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Cosmic Muon-Induced Gamma Background for Rare Decay Searches

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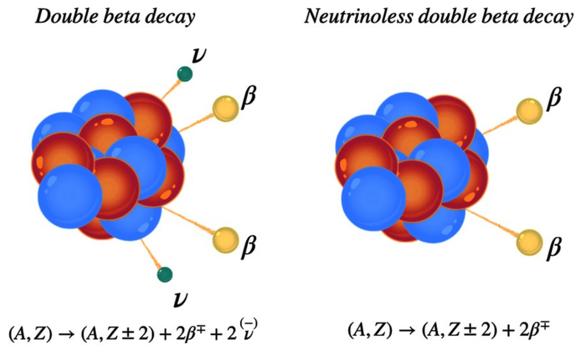
Muon Induced Backgrounds in Shielding and ACS Materials

Why is this important?

- Background suppression is critical for rare decay searches
  - Example: $^{96}Zr \rightarrow {}^{96}Nb \rightarrow {}^{96}Mo^{*}$

  Regions of Interest (ROIs): 569 keV, 778 keV, and 1091 keV.
  - Dark matter interactions, low cross-section nuclear astrophysics measurements
- Anti-Compton Shields (ACS) are standard tools to improve Signal-to-background by vetoing Compton-scattered events



- The Problem: Muon interactions within the ACS/shielding materials can generate secondary particles (neutrons, gammas) that create new background signals in the primary detector (HPGe).
- This Work: We investigate this muon-induced background using the CRADLE setup at TIFR-Mumbai, specifically focusing on the BGO and CsI(Tl) ACS.

Cryo-cooled detector for RAre Decay and Low Background Experiment (CRADLE)

Top view

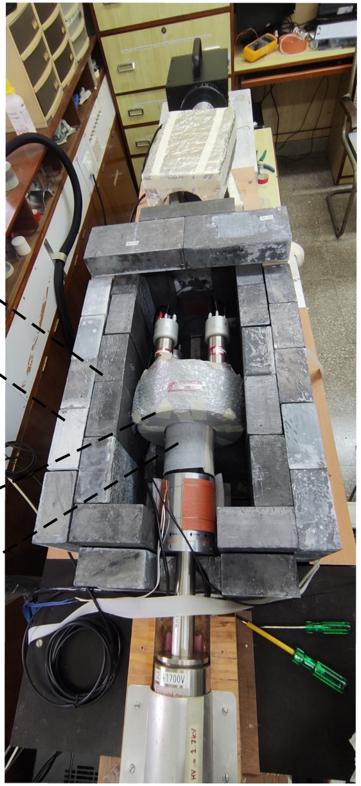
Side view

< 0.3 Bq/kg

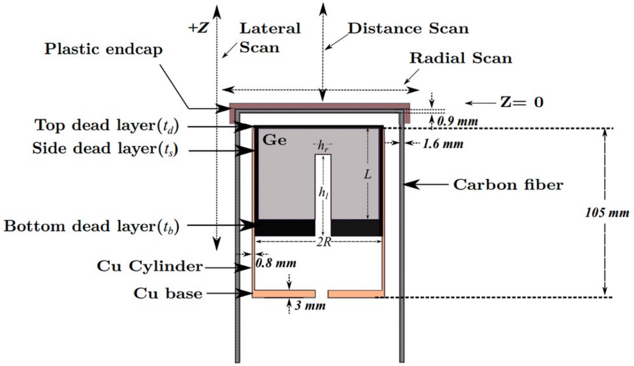
< 19 Bq/kg

CsI(Tl) ACS

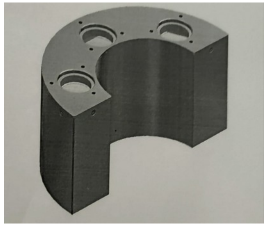
HPGe



HPGe schamatic



Annular BGO



- HPGe Detector (GEM p-type coaxial)
  - 35% relative efficiency
  - Carbon fiber body
- Annular BGO and CsI(Tl) ACS of 2.5 and 4 cm thick resp.
- Plastic Scintillators (50 x 50 x 1 cm^3) (efficiency ~ 95%)
- CAEN N6724 (14bit, 100 MS/s), CoMPASS software

How Muons Generate Background in Shielding & ACS?

Primary processes

- Electromagnetic Interactions
  - Bremsstrahlung
  - Pair Production
- Nuclear Interactions (Spallation)
- Muon capture
  - $\mu^- + (A,Z) \rightarrow \nu\mu + (A, Z\text{-}1)^* \rightarrow (A, Z\text{-}1)$ + Neutrons + Gammas

Process	Energies
Muon spallation	> 300 MeV
Muon capture	Stopping muons
Production in EM showers	~ 140 MeV
Photonuclear absorption	10 MeV to 1 TeV

Secondary processes

- Neutron-Induced Gammas (Often the most problematic)
  - Fast Neutrons (from spallation, μ^- capture)
    - Inelastic Scattering
  - Thermal/Slow Neutrons (after moderation)
    - Radiative Capture
- Activation Products

Neutron Induced gammas

Inelastic Scattering Examples

^{207}Pb(n,n'γ) at 569 keV,

^{72}Ge(n,n'γ) at 691 keV,

^{74}Ge(n,n'γ) at 596 keV.

Radiative capture

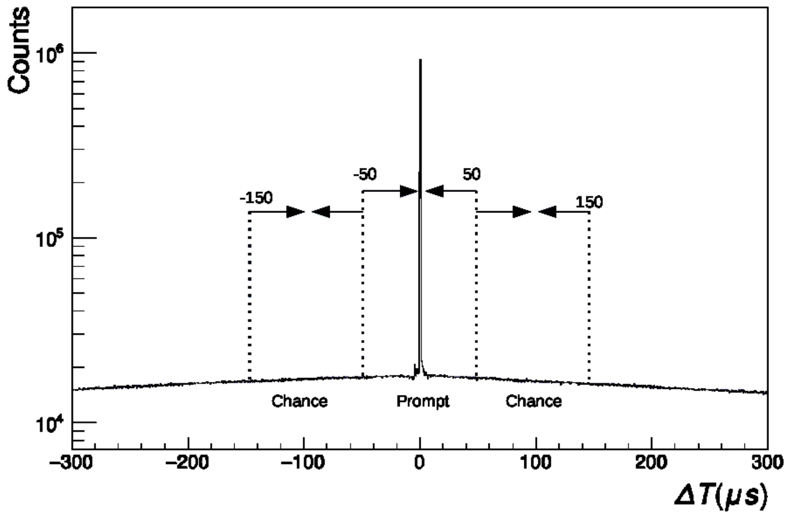
(n, γ) on shield, ACS, or HPGe (Ge)

