Monte Carlo simulation of background components in low level Germanium spectroscopy

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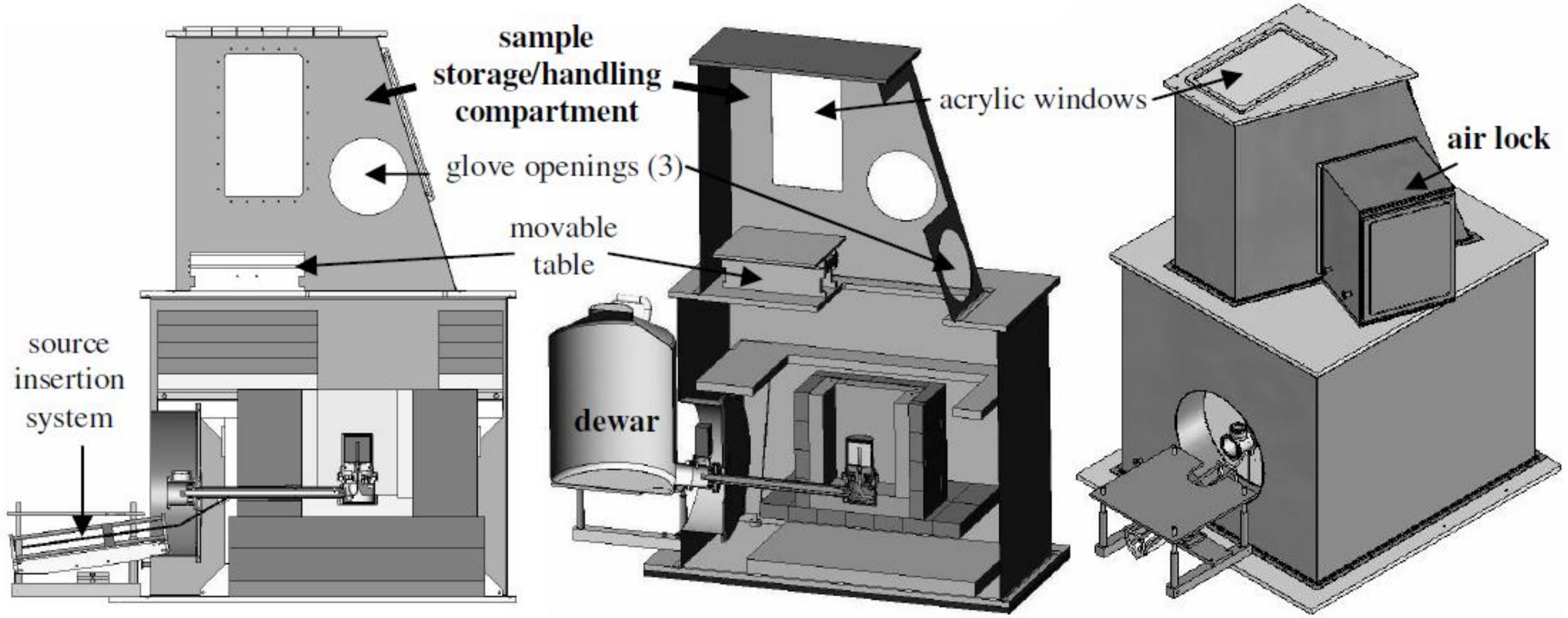
GeMPI detectors at the LNGS underground laboratory

- 4 setups with highly sensitive Germanium spectrometers (active mass: 2.2 – 2.4 kg)
- Used for screening of materials for low background experiments
- Located at a depth of 3800 m w.e.
- Sensitivity for U and Th: 10 µBq/kg (most sensitive Ge spectrometers worldwide)

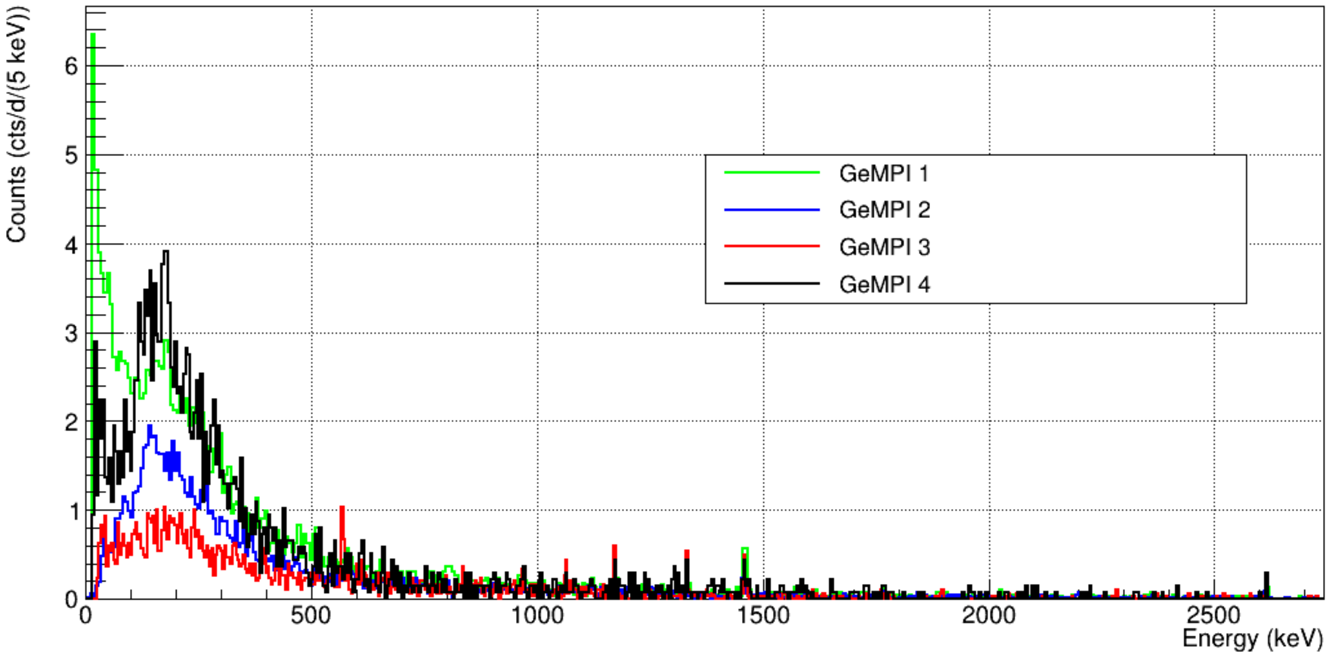
Basic detector design:

- 20 cm lead shield
- 5 cm copper shield
- Sample chamber flushed with Nitrogen gas
- Ge diode inside ultra low background copper cryostat



[1]

Background spectra of GeMPI detectors



Detector	Bkg. Count rate [40, 2700] keV (cts/d/kg)
GeMPI 1	71 ± 1
GeMPI 2	38 ± 1
GeMPI 3	24 ± 1
GeMPI 4	65 ± 1

- Very low background achieved ↔ current sensitivity for U and Th: 10 µBq/kg

  → Improvement of sensitivity possible through further reduction of background
  → Understanding of background through Monte Carlo simulations

Potential sources of background

Cosmic ray muons

- Greatly reduced flux compared to sea level (x 10^{-6}): (3.41 ± 0.01) x $10^{-4} m^{-2} s^{-1}$ [2]
- High mean energy: 262 GeV
- Possible muon veto system in future GeMPI generations ?

Muon-induced neutrons from surrounding rock

- Induced by cosmic ray muons
- Very small flux: (4.27 ± 0.01) x $10^{-6}\ m^{-2} s^{-1}$ [3]
- Energies up to 1 TeV [3]
- Possible neutron shield (made from PE) in future GeMPI generations ?

