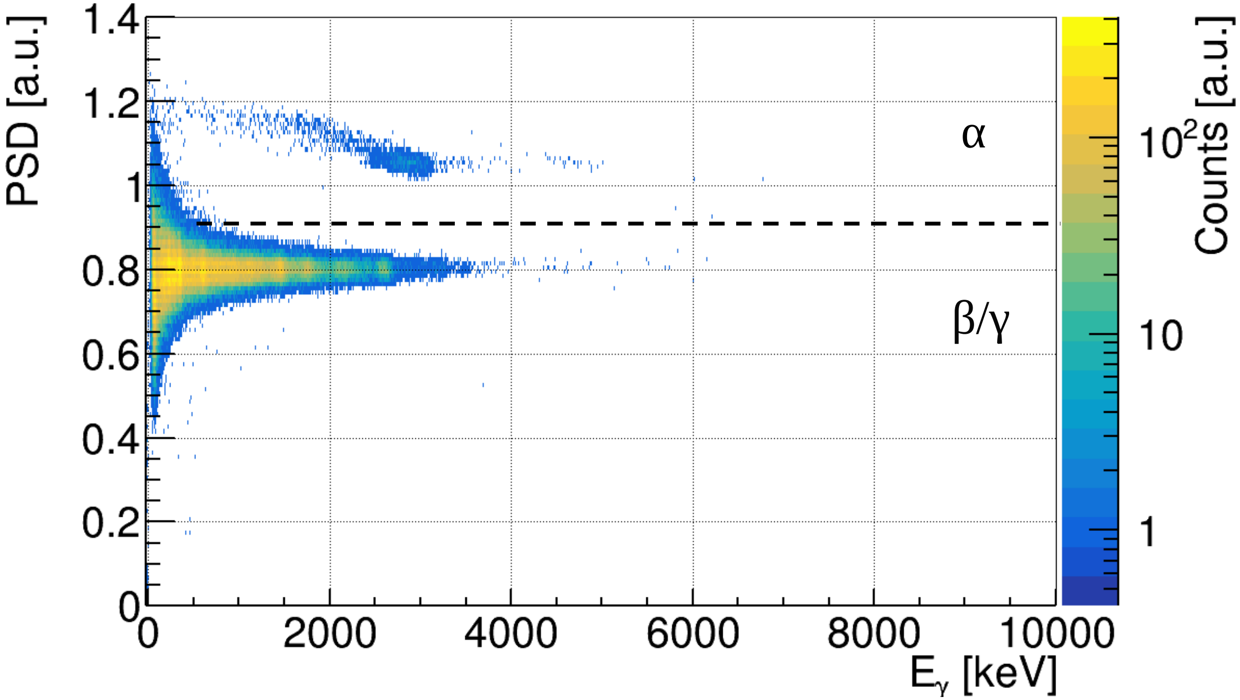
High-purity NaI crystal (ϕ = 7.62 cm, h =7.62 cm)

Neutron-induced high-energy β/γ are detected by the two NaI scintillators

Low-background measurements

- Low-background setup at LNGS
- Energy resolution: ~4% at 2615 keV
- *PSD* identifying β/γ and α

