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CHARACTERISATION OF THE NATURAL GAMMA-RAY BACKGROUND IN THE UNDERGROUND CALLIO LAB FACILITY

V. Gostilo¹, A. Sokolov¹, S. Pohuliai¹, J. