First Measurement of High-Energy Neutron-Induced γ-Rays with a Low Background GAGG Neutron Detector

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Abstract

A precise measurement of neutrons is crucial for underground experiments searching for rare events. We assembled a prototype detector using a 100 cm^3 GAGG crystal coupled to a photomultiplier tube at LNGS to detect high-energy neutron-induced γ-rays. The detector features excellent pulse shape discrimination (PSD), enabling separation of signal-like events and backgrounds which are studied in detail using the delayed coincidence. The neutron response measured underground shows the first measurement of high-energy γ-rays with such a crystal. We performed Monte Carlo simulations to verify and optimize the setup.

The setup at LNGS

Neutron detector for low background applications

GAGG crystal as the neutron detector

- Highest neutron capture cross-section
  $^{155}Gd + n \rightarrow {}^{156}Gd + \gamma$ (8.53 MeV), $\sigma_n = 61$ kb
  $^{157}Gd + n \rightarrow {}^{158}Gd + \gamma$ (7.95 MeV), $\sigma_n = 254$ kb

$Gd_3Al_2Ga_3O_{12}$ crystal

- **Clean signature**: γ cascades above the highest natural background γ-line

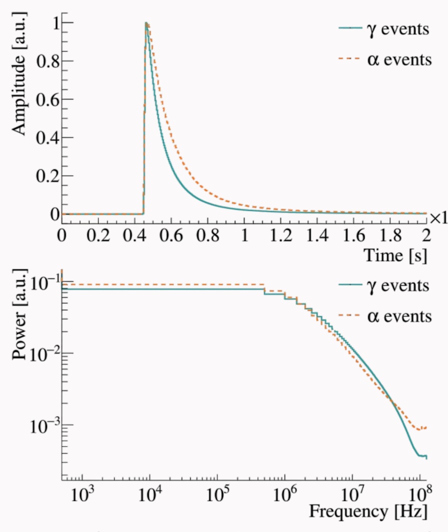
Going underground to suppress muons

The prototype for measuring background

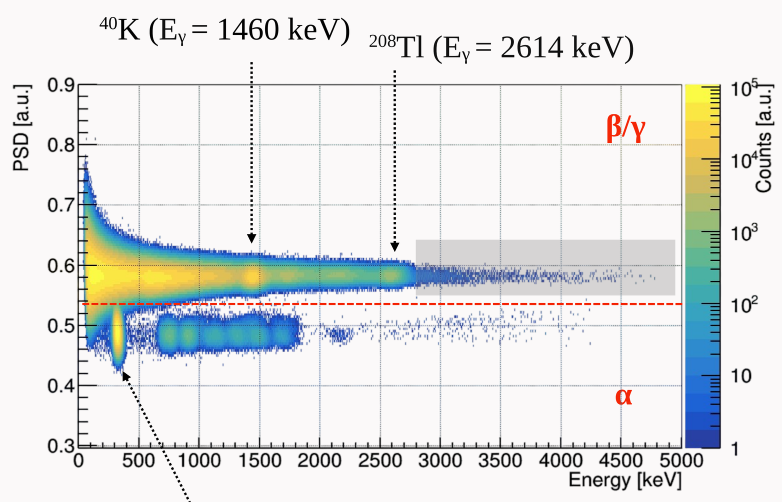
- **Shielding**: rock with 3600 mwe. and borated polyethylene
- Large crystal: $\phi = 5$ cm, h = 5 cm
- High light yield (45000 ph/MeV) and fast time response (90 ns) [1]

Excellent α backgrounds rejection power

Discrimination parameter ***PSD*** **based on different decay times of β/γ and α events**
Background data showing well separated β/γ and α bands
→ in the β/γ band, **β+γ** events from ^{208}**Tl** appeared above 2614 keV
→ α band: contamination unknown due to quenching



PSD = Amplitude/Integral
in the frequency domain



Waveforms at the time and frequency domain

α decay of ^{152}Gd (Q = 2204 keV) and ^{147}Sm (Q = 2311 keV)