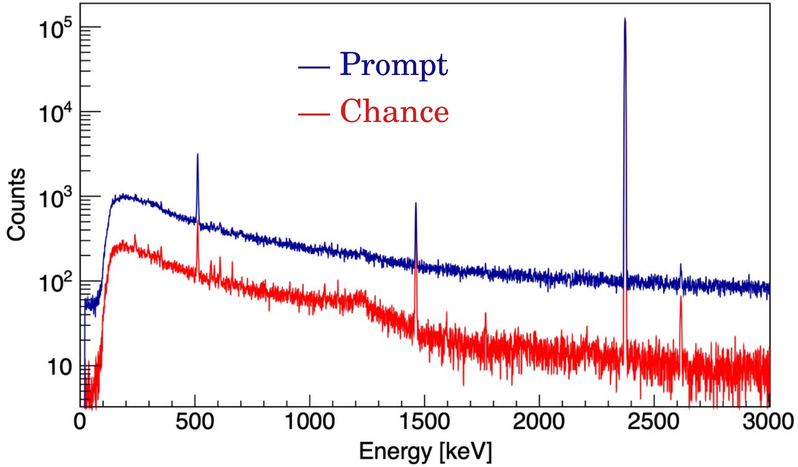
Data Analysis and Results

Data collection

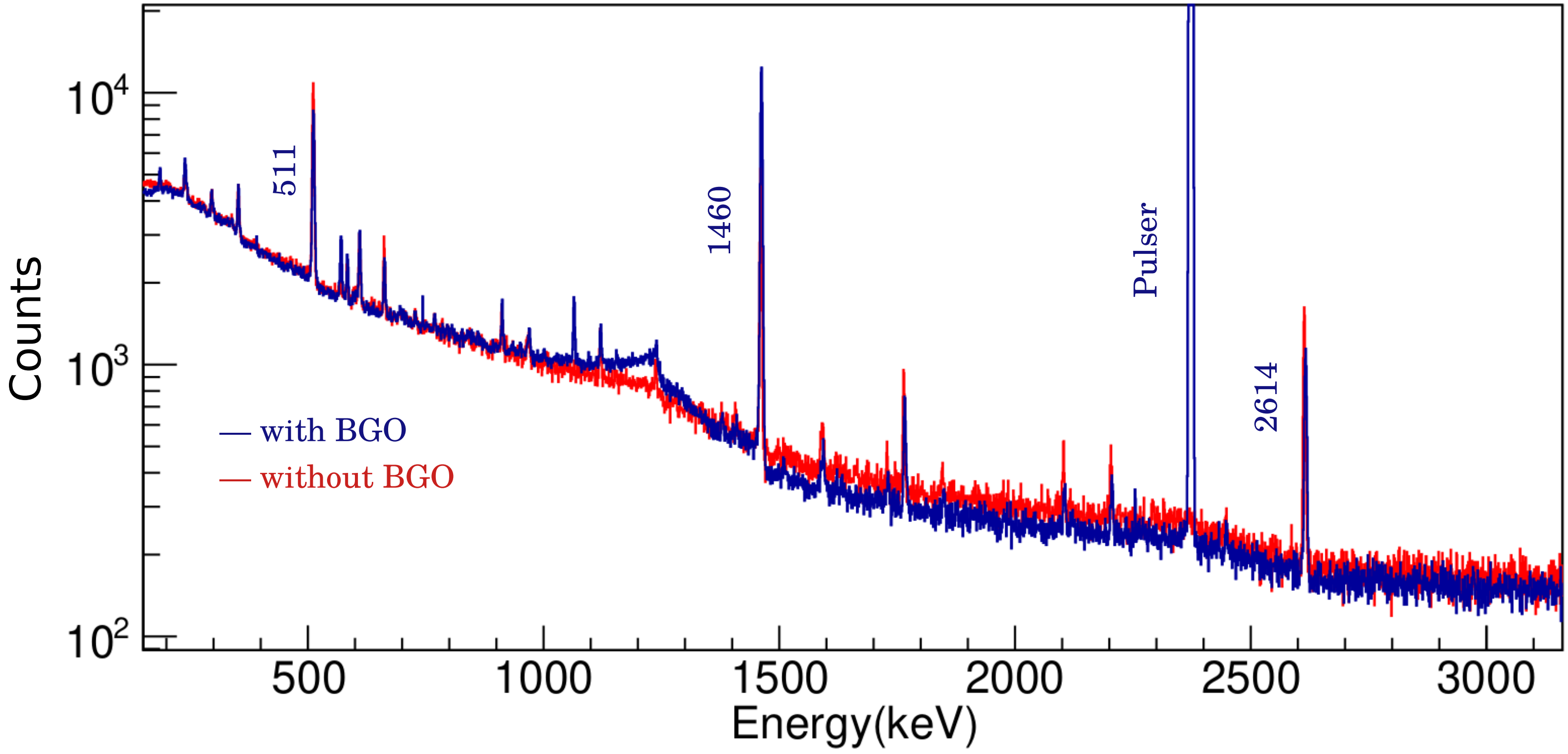
With BGO	30 days
With CsI(Tl)	15 days
Without ACS	15 days

- Muon-induced events were identified by coincidences: within 100 ns between plastics and then within 50 µs with the HPGe.
- Time normalization and chance correction have been appropriately applied.





Gamma spectrum in singles:
with BGO as passive shield vs without BGO



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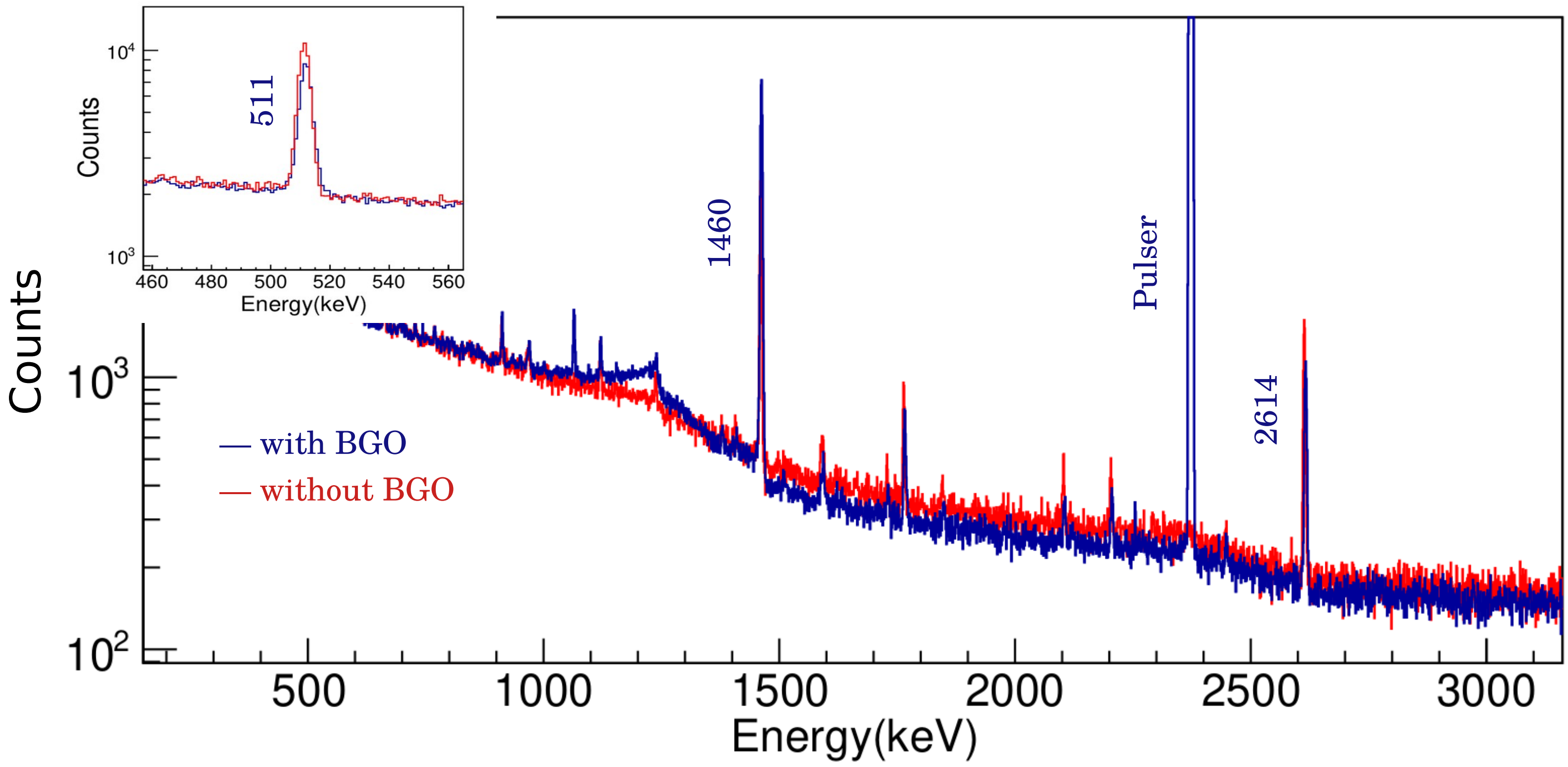