32 days of background data

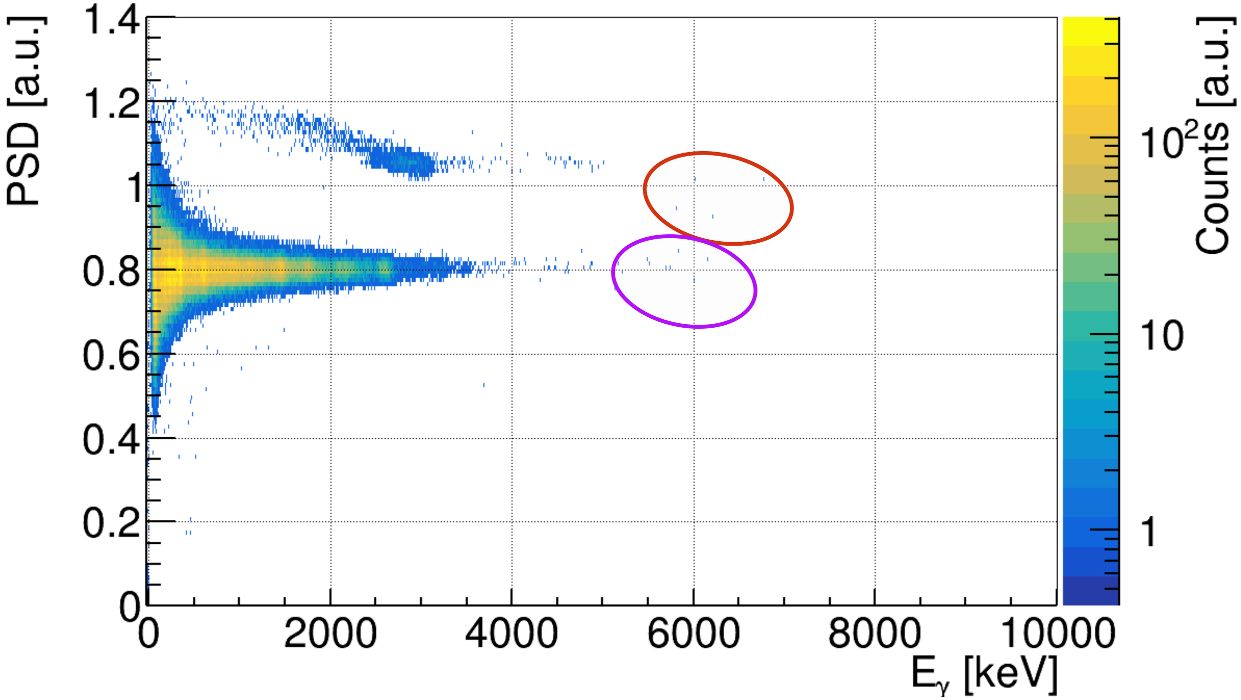


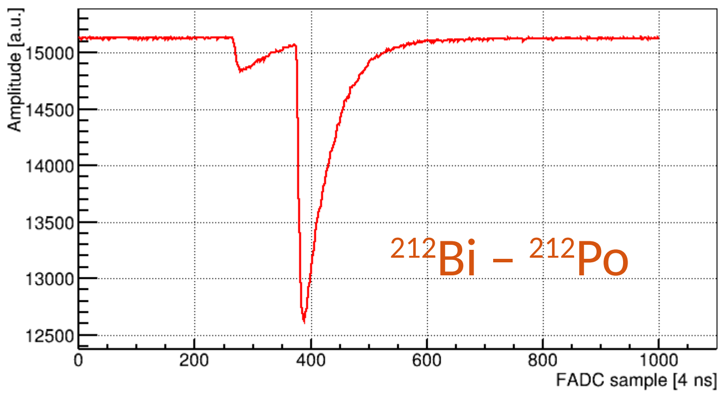
NaI(Tl)

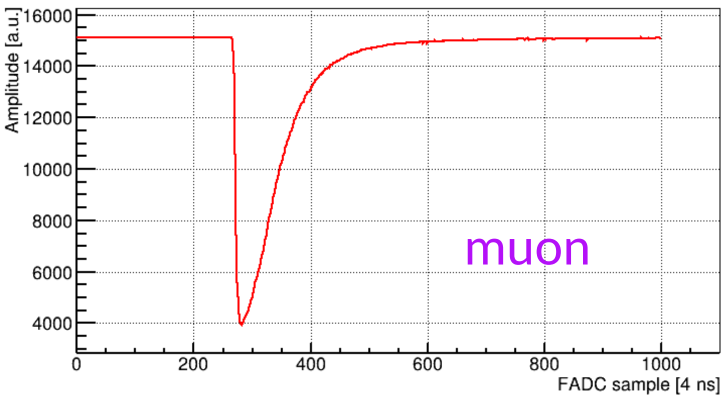
R6233 PMT

NaI detector background characterization

- ^{212}Bi – ^{212}Po (^{232}Th) contamination → (2.66 ± 1.09) μBq/kg
- Count rate in the β/γ band above 5 MeV (muons): 0.31/day