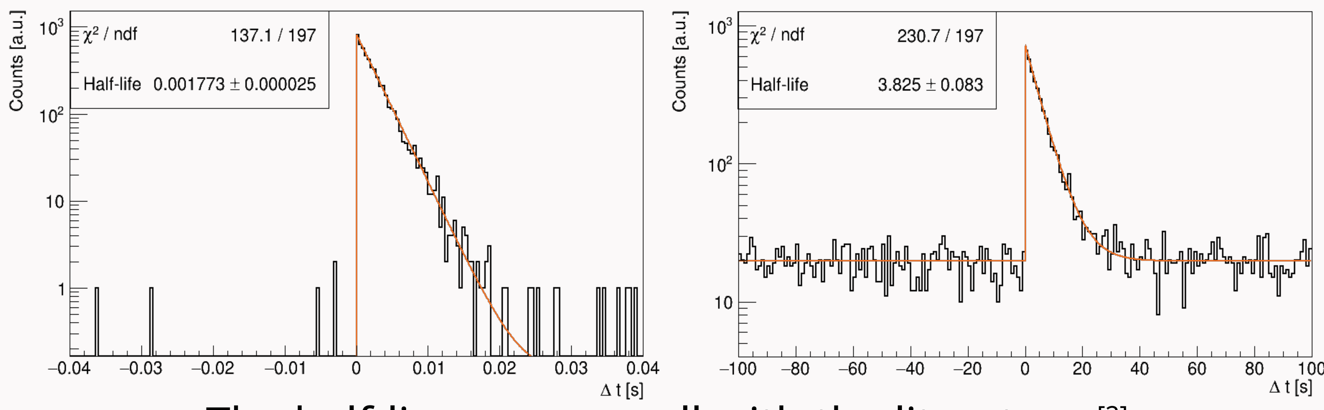
Results from measurements

Characterizing intrinsic alpha background with delayed coincidence

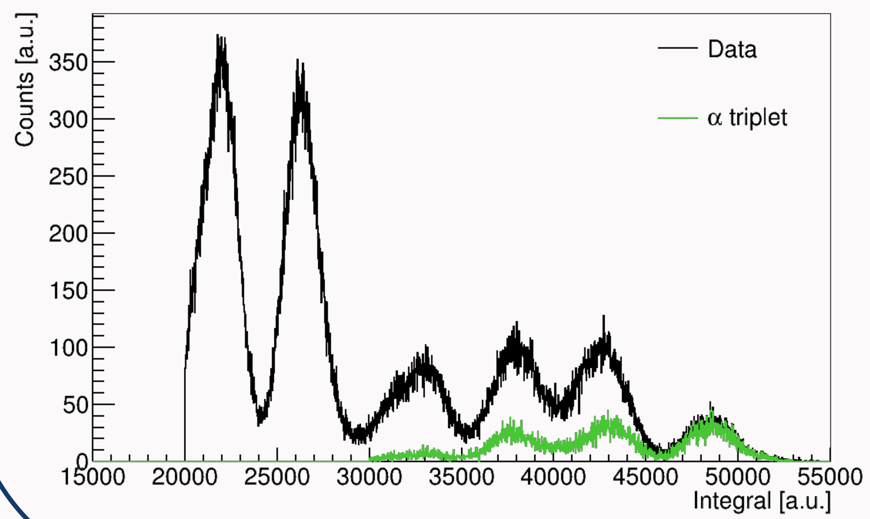
The delayed coincidence identifies the decays with short half-lives in natural decay chains via the time difference of two subsequent α events, Δt,

$$^{223}Ra \xrightarrow{} {}^{219}Rn \xrightarrow{3.96\ s} {}^{215}Po \xrightarrow{1.78\ ms} {}^{211}Pb$$