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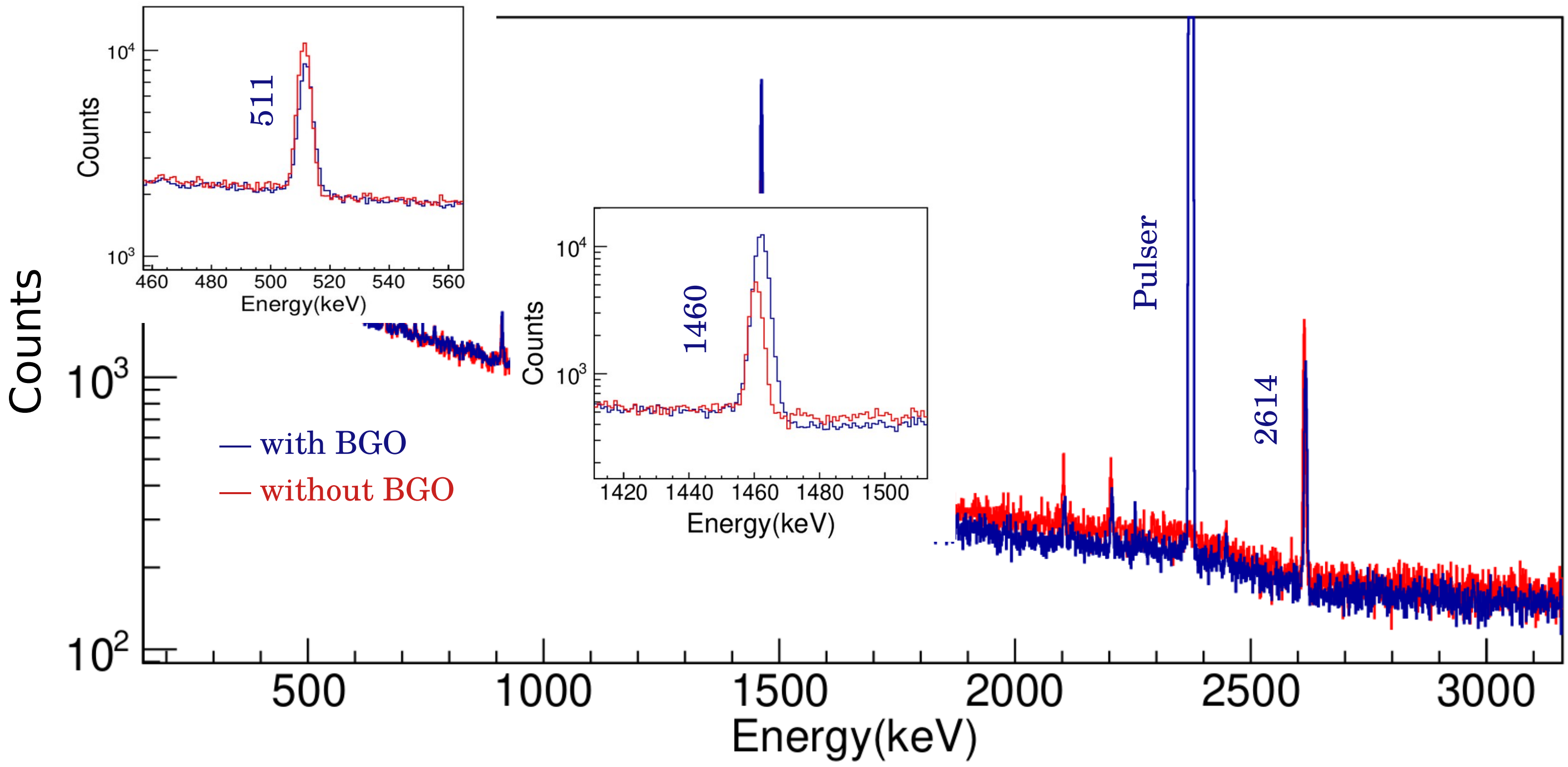

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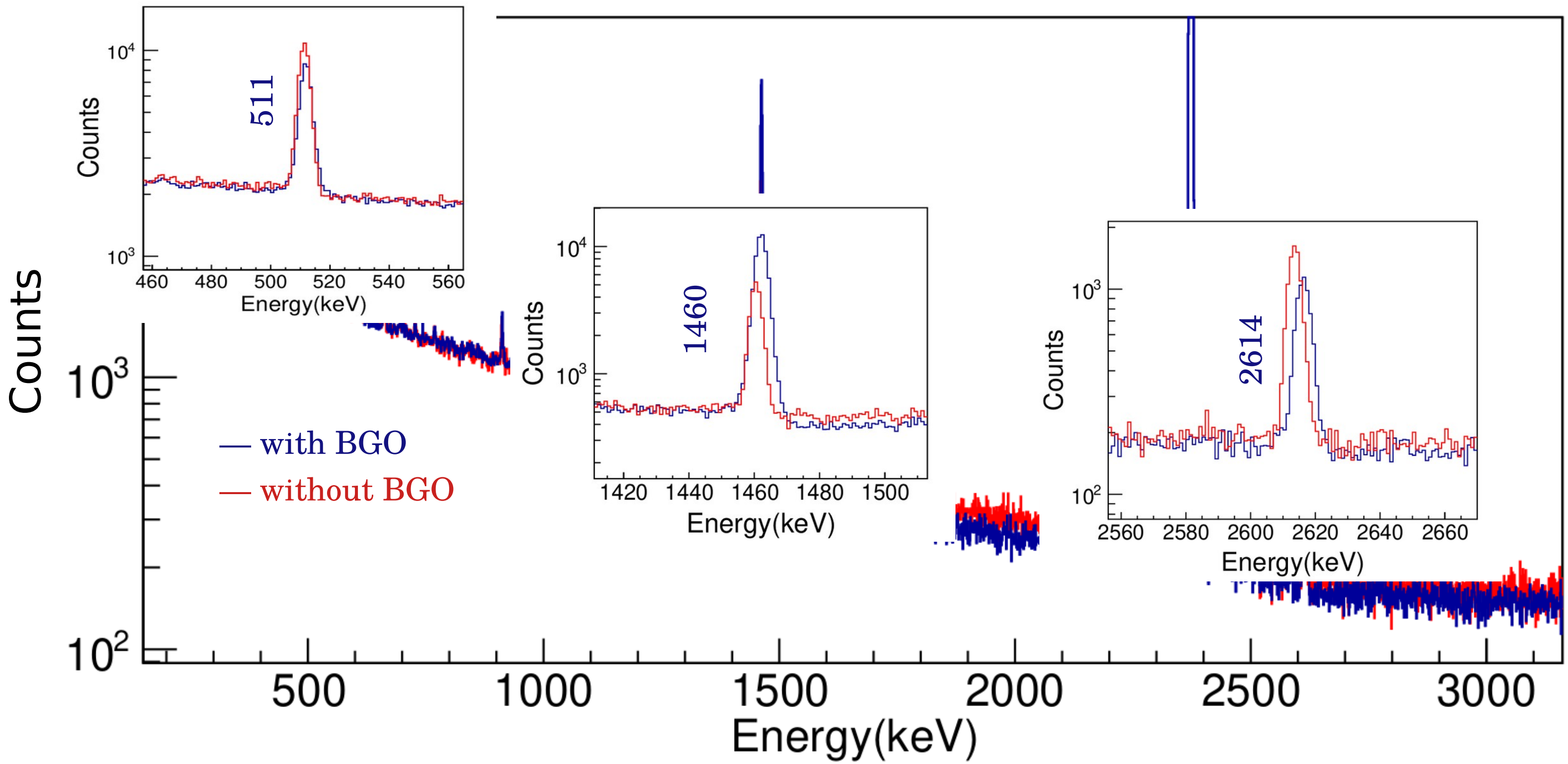

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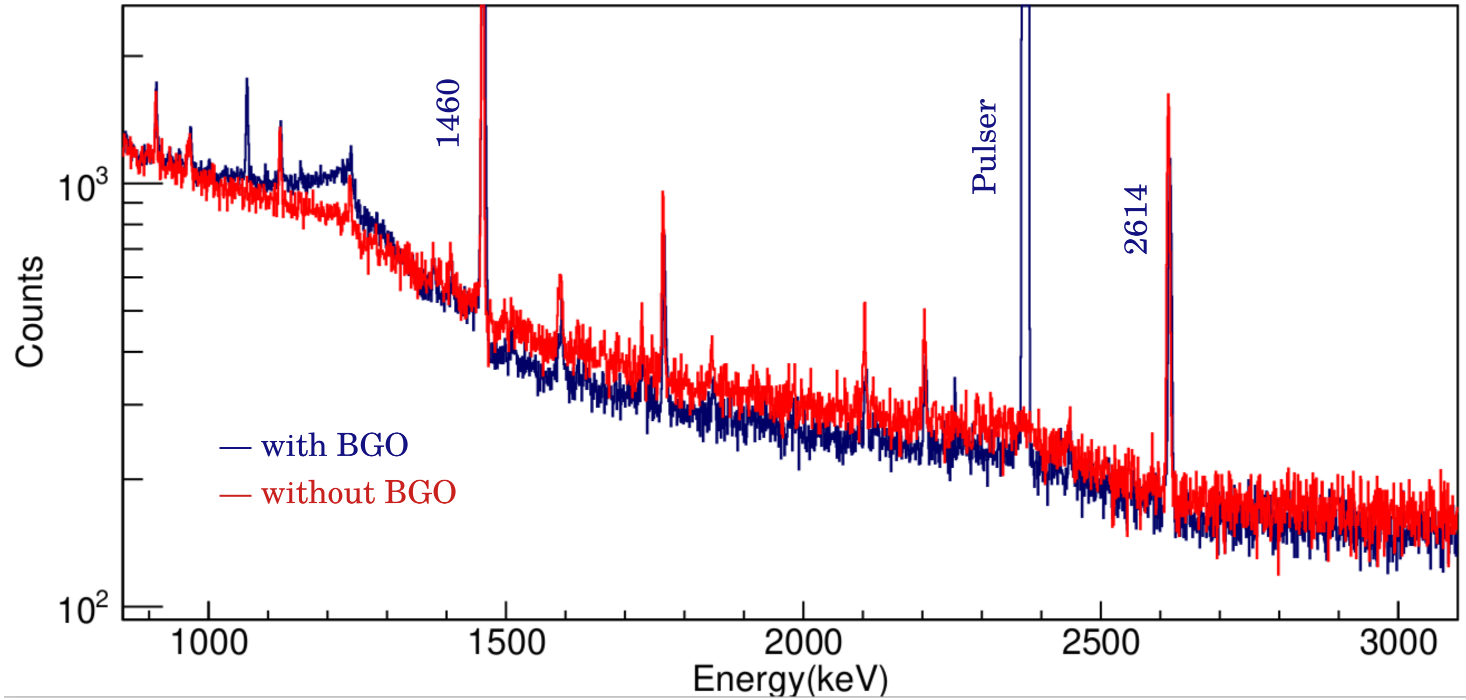
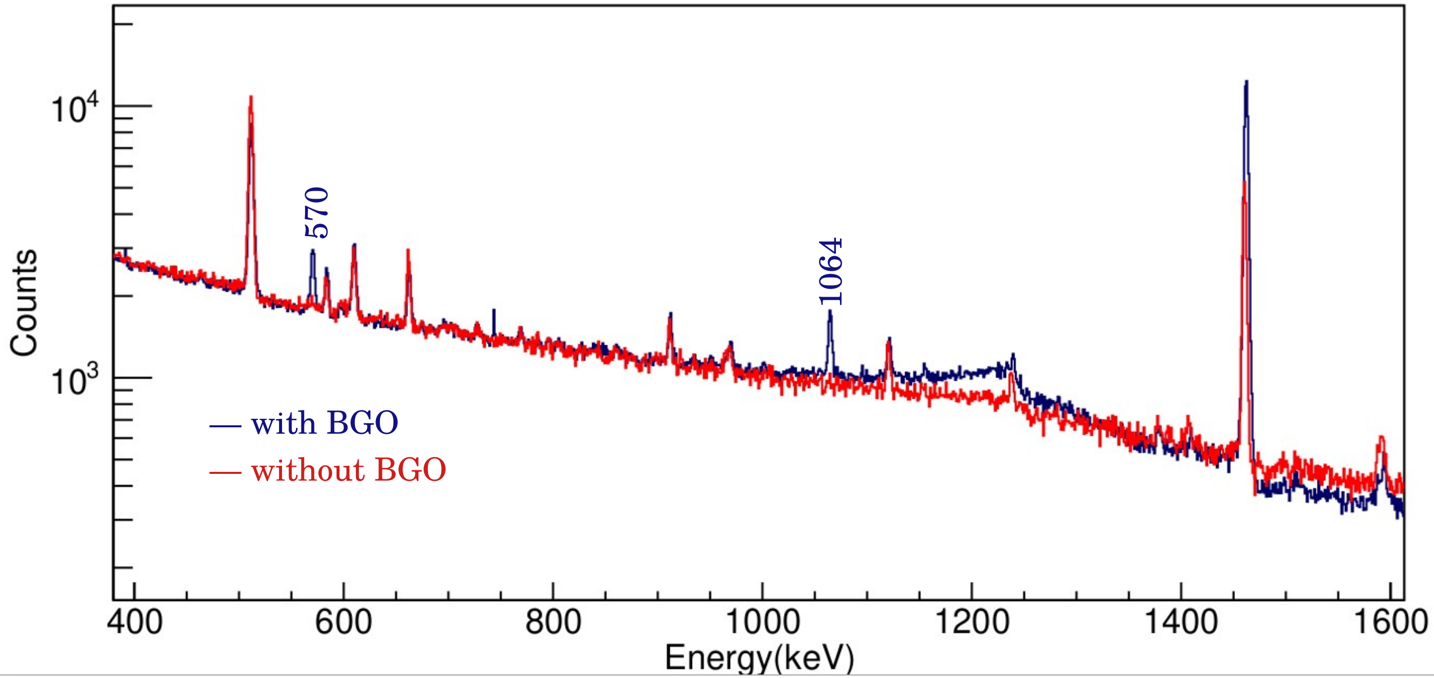
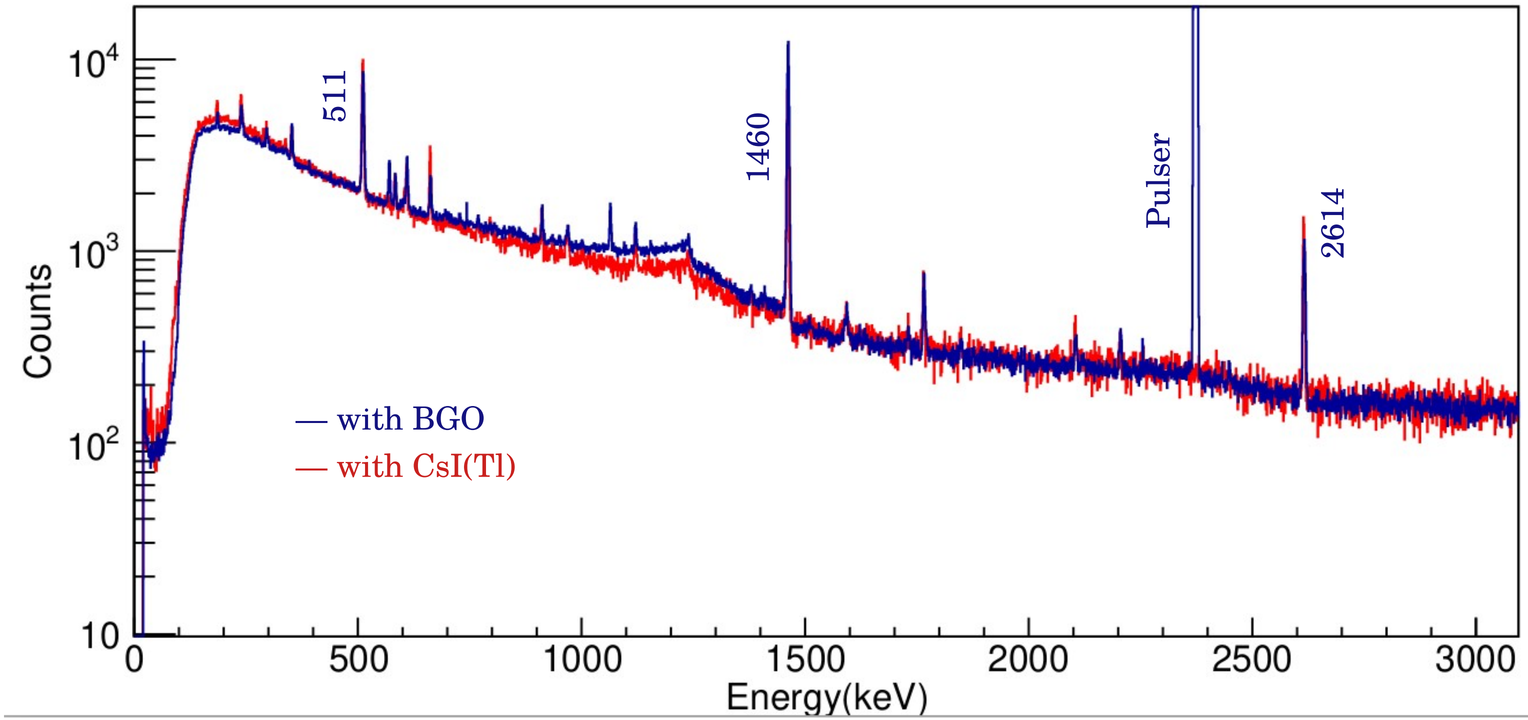


BGO internal activity



BGO's internal ^{207}Bi lines (570, 1064 keV) directly impact key ROIs (e.g., 569, 1091 keV for ^{96}Zr ββ decay)

Gamma spectrum in singles: with BGO vs with CsI(Tl) both as passive shields



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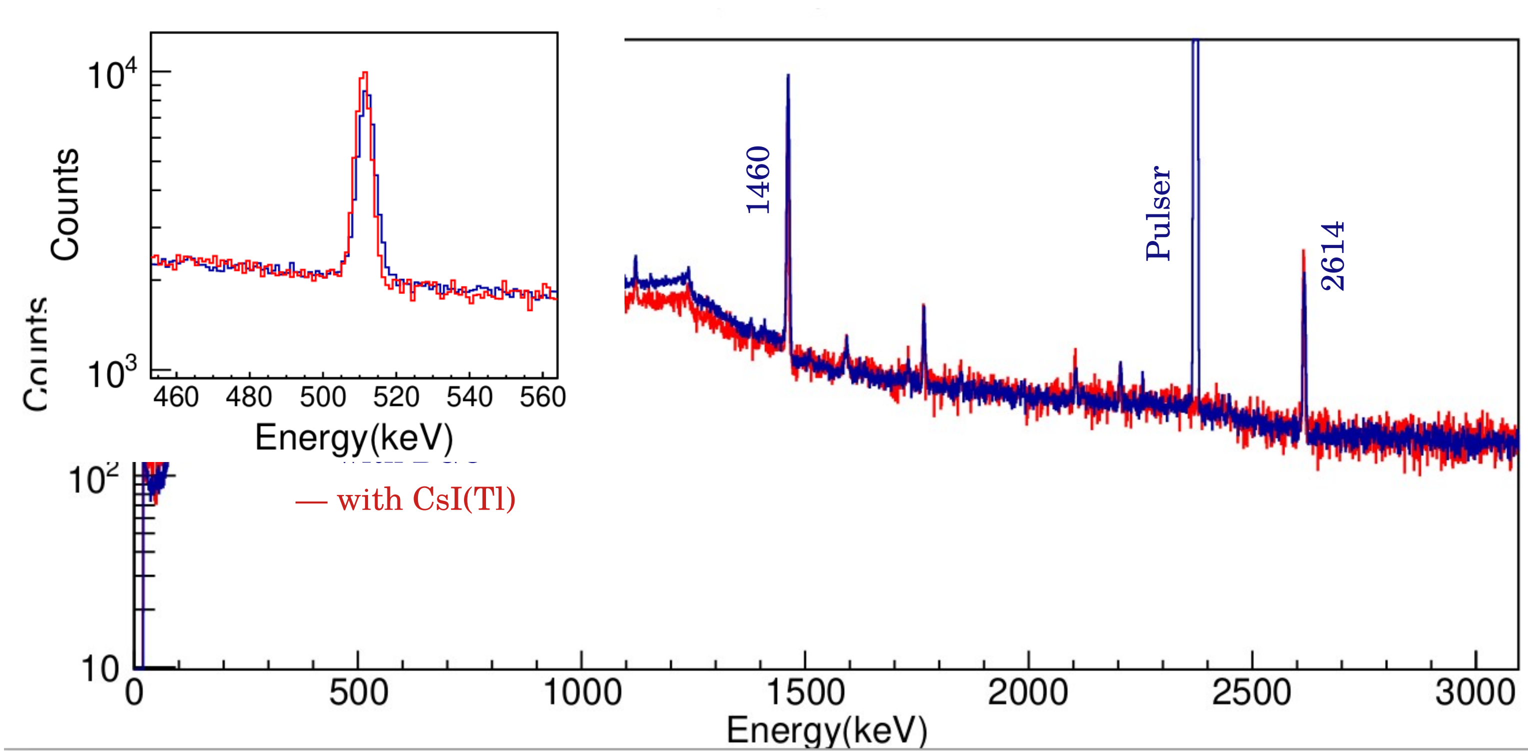

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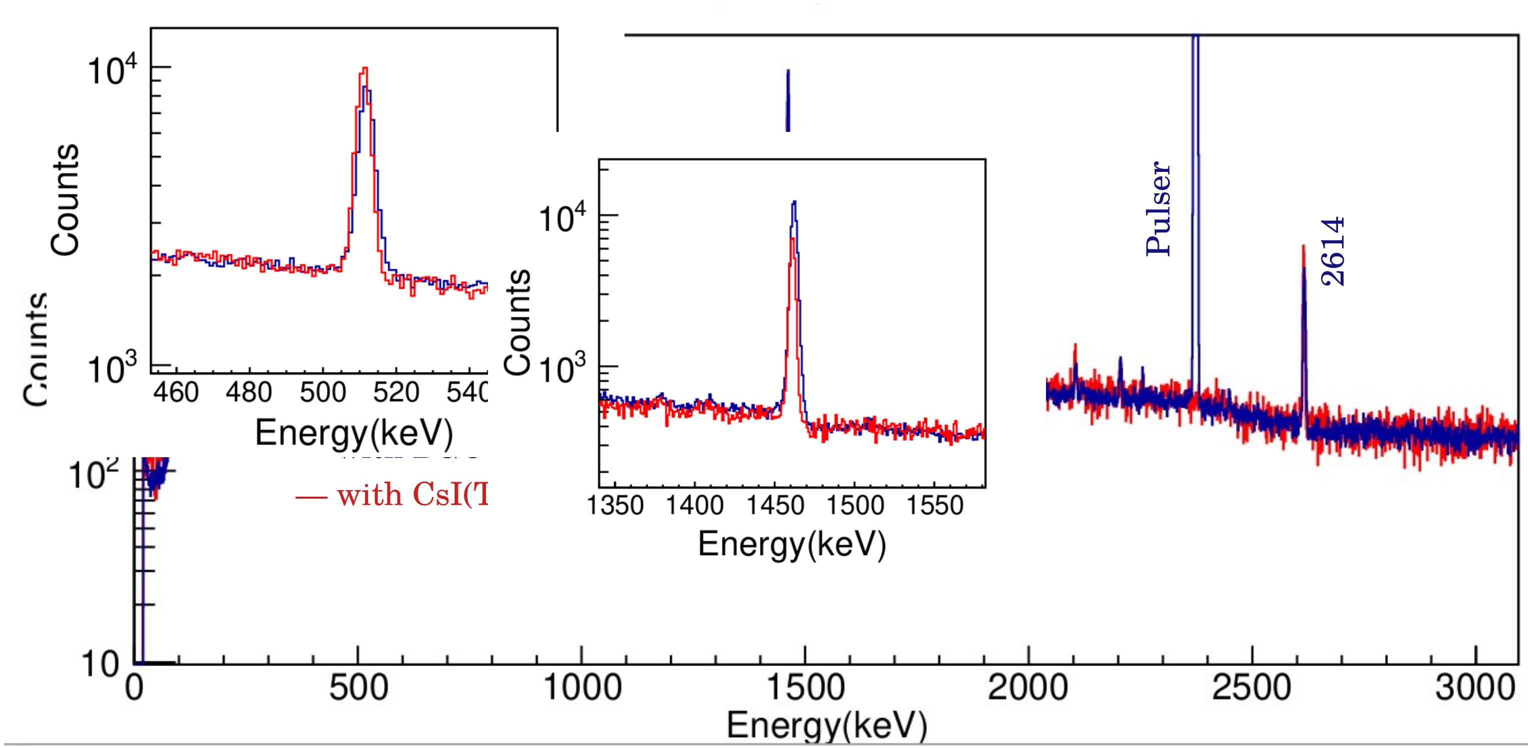

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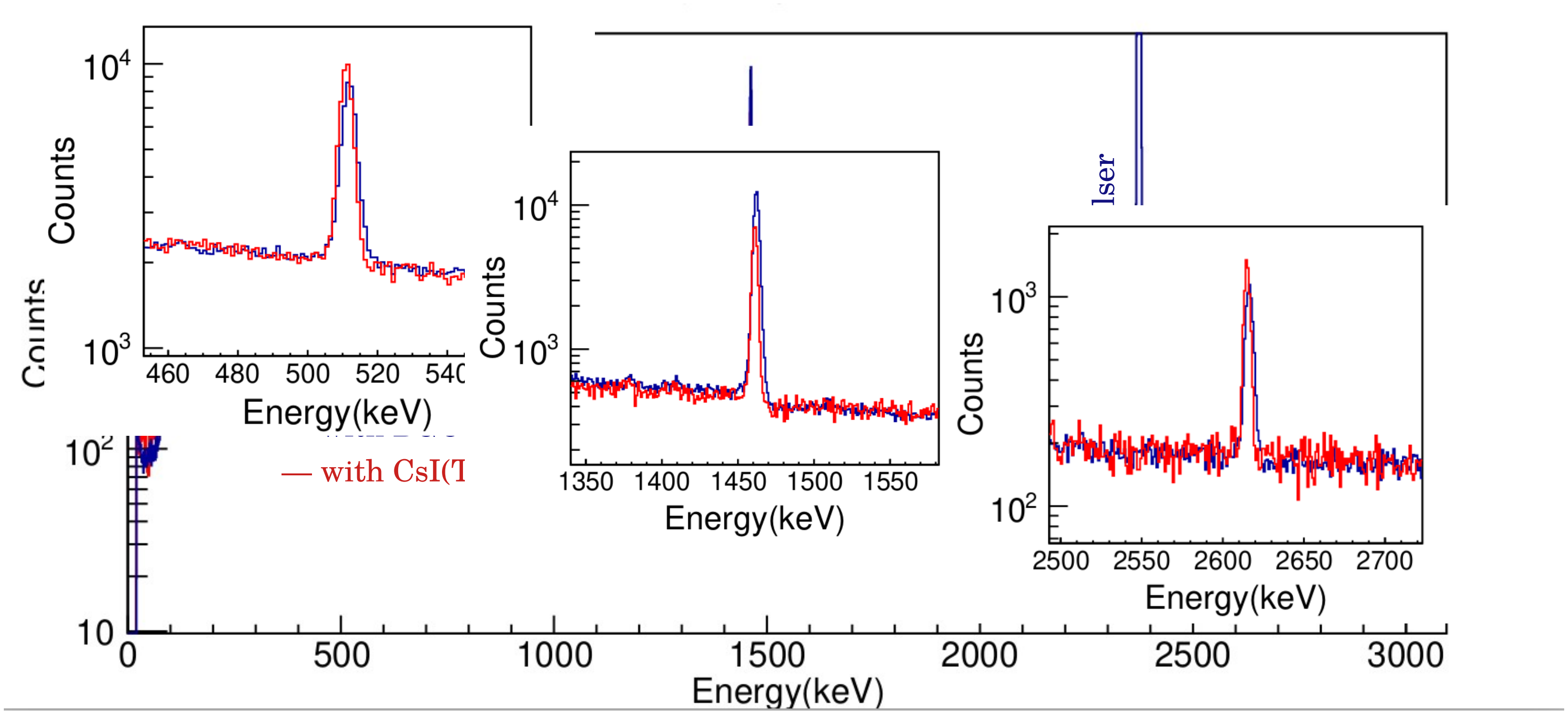
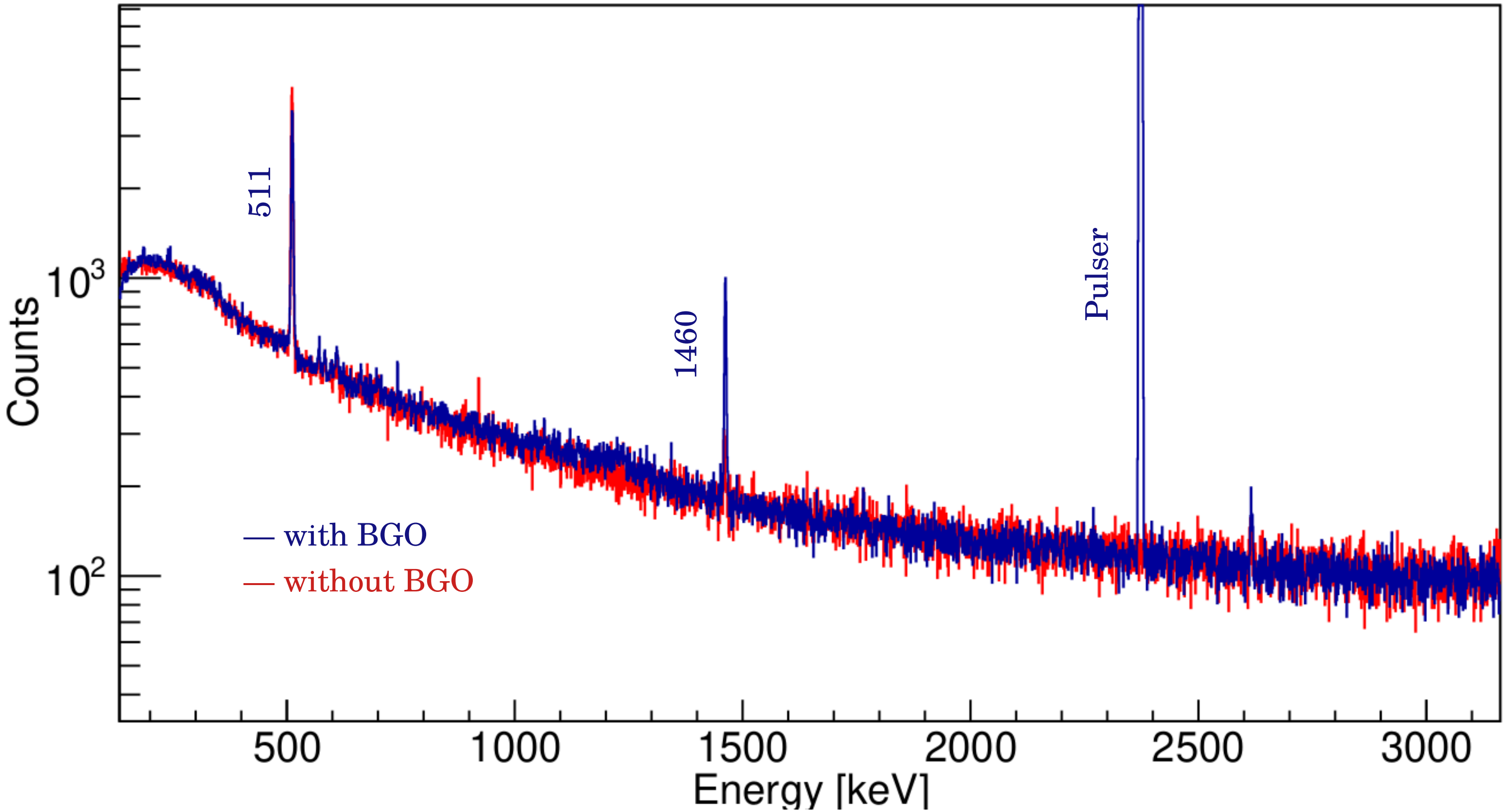


Gamma spectrum in plastic coincidence: with BGO vs without BGO



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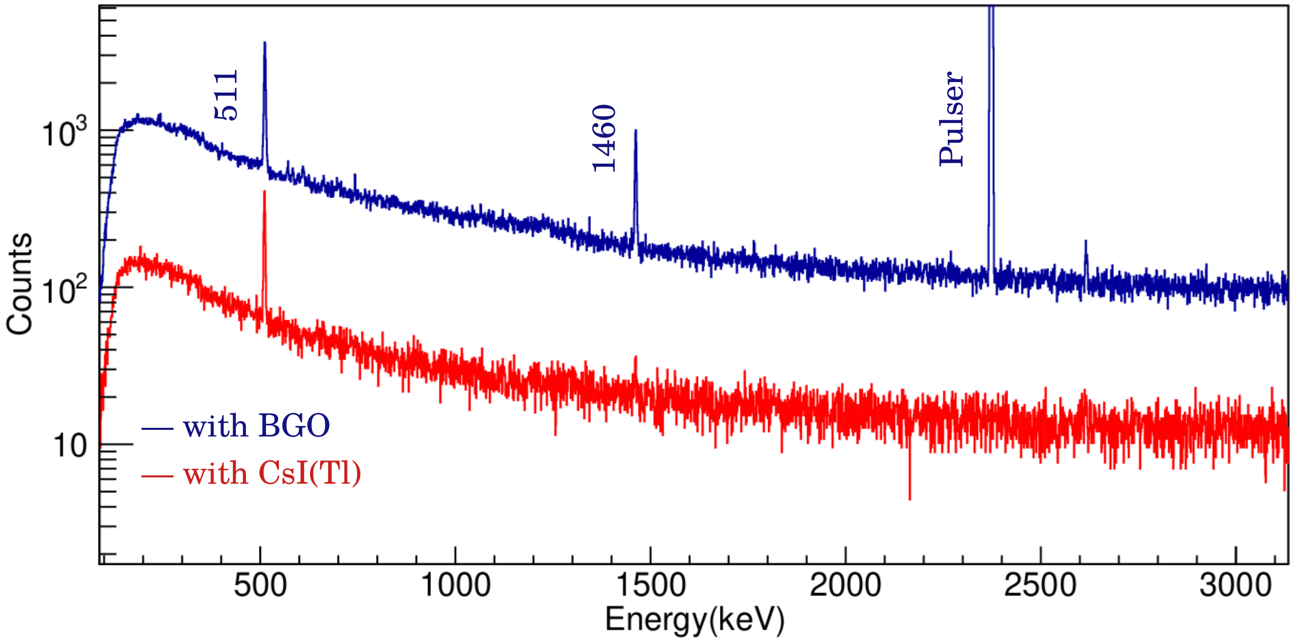

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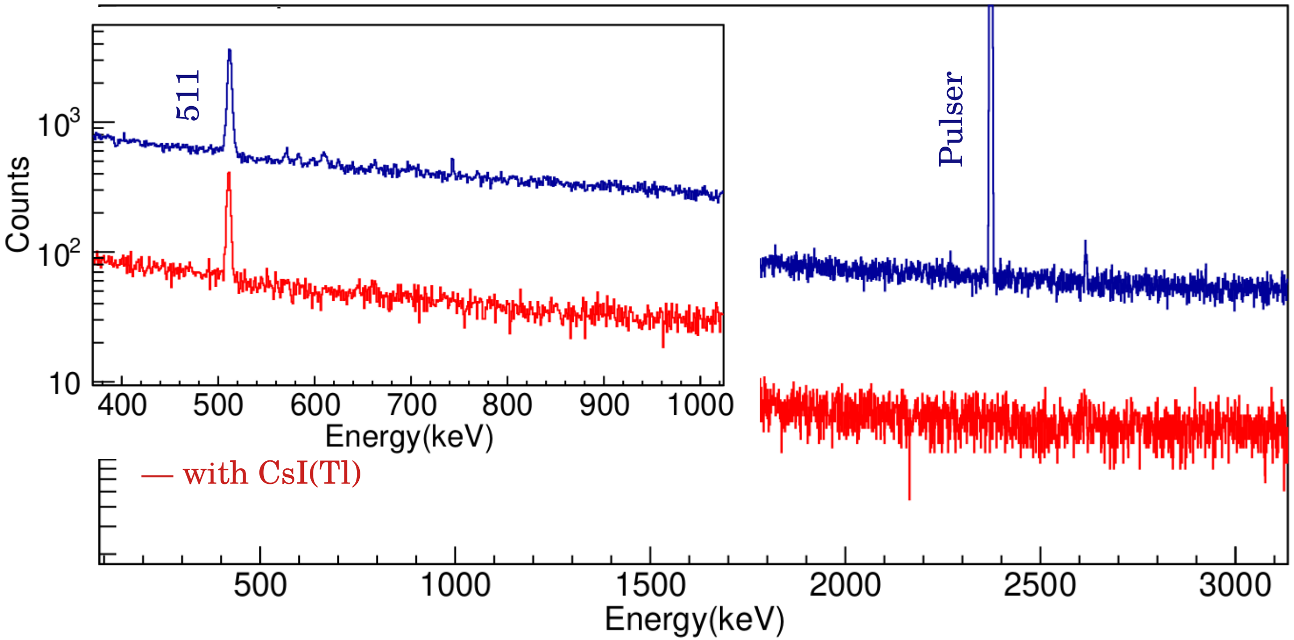
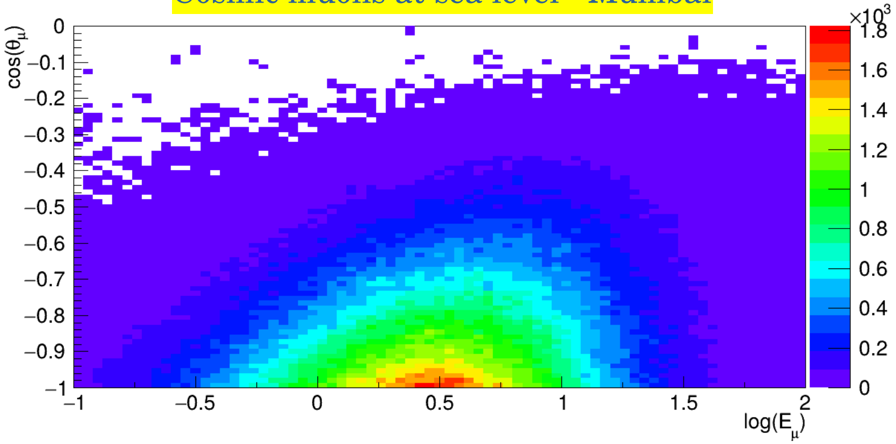


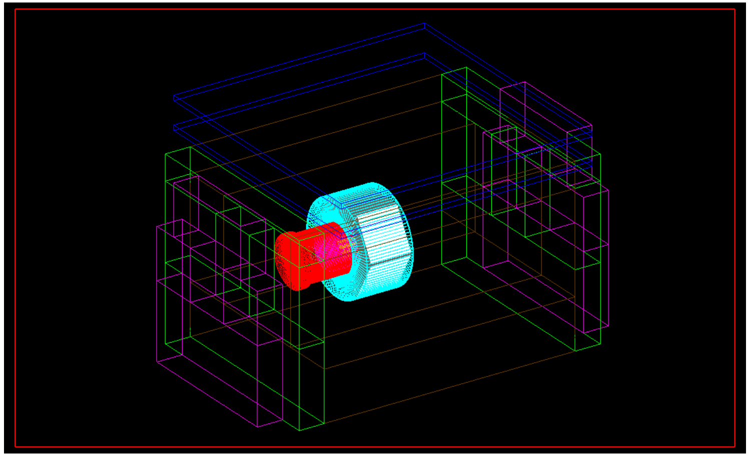
Geant4 Simulation

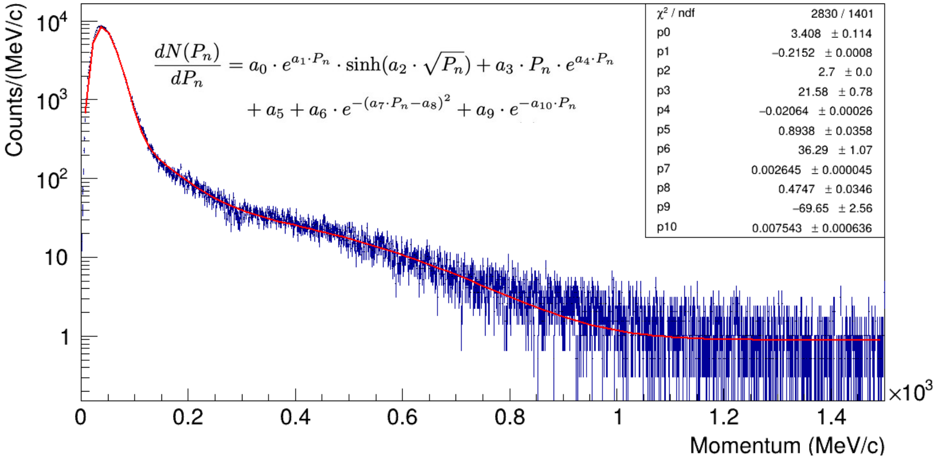
Cosmic muons at sea level - Mumbai



Ref: Eur. Phys. J. A. (2019) 55 136

CRADLE simulation in Geant4-v11.2.2

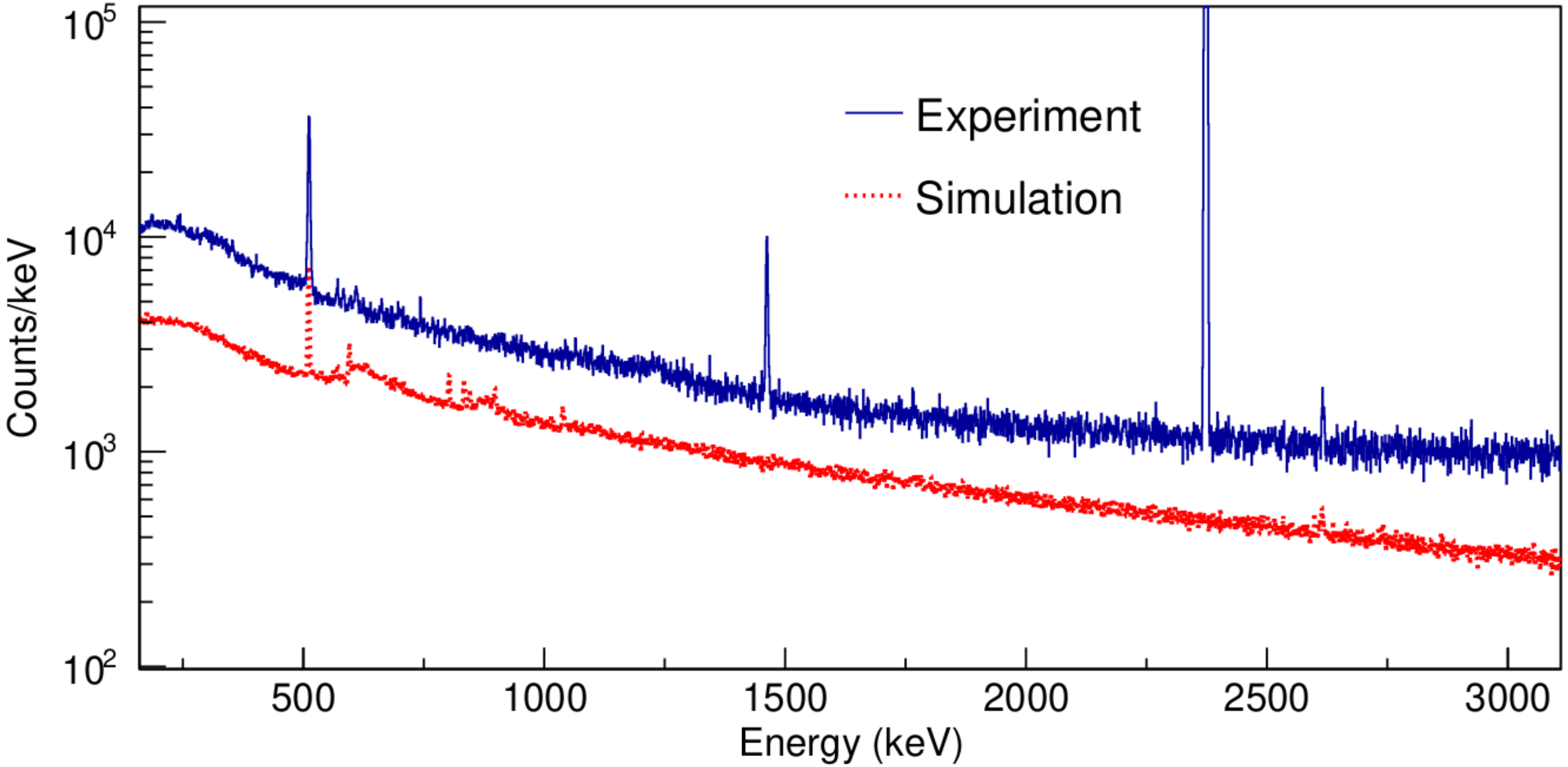




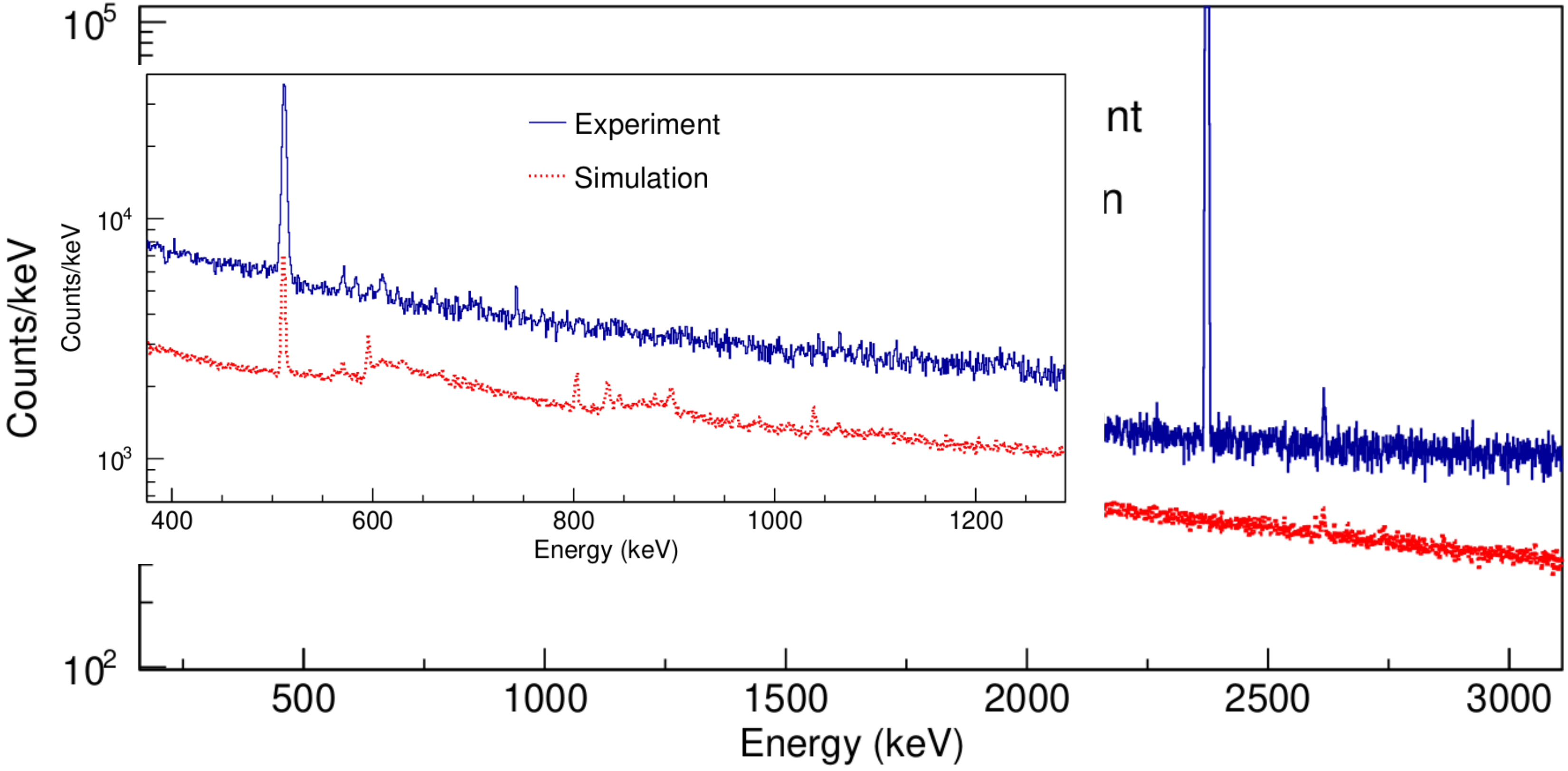
Step1: Provided Muon energy and angular distribution at sea level from CORSIKA and obtained secondary neutron distribution.

Step2: Neutrons were uniformly distributed spatially within the shielding volume, with the energy spectrum shown.

Neutron induced-gamma: simulation vs experiment



Neutron induced-gamma: simulation vs experiment



Gamma lines observed:

Energy (keV)	Source	Chance Corrected
511	^{208}Tl, ^{40}K annihilation	13277 $\pm$ 349
570	^{207}Pb(n,n$'\gamma$)^{207}Pb	–
583	^{208}Pb(n,n$'\gamma$)^{208}Pb	127 $\pm$ 79
596	^{74}Ge(n,n$'\gamma$)^{74}Ge	204 $\pm$ 74
609	^{214}Bi(n,pγ)^{214}Po	255 $\pm$ 86
662	^{137}Cs*	–
1064	^{207}Pb(n,pγ)^{207}Bi / ^{209}Bi(n,2n$'\gamma$)^{207}Bi	–
1120	^{214}Bi*	–
1460	^{40}K	–
2615	^{208}Pb(n,n$'\gamma$)^{208}Pb	–

Summary

- Cosmic muon-induced gamma backgrounds were studied for BGO and CsI(Tl) anti-Compton shields (ACS) using the CRADLE low-background HPGe setup.

- The BGO ACS exhibited contributions from internal activity and more prominent neutron induced background compared to the CsI(Tl) ACS, which showed a relatively cleaner spectrum in these regards.

- The observed gamma rays are also reproduced in the simulation.

- The high effective Z and density of BGO provide superior passive shielding against external gammas.

Summary

- A significant enhancement of the 1460 keV (^{40}K) line was observed with both ACS materials as expected.

- The optimal ACS choice for rare decay studies is therefore ROI-dependent, balancing passive shielding capabilities against the specific muon-induced backgrounds generated within the ACS.

- Detailed Geant4 simulations are ongoing to further quantify these effects and to model the ACS performance comprehensively.

- Additional measurements are planned in the basement lab with concrete shielding.

Thank You

Acknowledgement:
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