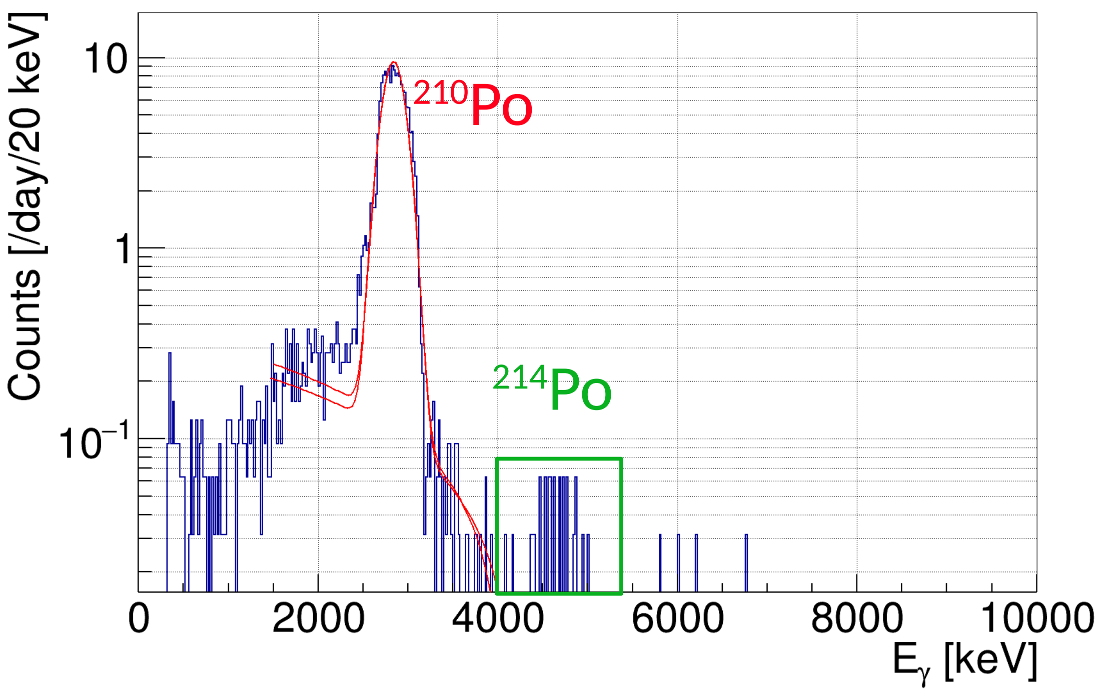




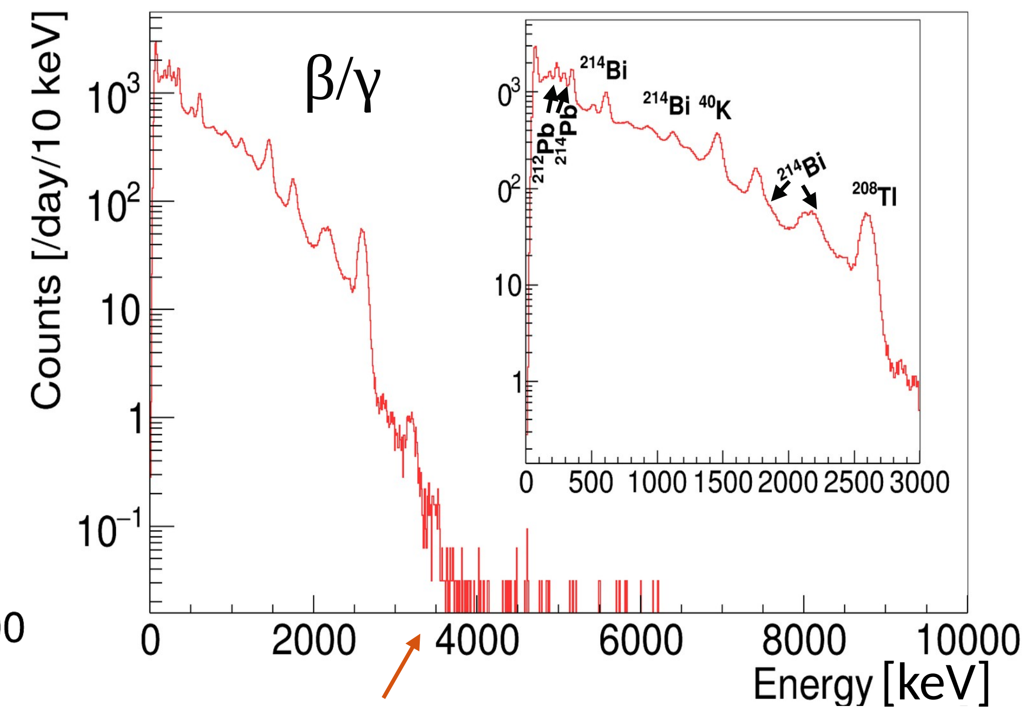


NaI detector background characterization

- Total α contamination: (1.64 ± 0.021) mBq/kg
- α peak from ^{210}Po due to ^{210}Pb: (1.33 ± 0.019) mBq/kg
- ^{214}Bi – ^{214}Po (^{238}U) coincidence: < (6.24 ± 1.33) μBq/kg



α spectrum



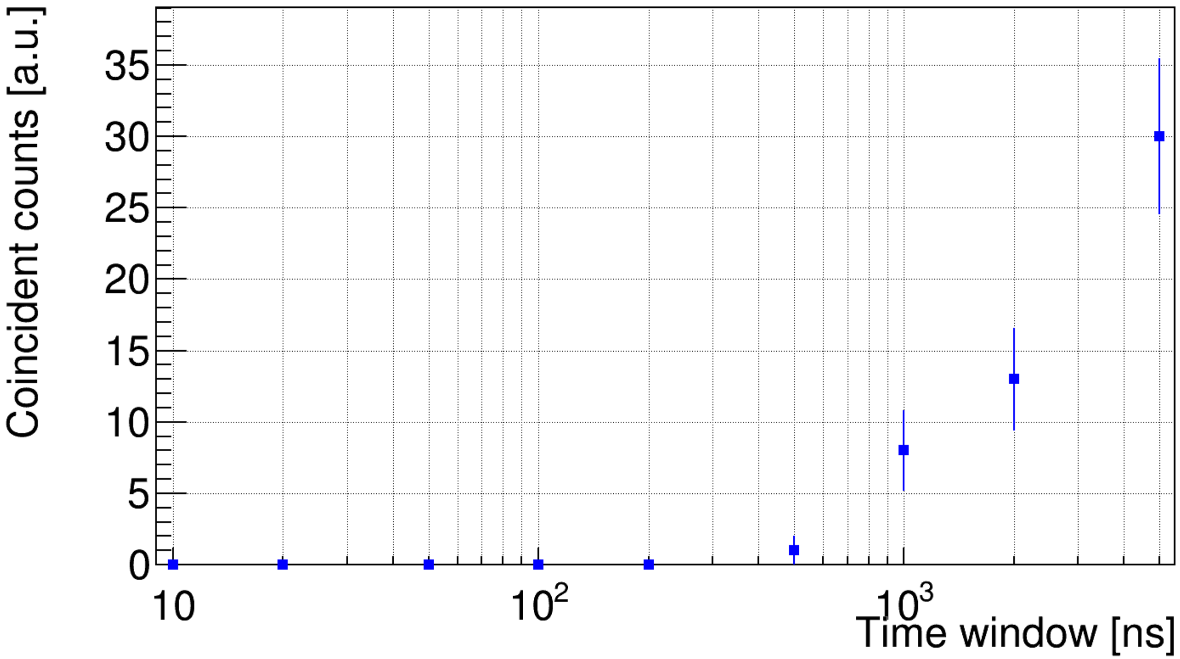
Continuum needs to be suppressed

Background estimation from toy MC

- Detection technique: **Coincidence analysis**

  → time window (maximize the signal-to-background ratio)