5979 keV   6946 keV   7526 keV

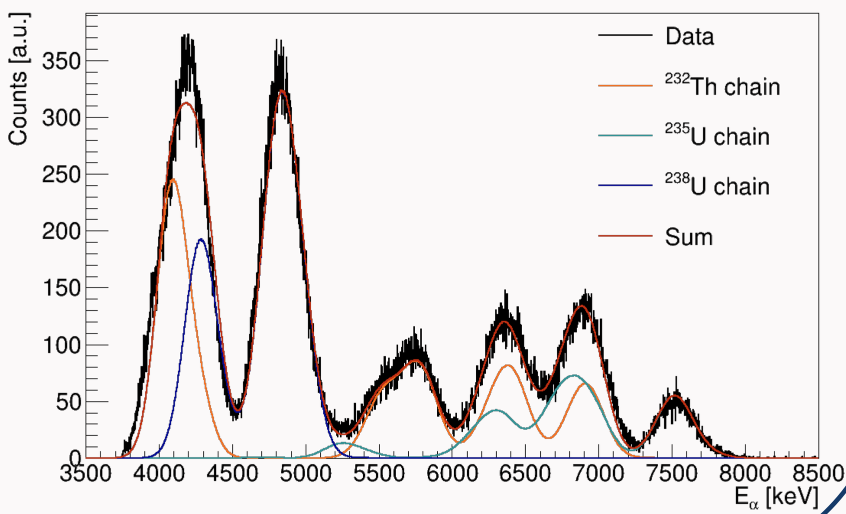


The half-lives agree well with the literature [2]

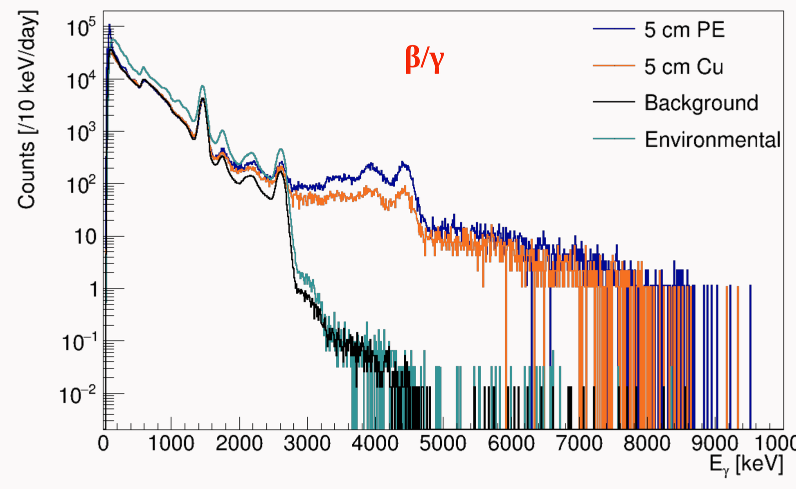


Calibration parameters (Integral → E), energy resolution, as well as contamination as input

All components are characterized by a **background model**



Detector response to neutrons



5 cm thick PE

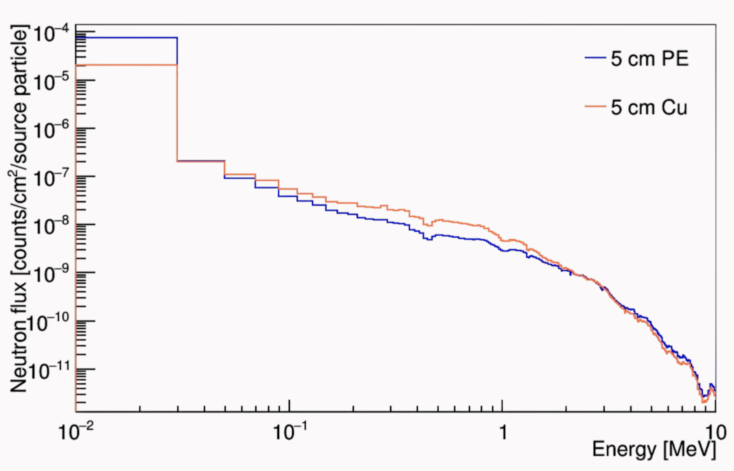
5 cm thick Cu

- Standard polyethylene (PE) slows down neutrons from the AmBe source, while the Cu plate reduces source-emitted γ-rays at ~4.4 MeV
- Count rate in the background spectrum within [5 MeV, 10 MeV]: (0.28 ± 0.06) cts/d, mostly from neutrons produced in the detector
- The environmental neutron flux at LNGS was measured with the unshielded detector, ~1×10^{-6} cts/cm²/s, comparable with others [3]