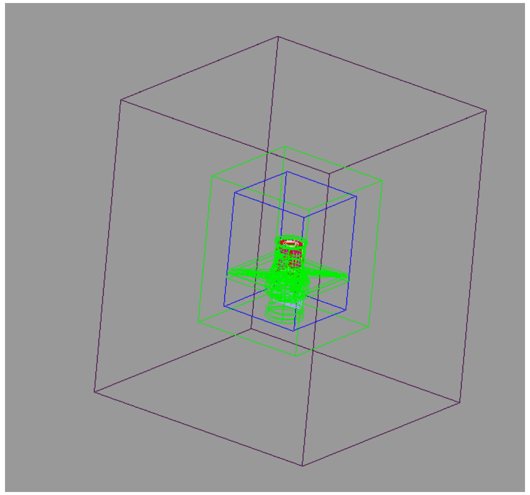
Neutrons from natural radioactivity

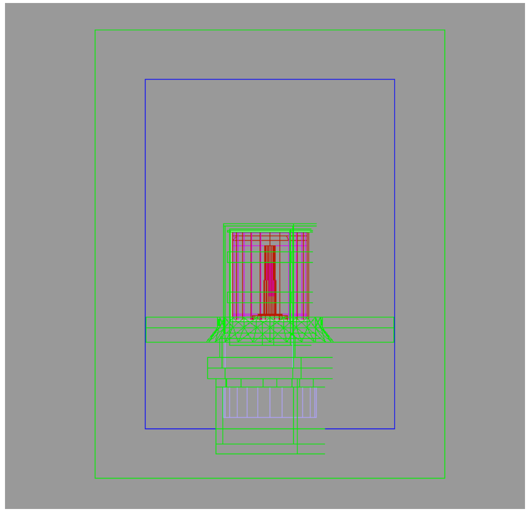
- Neutrons fom (α,n)-reactions and rad. U and Th decays in the surrounding rock
- Flux between (0.5 ± 0.1) x $10^{-2}\ m^{-2} s^{-1}$ and (3.0 ± 0.1) x $10^{-2}\ m^{-2} s^{-1}$ [4]
- Energies of a few MeV [4]
- Possible neutron shield (made from PE) in future GeMPI generations ?

Contaminations of shielding materials

- Shielding materials (Pb, Cu, PE etc.) can contain tiny radioactive contaminations
- Contaminations include: Th232, U238, Co60, K40, Pb210
- Isotope with highest background contribution: Pb210 in lead shield

Detector modelling and particle simulation with Geant4-based toolkit MaGe



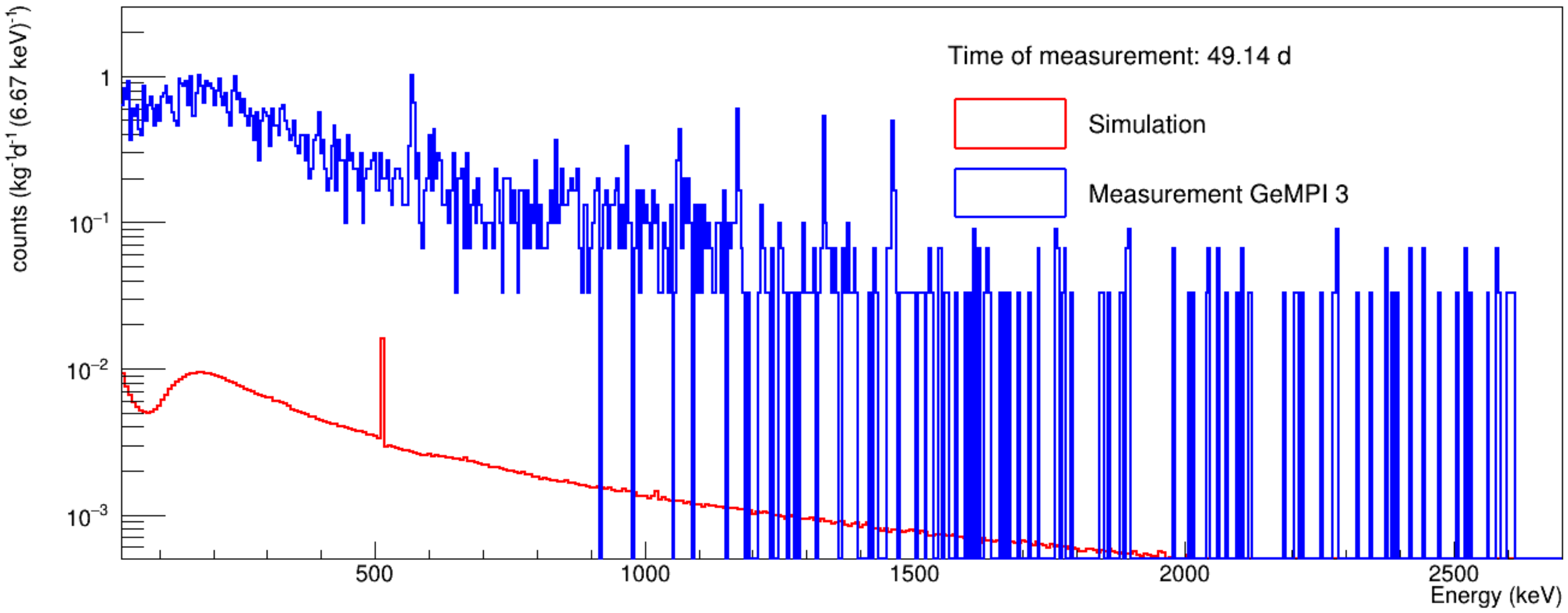


- MaGe based on Geant4, developed for Majorana and Gerda experiment [5]
- Detector geometries implemented using measurements from detector construction
- All 4 detectors share a very similar design → Simulations only done on one detector geometry (except for simulation of material contaminations)

Input for simulations

- For muons and neutrons:
  Energy and angular distributions in the LNGS laboratory
  (Muon distributions courtesy of the XENON collaboration)
- For contaminations of materials:
  Material screening measurements of activities of radioactive isotopes in the materials (when available)

Results: Muon-induced background

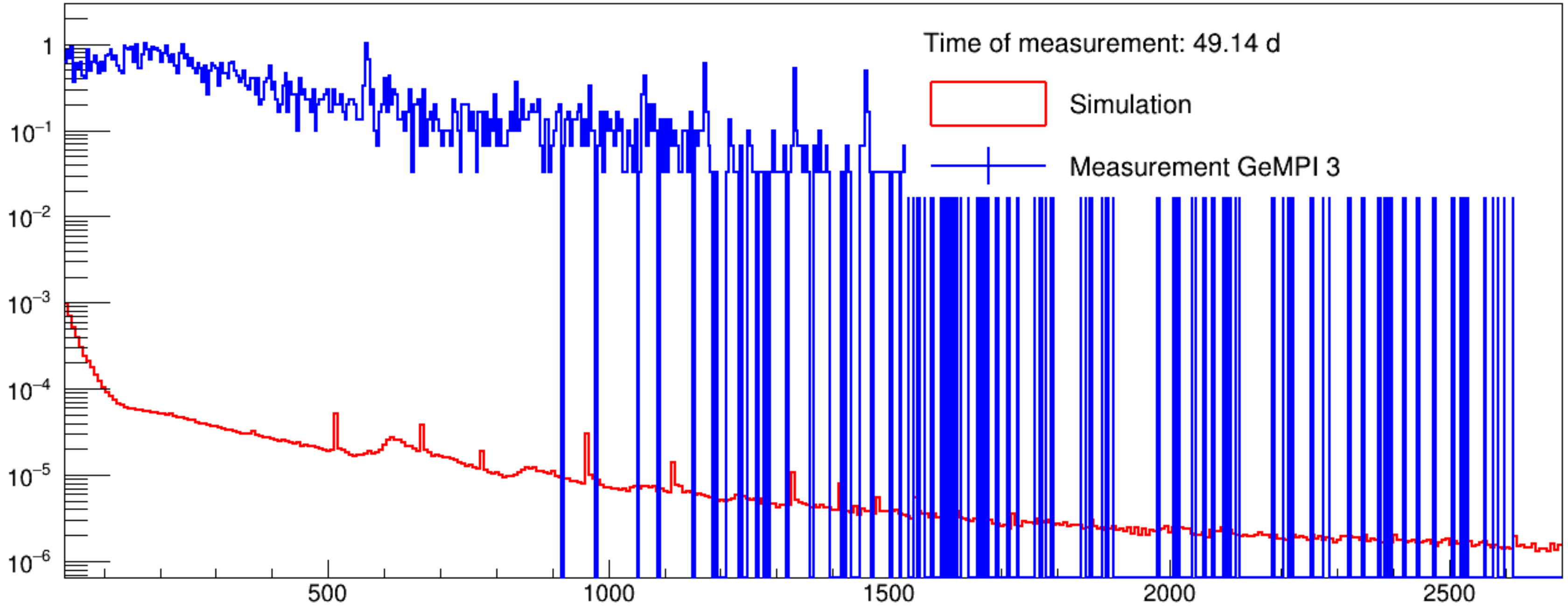


Count rate from simulations [40, 2700] keV (cts/d/kg)	Percentage of total bkg. rate [GeMPI 3] (%)
0.8 ± 0.1	3.3 ± 0.6

- Muons only contribute to a small part of the GeMPI background

→ Muon veto system in future GeMPI generations not necessary

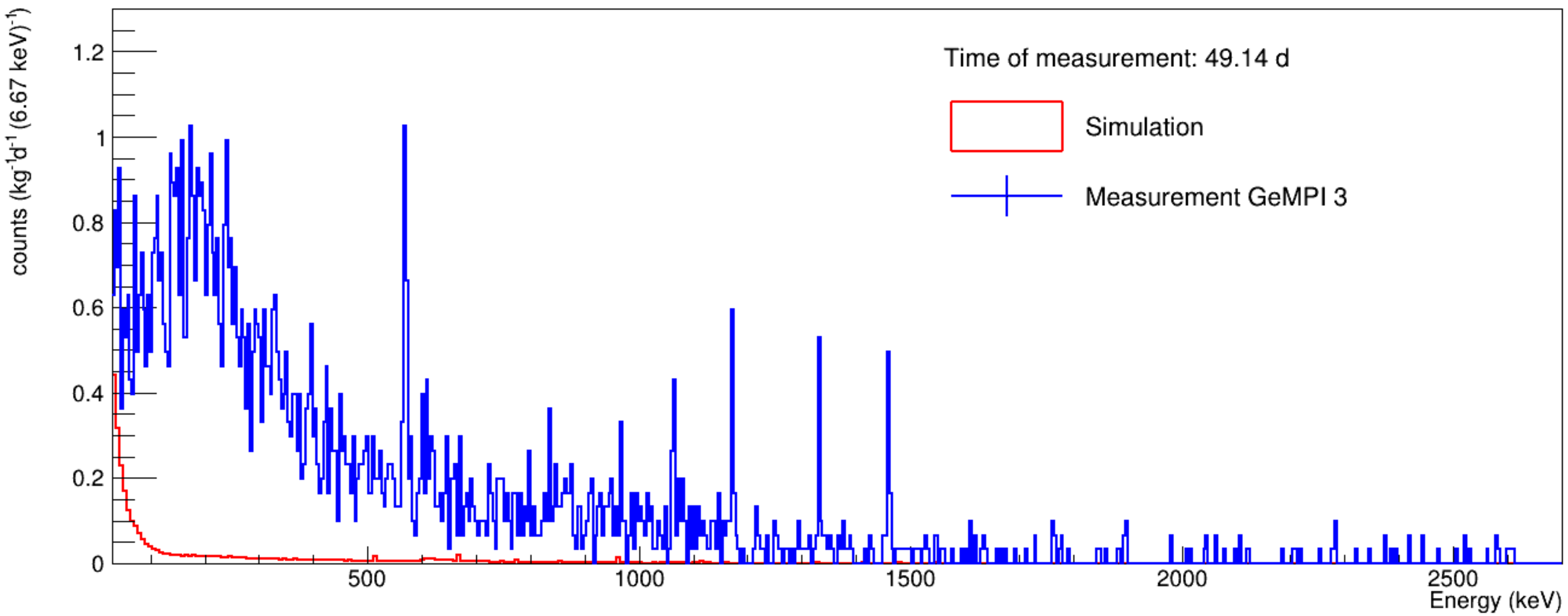
Results: Neutron background - Neutrons from muon interactions in surrounding rock



- Muon-induced neutrons only contribute a tiny part to the GeMPI background (despite very high energies)

Count rate from simulations [40, 2700] keV (cts/d/kg)	Percentage of total bkg. rate [GeMPI 3] (%)
0.0008 ± 0.0002	0.003 ± 0.001

Results: Neutron background - Neutrons from nat. radioactivity in surrounding rock

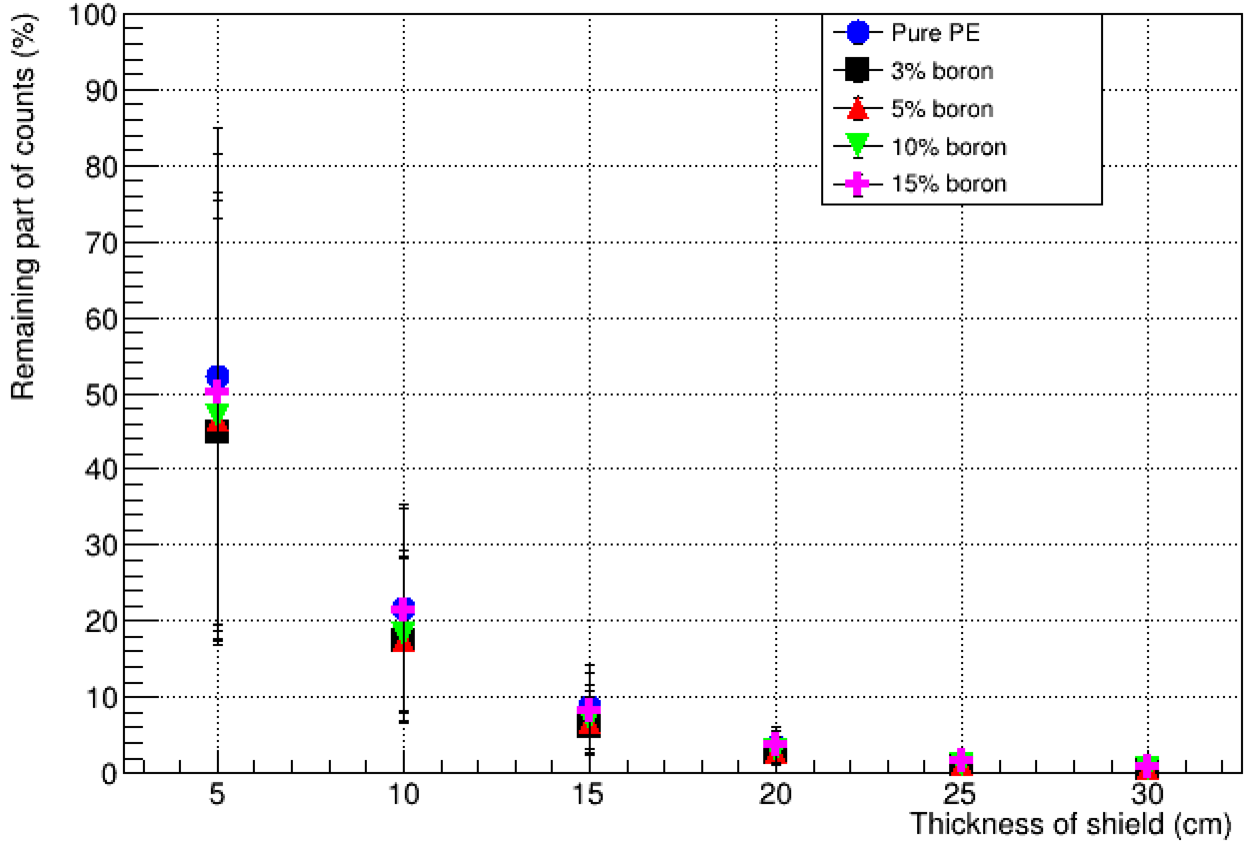


- Neutrons from natural radioactivity make up a significant part of the GeMPI background

→ Future GeMPI generations should include a Polyethylene neutron shield

Count rate from simulations between [40, 2700] keV (cts/d/kg)	Percentage of total bkg. rate [GeMPI 3] (%)
3.1 ± 2.0	12.9 ± 8.2