  → expected random coincidences from toy simulations



Assuming constant count rates of two NaI crystals

One month data-taking

Time window from 10 ns to 5 μs

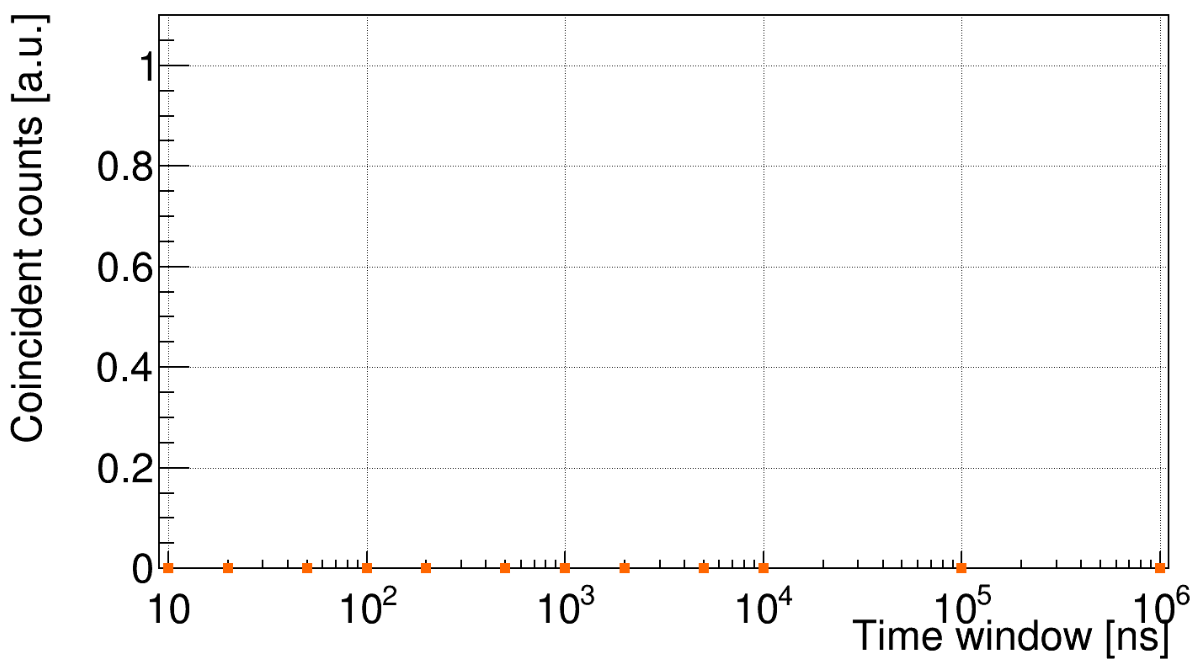
Background estimation from toy MC

- Detection technique: **Coincidence analysis**

  → time window (maximize the signal-to-background ratio)

  → expected random coincidences from toy simulations

Add the energy cut (E_1 > 3 MeV && E_2 > 3 MeV)



Assuming constant count rates of two NaI crystals

One month data-taking

Time window from 10 ns to 1 ms

Potential to search for double beta decays of ^{160}Gd with the high-purity GAGG crystal

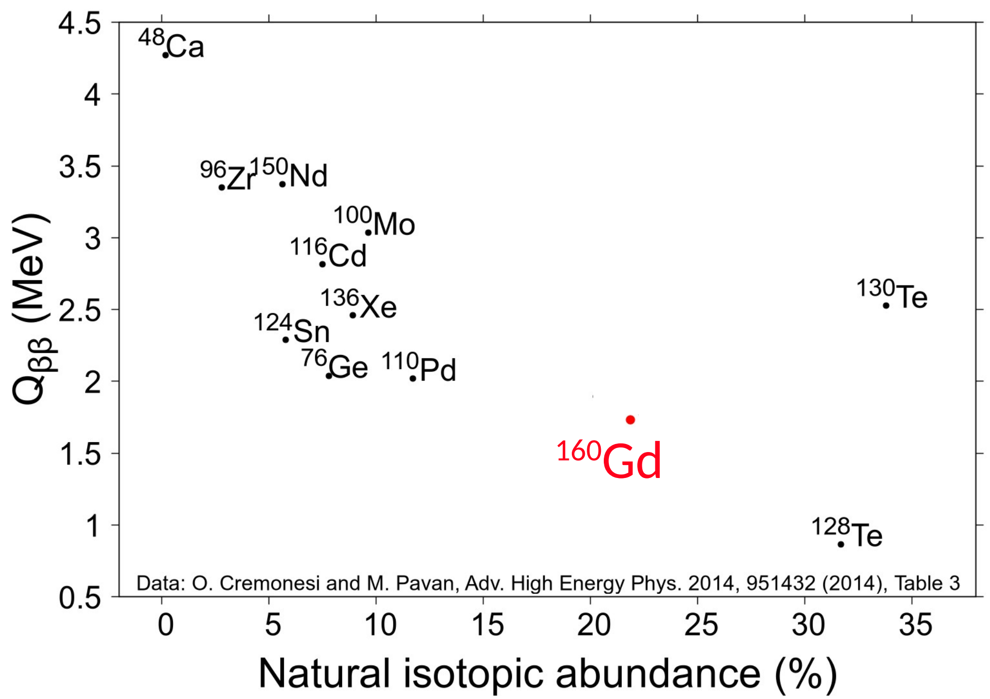
Double beta decay of ^{160}Gd

- $^{160}_{64}\mathrm{Gd} \rightarrow ^{160}_{66}\mathrm{Dy} + 2\mathrm{e}^- + 2\bar{\nu}_\mathrm{e} + Q_{\beta\beta}$ (with $Q_{\beta\beta}$ = 1730 keV)
- Natural abundance 21.8%
- Theoretical predictions

  → 3.4×10^{20} yr (semi-empirical formula)
  → 7.4×10^{20} yr (QRPA)
  → 9.6×10^{21} yr (pseudo-SU(3))

  doi:10.1016/j.nima.2025.171023

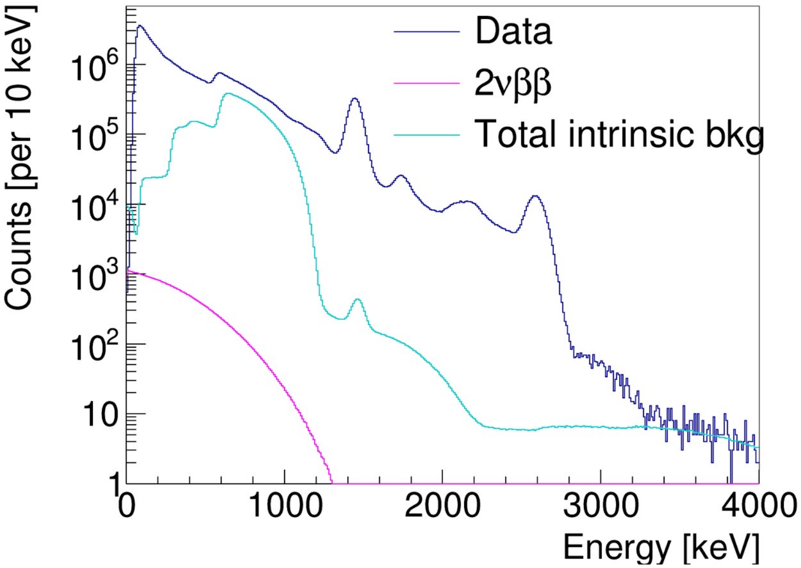
- World's best limit so far: > 2.1×10^{19} yr



Preliminary background model

Comparison with other GAGG crystals

	This work	Belli et al.	PIKACHU
Decay	Contamination values [mBq/kg]		
^{232}Th chain			
^{232}Th	8.4 ± 0.1	14.44 ± 0.14	17.5 ± 0.3
^{228}Th	2.34 ± 0.02 (2.34)	11.43 ± 0.5	1.55 ± 0.04
^{238}U chain			
^{238}U	6.3 ± 0.1 (6.34)	41.1 ± 0.2	112.9 ± 0.3
^{234}U	6.3 ± 0.1	40.0 ± 0.3	90.2 ± 0.4
^{230}Th	6.3 ± 0.1	13.1 ± 0.2	60.6 ± 0.4
^{226}Ra	<1.1 (0.46)	0.02 ± 0.01	< 0.28
^{210}Pb	(0.46)	<0.7	3.5 ± 0.1
^{235}U chain			
^{235}U	0.30 ± 0.05 (0.35)	<2.8	<0.03
^{227}Ac	1.51 ± 0.02 (1.52)	1.8 ± 0.3	0.2 ± 0.02
^{176}Lu	> 698 (3556.33)	11026 ± 100	
^{40}K	<12 (11.65)	<8	26.3 ± 0.6
^{137}Cs	<1.3 (1.19)	<4	
^{138}La	(2.23)	<2 (2.23)	



2νββ: assuming a half-life of 3.4×10^{20} yr

Improving sensitivity for 2νββ searches

$$T_{\frac{1}{2}}^{\mathrm{lim}} > \frac{\ln 2 N \varepsilon t}{S_{\mathrm{lim}}}$$

- External background: multiple passive shielding layers

  → Lead, Copper, Nitrogen flushing

- Nearby components: low radioactivity PMT

- Exposure: Developing high radiopurity GAGG crystals

  → reduce the dominant contamination

  → also beneficial for neutron detection

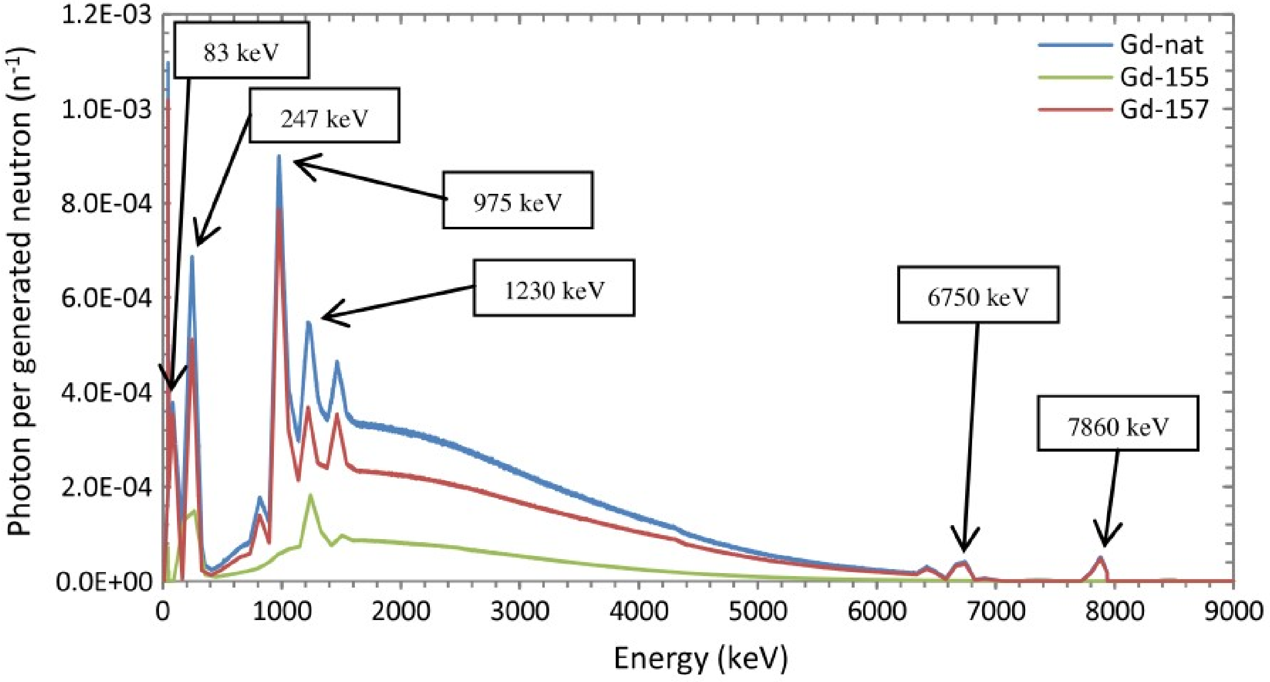
Outlook

- Assemble sandwich neutron detectors
- Build Bonner sphere to obtain the energy and flux at different locations
- Sensitivity studies for rare decays with reduced external background
- Develop high-purity GAGG crystals to search for rare events

Thank you for your attention

Backup

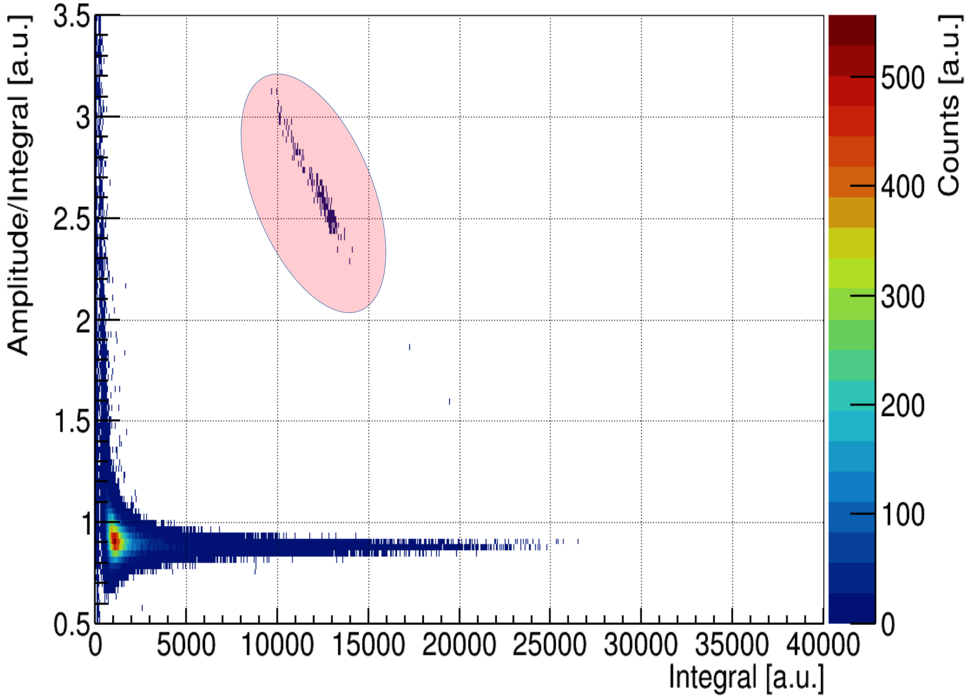
Neutron capture with $^{155/157}$Gd



Measurements with Pb

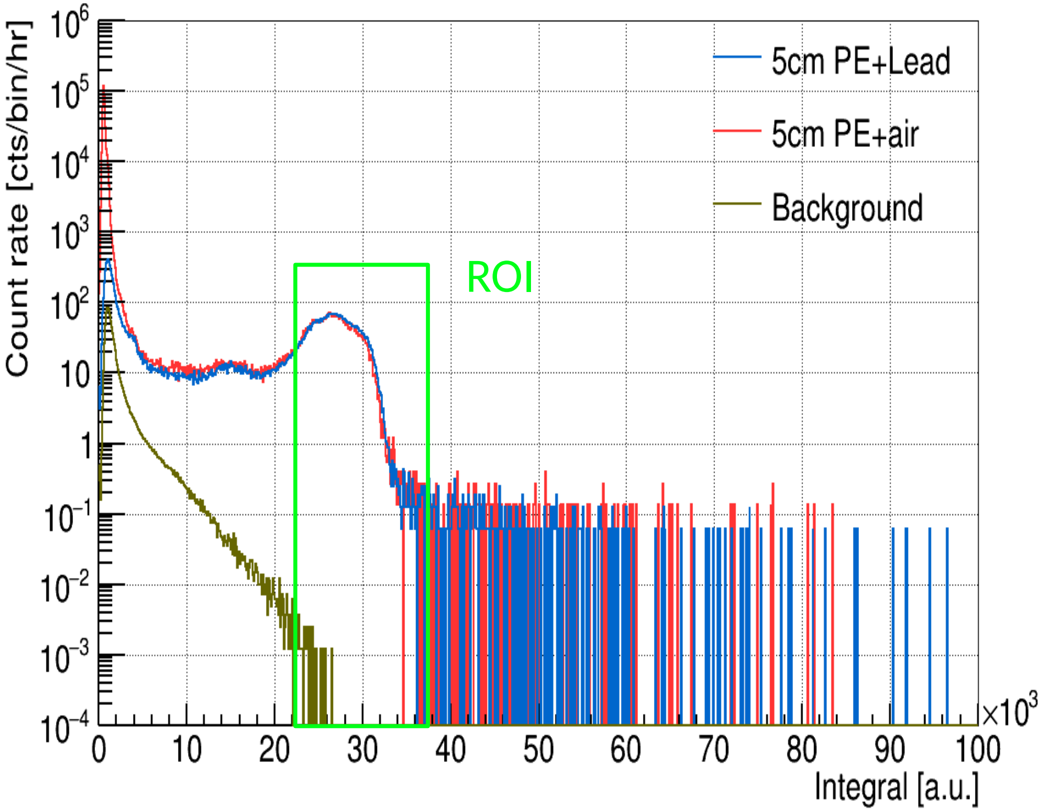
Discrimination of physics and noise events

- Background data (duration: 34.2 days)
- Around 200 noise events at integral > 10000
- Noise events rejected via pulse shape discrimination



LiI measurements

- AmBe neutron spectra vs background
- ROI: 22000 - 36000



count rate:

4351/hr

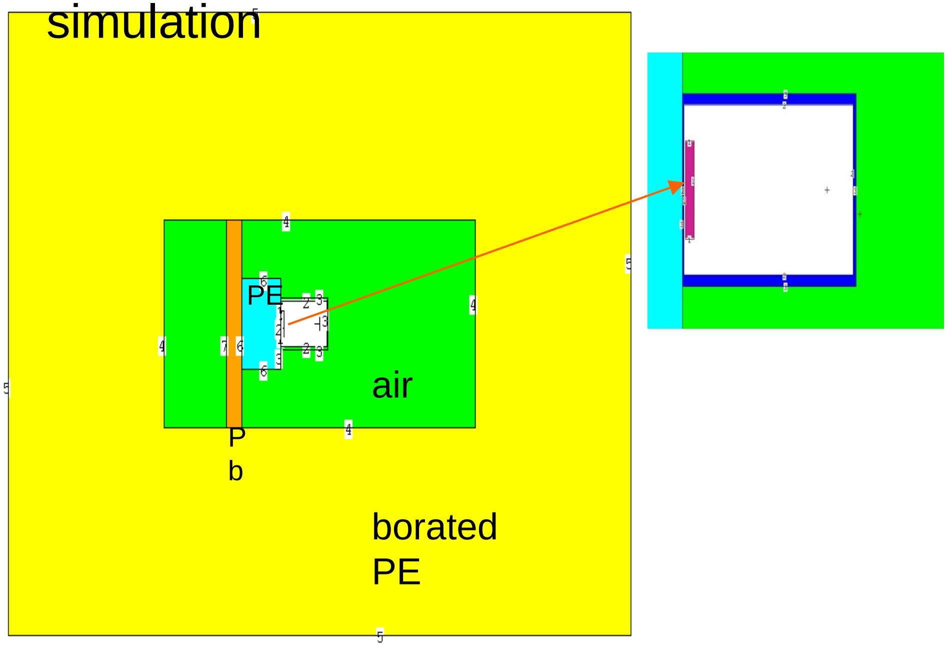
4158/hr

0.05/hr

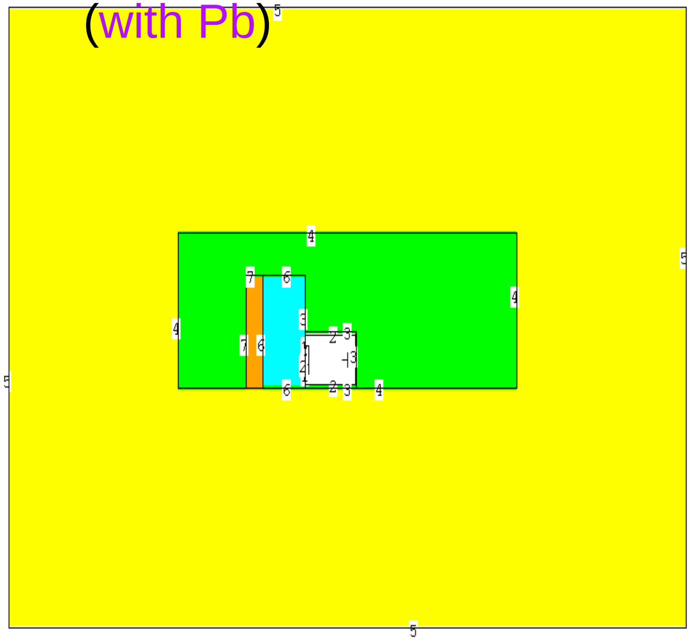
^{6}LiI experimental setup in the MCNP

- Am-Be neutron source input from the ISO standard
- PE moderator (5 cm) and Pb (2 cm) placed between the source and the detector

X-Y sketch from the simulation



X-Z sketch from simulation (with Pb)



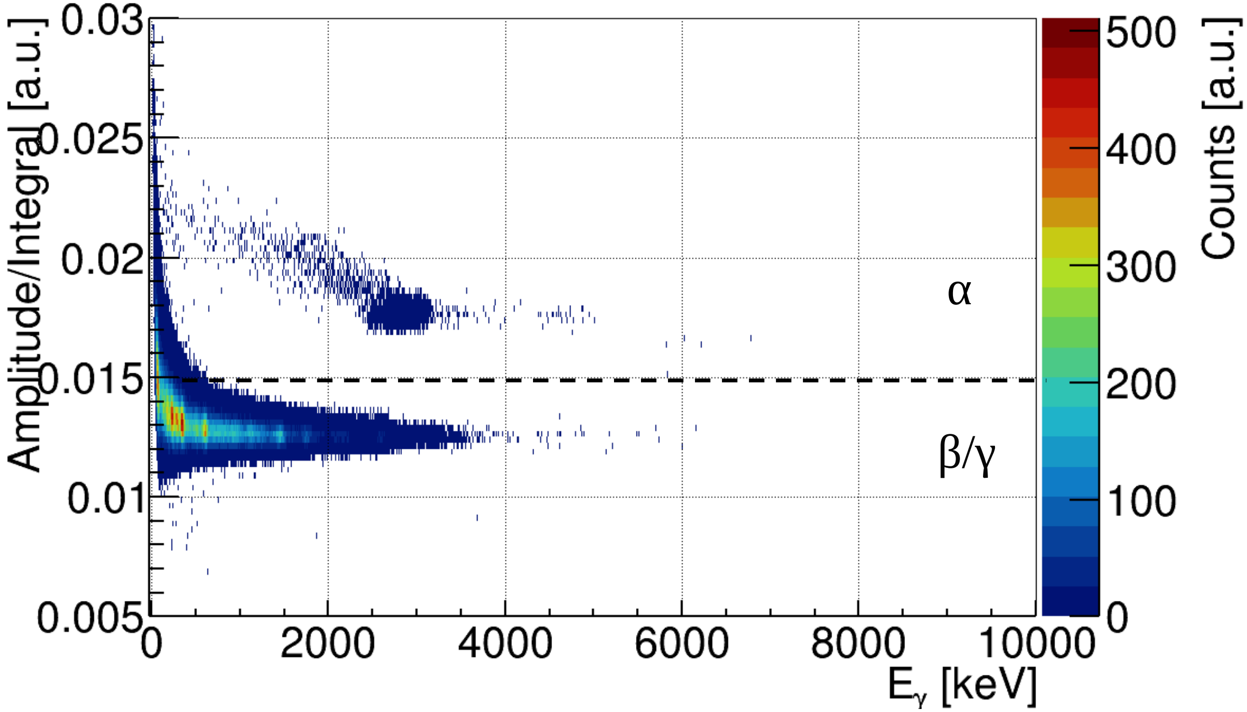
Physics implemented in MCNP

- Number of source particles: 1e8
- F4 tally + FM card with the **correct** reaction number
- Output: the total neutron capture rate

Low-background measurements

- Low-background setup at LNGS
- Energy resolution: ~4% at 2615 keV
- *PSD* identifying β/γ and α

32 days of background data



H15266 PMT

NaI detector background characterization

- Comparison of two NaI detectors in the β/γ band