Comparison with Monte Carlo simulations

MCNP simulation verification to estimate the neutron detection efficiency

MCNP simulated AmBe neutron spectra in two configurations



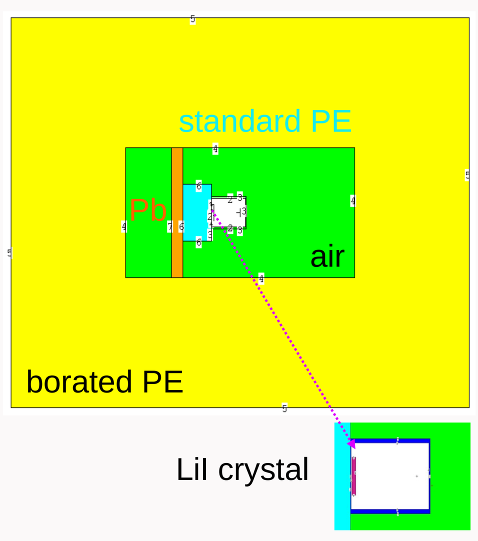
- As expected, more thermal neutrons are stopped in the GAGG with the PE

Measured $\frac{rate^{PE}}{rate^{Cu}} = 0.61$

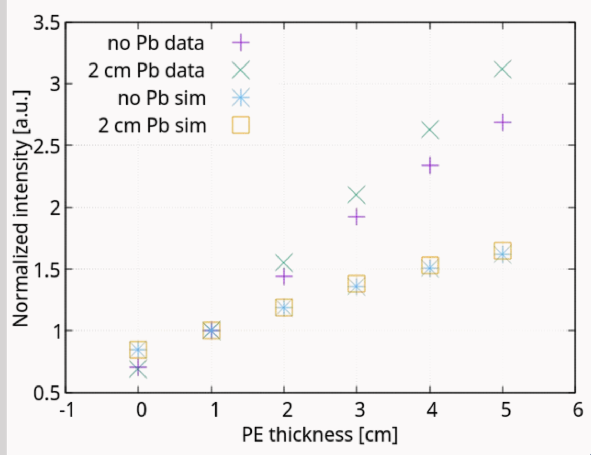
Simulated $\frac{flux^{PE}}{flux^{Cu}} = 0.31$

- **The simulation underestimates the data by about a factor of two**

Test the simulation with the low background LiI neutron detector [4]



- Nuclear reaction in the detector
  $^6Li + n \rightarrow {}^4He + {}^3H + Q$ (Q = 4.78 MeV)
- Measurements
  2 cm thick Pb + PE (0-5 cm thick)
  no Pb + PE (0-5 cm thick)
- Measured neutron intensity increases faster with PE thickness than predicted by simulation



Highlight (Our paper on arXiv:2504.16889)

The first measurement of high-energy γ-rays using the GAGG neutron detector at the LNGS is achieved in this work, and detailed background characterizations give us a good understanding of the detector's radiopurity. The detector provides a new comparative technique for underground experiments to measure neutron flux.

With the dedicated Monte Carlo simulations, a Bonner sphere with several such detectors will be set up in the near future. Furthermore, we aim to overcome the limitation of applying the GAGG neutron detectors for above-ground use, which would be of great interest to a wider community.

Publication:

L. Ascenzo, G. Benato, Y. Chu, G. Di Carlo, A. Molinario, S. Vernetto, Characterization of a GAGG detector for neutron measurements in underground laboratories, submitted to EPJC

Reference:

[1] O. Sakthong et al. Radiat. Meas. 87, 24-28 (2016)
[2] IAEA Interactive Chart of Nuclides https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
[3] A. Best et al. Nucl. Instrum. Meth. A 812, 1–6 (2016)
[4] G. Benato, PhD thesis, 2015