Results: Simulations of possible neutron shields



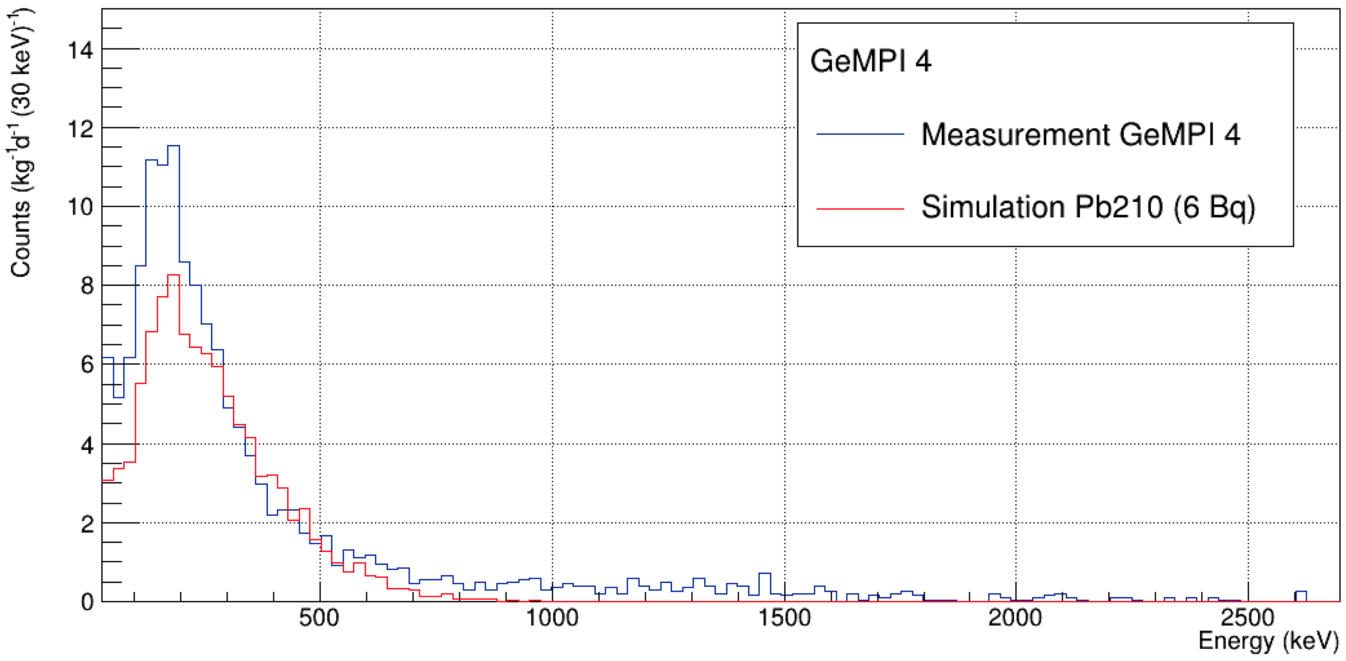
- Hydrogen (in PE) ideal for deceleration of fast neutrons
- Boron has high cross section for thermal neutron capture

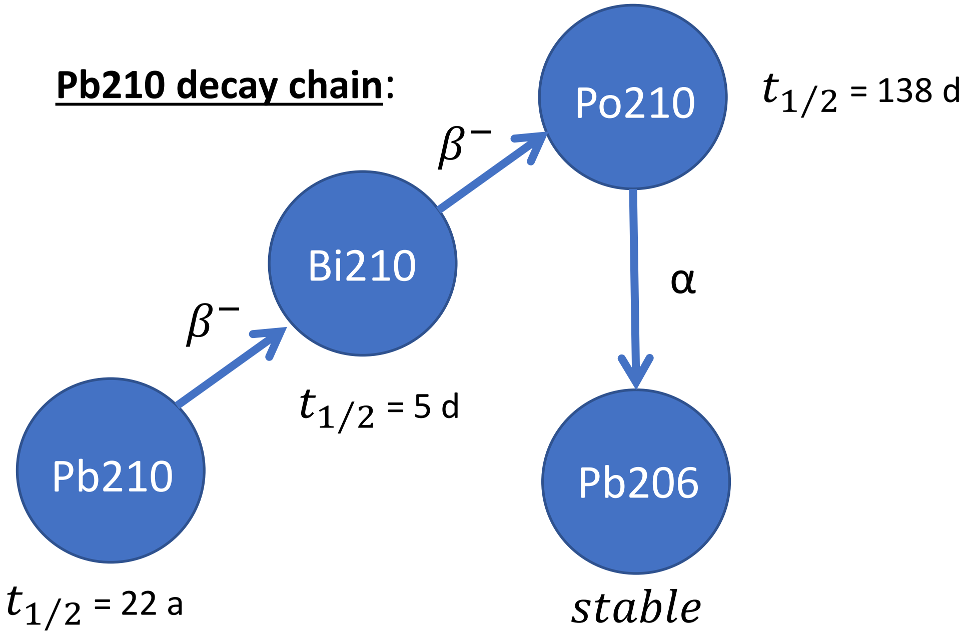
→ Simulation of neutron shield made from borated PE with different boron contents

- <u>At a thickness of 15 cm</u>:
  - neutron contribution comparable to muon contribution
  - different boron contents do not have a significant influence on the effectiveness of the shield

→ 15 cm shield of pure PE for future GeMPI generations

Results: Contamination of detector materials – Pb210 in lead shield





	GeMPI 1	GeMPI 2	GeMPI 3	GeMPI 4
Pb210 Cont. (Bq/kg)	~ 6	~ 3	~ 1.7	~ 6
Contr. to Bkg. [40, 2700] keV (cts/d/kg)	45 ± 4	23 ± 2	13 ± 1	45 ± 4
Percentage of total bkg. rate (%)	63 ± 5	60 ± 5	54 ± 4	69 ± 6

Results: Possible ways to reduce contribution from Pb210 in lead shield

- Pb210 contamination in lead shield is biggest contributor to background despite copper shield

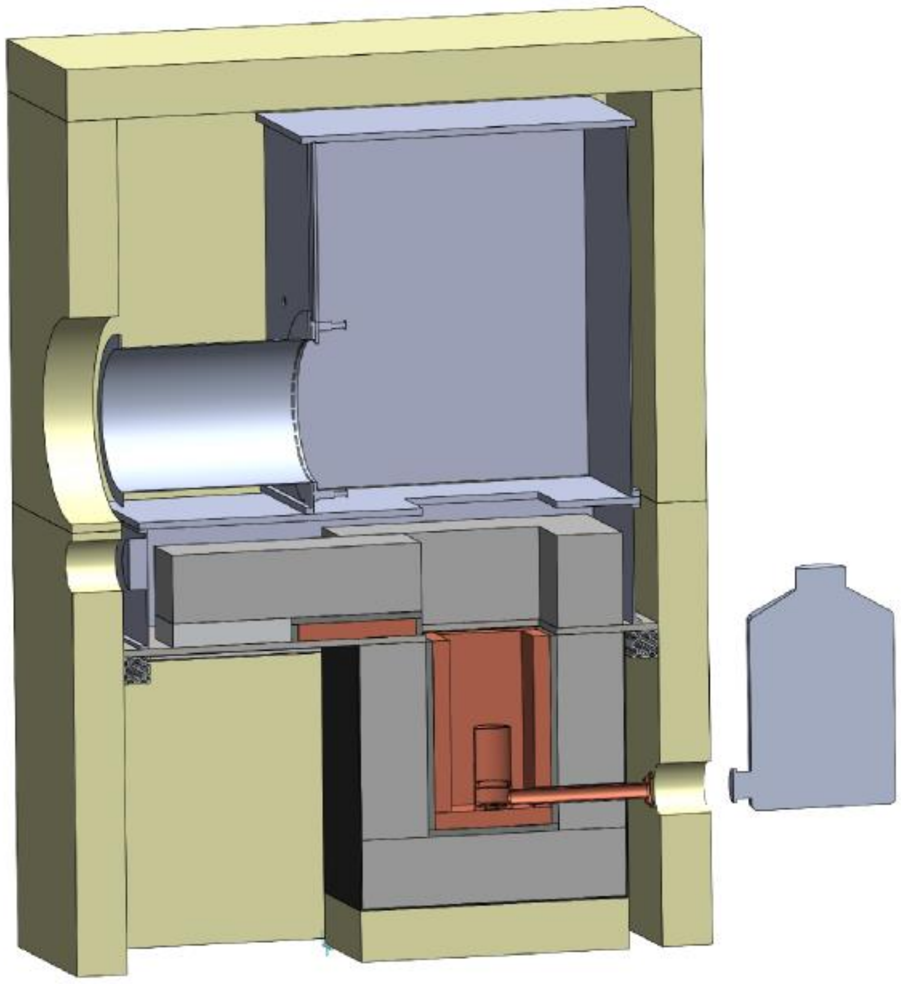
  → need different shield design to reduce contribution

- Simulations show that Pb210 contaminations in first two cm's of lead shield have the biggest impact (see table)

→ Replace first two cm of lead shield with a very pure layer

Layer	Percentage of total Pb210 contribution coming from layer (%)
0 – 1 cm	85 ± 4
1 – 2 cm	11 ± 1
2 – 3 cm	3 ± 1
3 – 4 cm	< 1
4 – 5 cm	< 1

Results: Suggested shield design with 2 cm of very pure lead as inner layer



- **2 cm layer of very pure Pb as inner shield**:

  Assuming 0.5 Bq/kg Pb210 in new inner layer and 10 Bq/kg in outer layer

→ Reduction of Pb210 contribution to (3.12 ± 0.59) cts/d/kg in the interval [40, 2700] keV

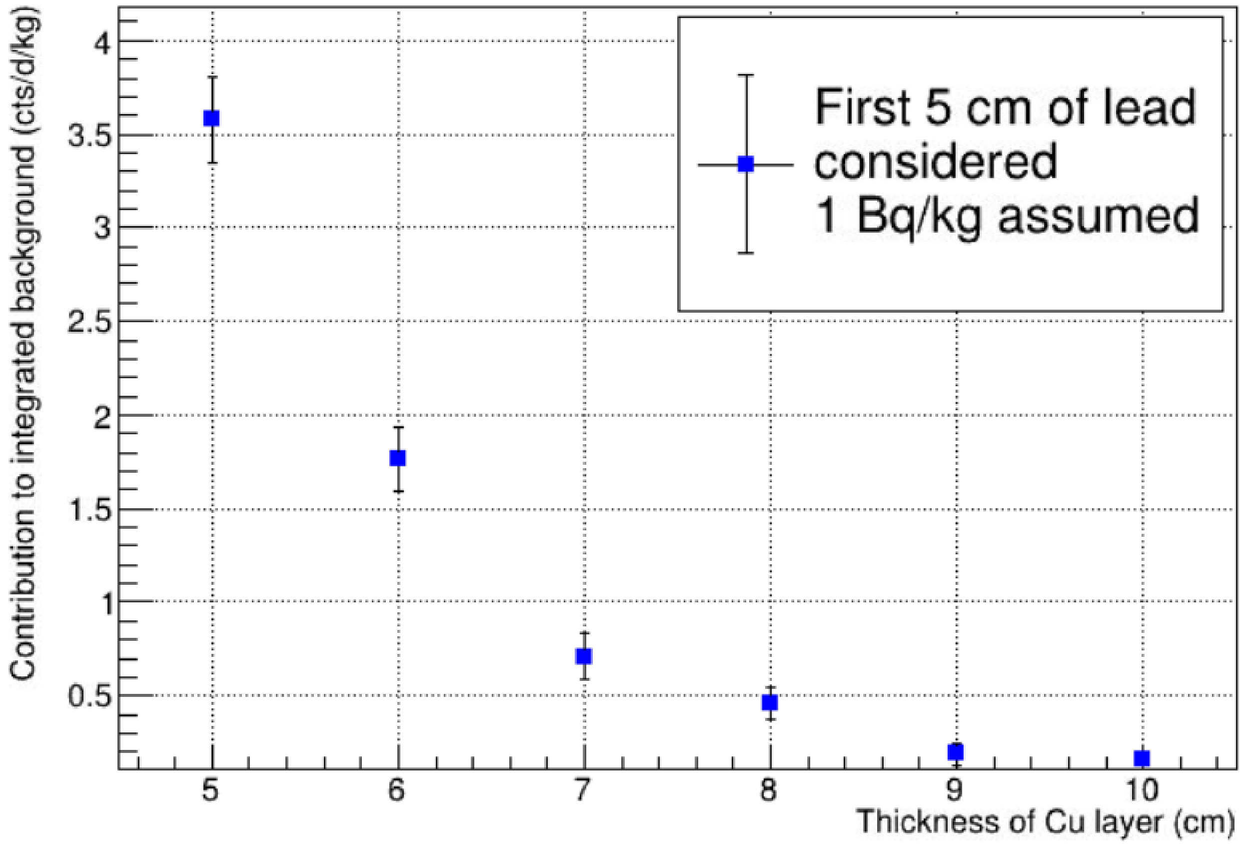
Results: Possible ways to reduce contribution from Pb210 in lead shield

- Another possible way to decrease the contributions from Pb210 in the lead shield:

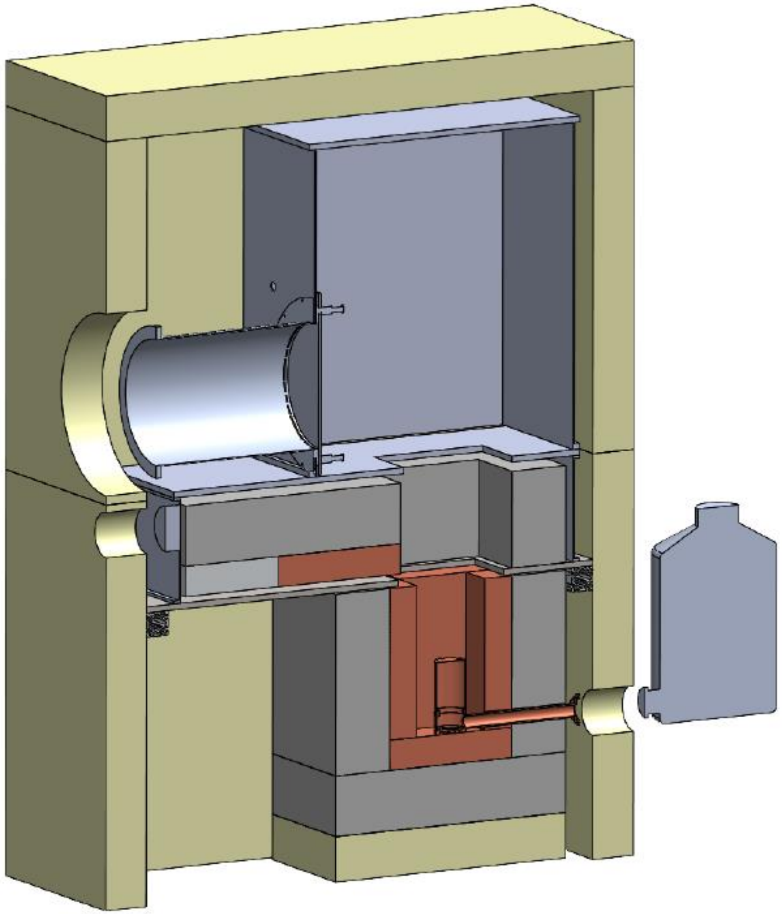
  Increase of the thickness of the ultra clean copper layer

- Increase of the thickness of the copper layer to 10 cm

  → Reduction of the background contribution from Pb210 in the lead shield to (1.60 ± 0.40) cts/d/kg (assuming 10 Bq/kg Pb210 in the lead shield)



Results: Suggested shield design with 10 cm copper layer



- **10 cm copper layer:**

  Assuming 10 Bq/kg Pb210 in lead shield:

  → (1.60 ± 0.40) cts/d/kg in the interval

BUT: thicker copper layer also leads to increase in background contributions from contaminations in the copper

- Assuming typical values for contaminations of copper with a high radio-purity (including Th232, U238, K40, Co60):

  → Contributions from 5 cm copper layer:

  (11.3 ± 0.9) cts/d/kg

  → Contributions from 10 cm copper layer:

  (13.6 ± 1.2) cts/d/kg

Summary and outlook

- **Simulation of background components of GeMPI detectors:**

  - Pb210 in lead shield is main background source (~ 60%)
  - Muon contributions are very small (1% – 3%)
  - Neutrons contribute up to 15%

- **Consequences for future GeMPI generations:**

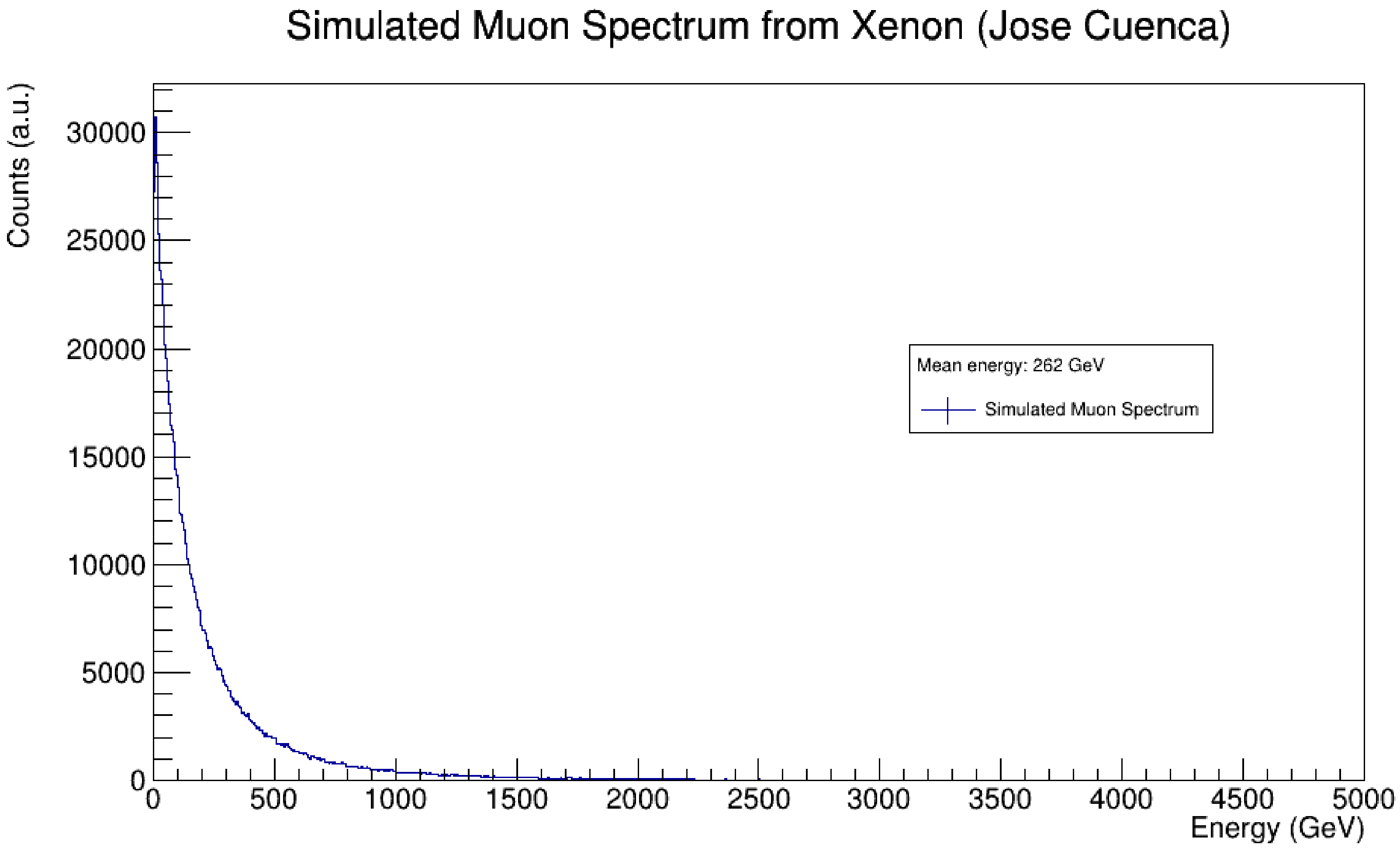
  - 2 new possible shield designs to reduce influence of Pb210 in lead shield: 10 Cu layer or 2 cm inner layer of very pure lead (or combination of both designs)
  - 15 cm layer of pure PE as neutron shield
  - no muon veto necessary
  - Background count rate of 15 cts/d/kg between 40 keV and 2700 keV seems feasible (GeMPI 3: 24 +- 1 cts/d/kg)

- **Next steps:**

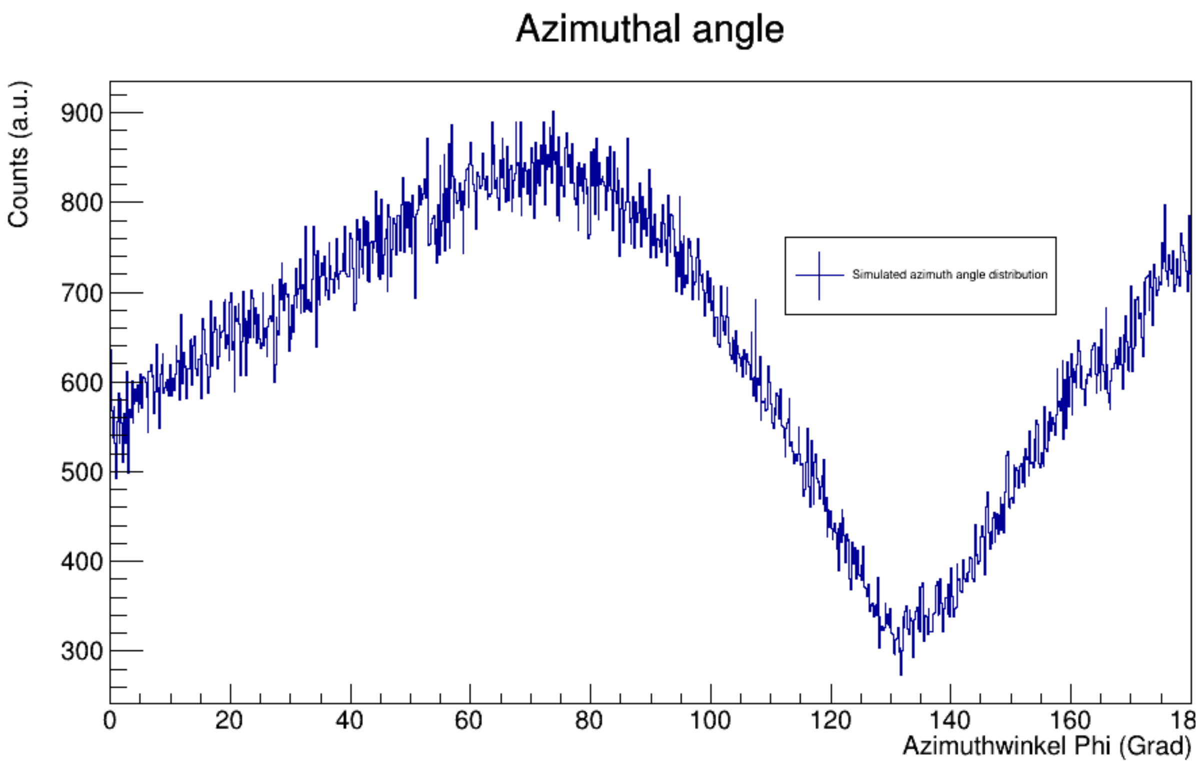
  - Procurement of radio pure Pb & Cu
  - Work on shield and detector design of a new material screening station at LNGS

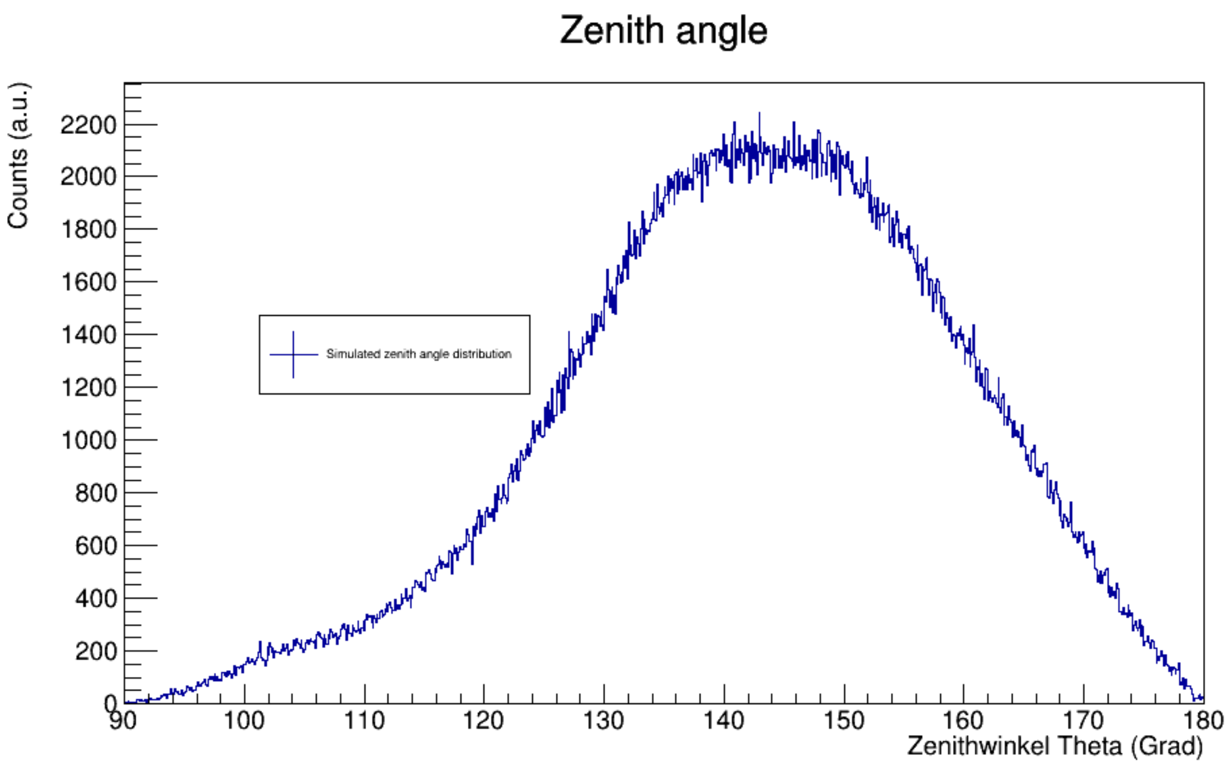
BACK - UP

Energy distribution of muons in the LNGS laboratory

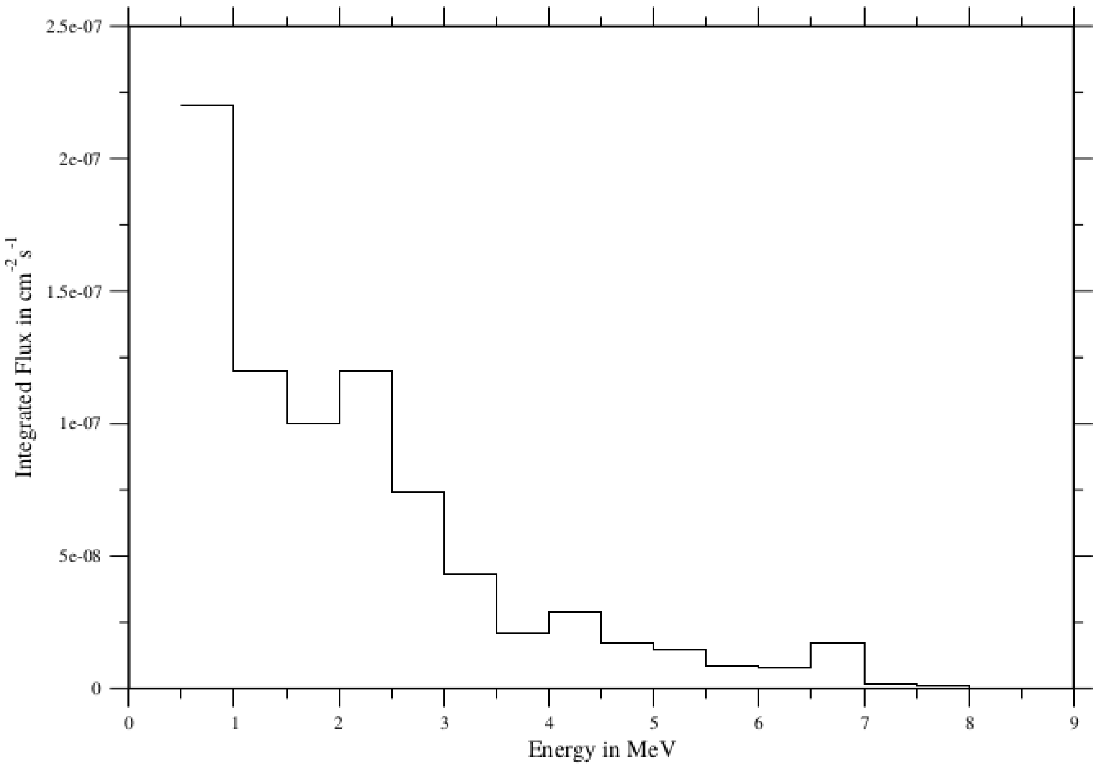


Angular distribution of muons in the LNGS laboratory

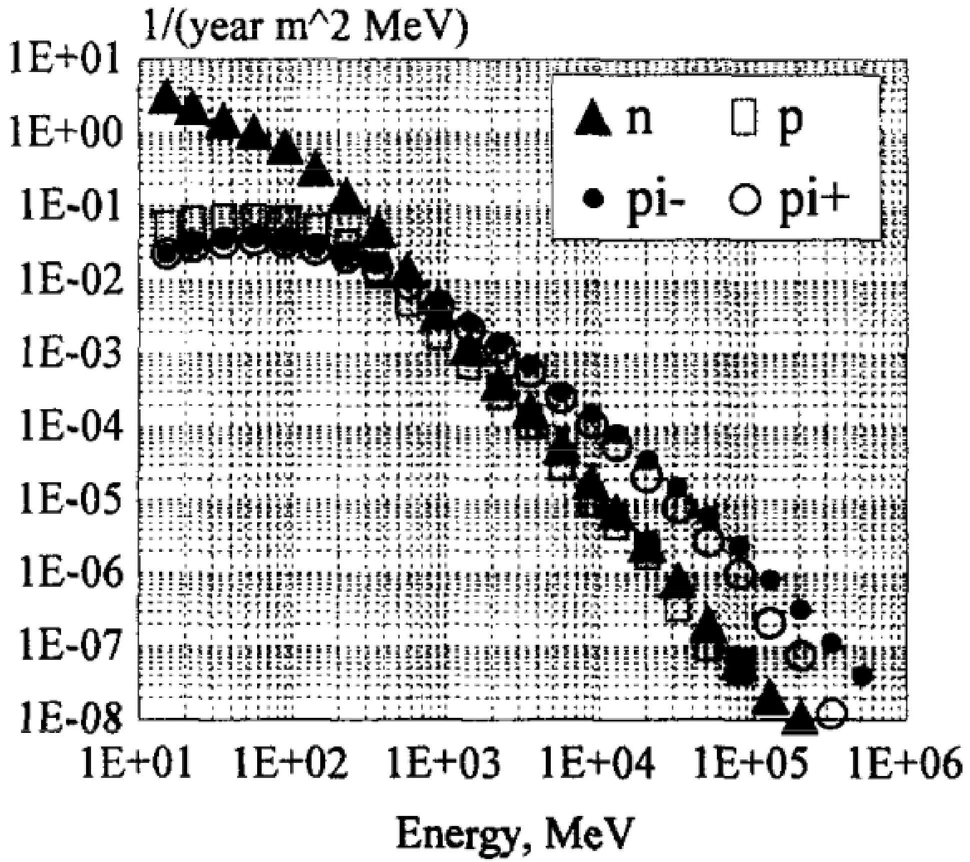




Energy distribution of neutrons in the LNGS laboratory

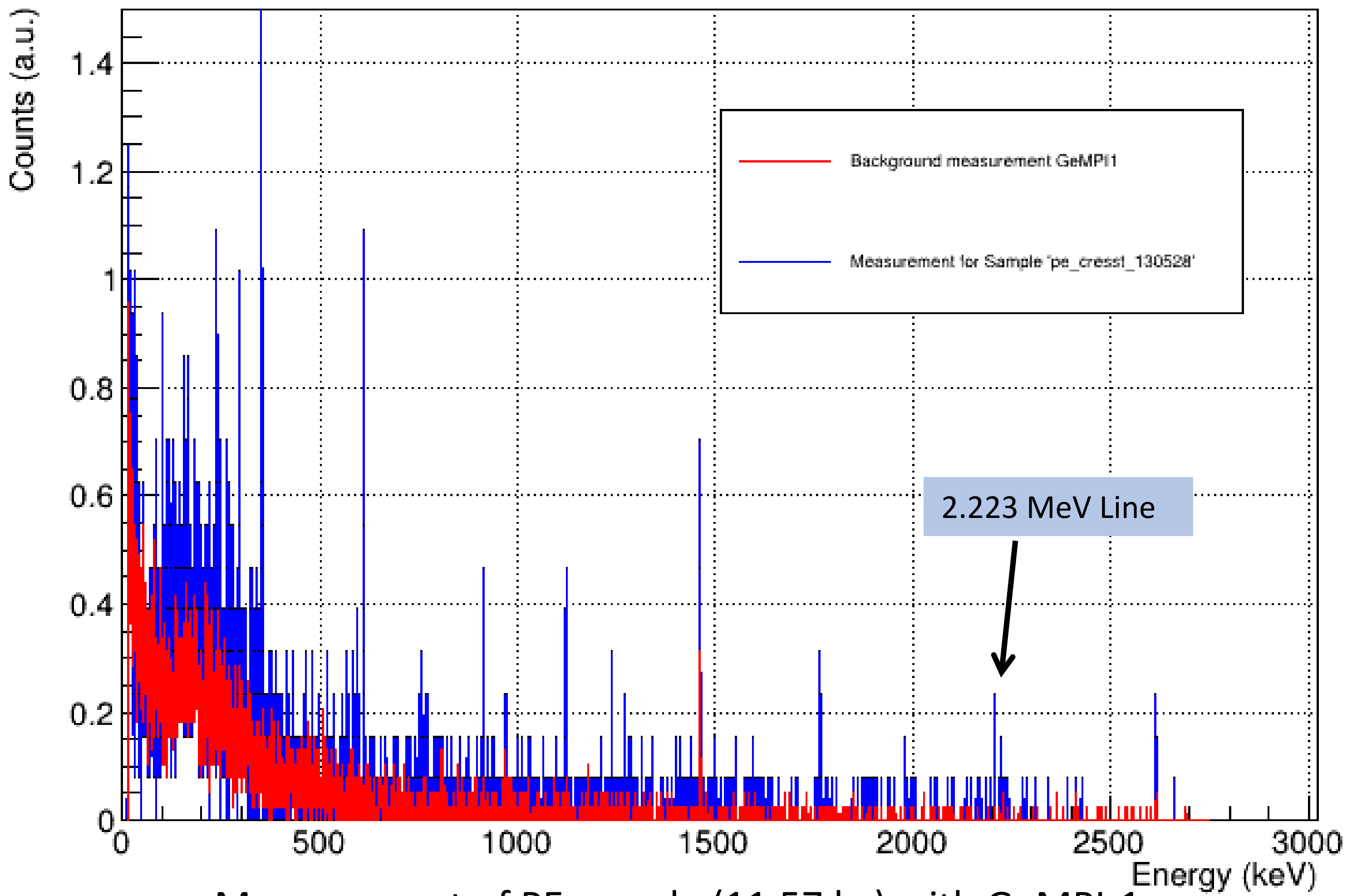


Neutrons from nat. radioactivity



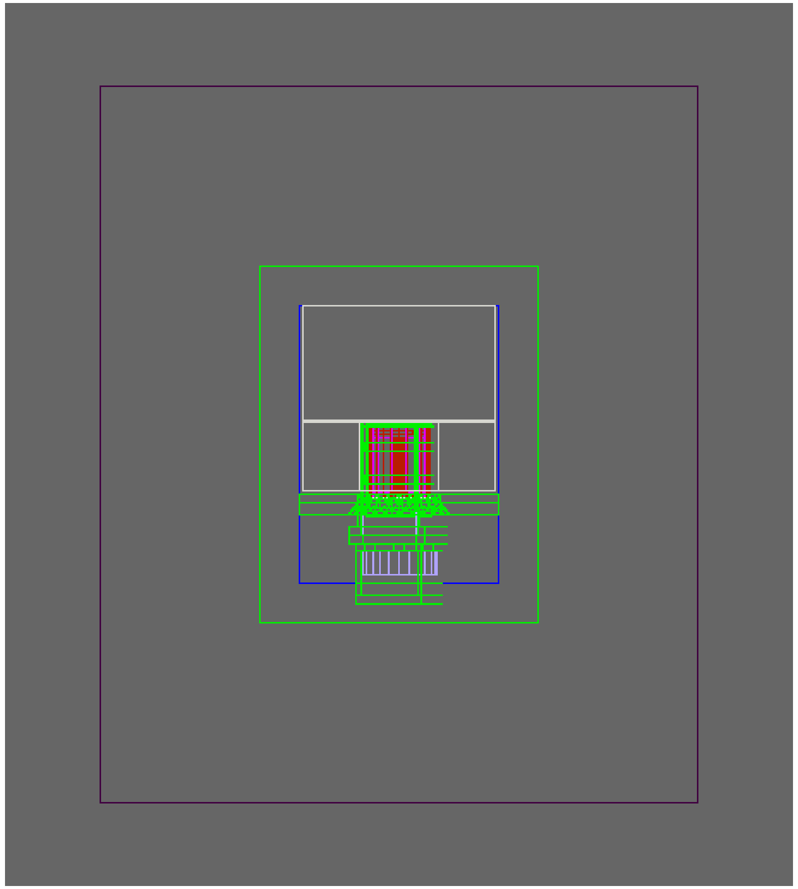
Muon-induced neutrons

Determination of flux of neutrons from nat. radioactivity



Measurement of PE sample (11.57 kg) with GeMPI-1 for Cress-Experiment

→ 2.2 MeV line is induced by neutron capture in PE



PE sample (white) in MaGe geometry

PE-Sample – Measurement and simulation

	Counts in 2.223 MeV line $(d^{-1}kg^{-1})$	Part of measured value (%)
Measurement	0.095 ± 0.058	
Muon-induced neutrons (shield)	0.003 ± 0.001	3.16 ± 1.05
Muon-induced neutronen (rock)	0.0002 ± 0.0001	0.21 ± 0.11
Neutrons from nat. radioavtivity*	0.058 ± 0.003	61.05 ± 3.16

*simulated with $0.7 * 10^{-6} \frac{n}{s\ cm^2}$

→ Remaining counts in line have to be induced by „missing“ flux from neutrons from natural radioactivity

→ Can be used to indirectly determine this „missing“ flux

→ Factor (1.6 ± 1.0) for flux of neutrons from nat. radioactivity

Increase of thickness of copper layer

Isotope	Assumed activity [µBq/kg]	Background contribution for 5 cm Cu layer [counts/d/kg]	Background contribution for 10 cm Cu layer [counts/d/kg]
^{60}Co	33	3.8 ± 0.3	5.2 ± 0.5
^{238}U	16	1.9 ± 0.1	2.1 ± 0.1
^{232}Th	19	4.8 ± 0.4	5.4 ± 0.5
^{40}K	88	0.8 ± 0.1	0.9 ± 0.1
Total	-	11.3 ± 0.9	13.6 ± 1.2

Composition of Bkg. Spectrum of GeMPI 3

Source	Integrated background count rate [40, 2700] keV [cts/d/kg]	Percenatge of detector background [%]
Muons	0.8 ± 0.1	3.3 ± 0.6
Neutrons	3.1 ± 2.0	12.9 ± 8.2
^{210}Pb in lead shield	13.0 ± 1.0	54.0 ± 4.0
^{60}Co in copper	3.3 ± 0.9	13.6 ± 3.7
^{238}U in copper	1.8 ± 2.2	7.5 ± 9.0
^{232}Th in copper	0.6 ± 0.3	2.3 ± 1.2
^{40}K in copper	1.6 ± 0.5	6.7 ± 2.2
^{207}Bi on crystal surface	2.0 ± 0.5	8.3 ± 2.1
Total	26.2 ± 7.5	108.6 ± 30.0

References

[1] „Low level germanium gamma-ray spectrometry at the µBq/kg level and future developments towards higher sensitivities“ - Heusser G., M. Laubenstein, H. Neder

[2] „The neutron background of the XENON100 dark matter experiment“ – XENON collaboration

[3] „Production and transport of hadrons generated in nuclear cascades initiated by muons in rock“ - A. Dementyev, V. Gurentsov, O. Ryazhskaya, N. Sobolevsky

[4] „Neutron Flux at the Grand Sasso Underground Laboratory Revisited“ - H. Wulandari, J. Jochum, W. Rau, F. von Feilitzsch

[5] „MAGE- a GEANT4-based Monte Carlo framework for low-background experiments” – Yuen-Dat Chan, Jason Detwiler, Reyco Henning, Victor Gehmann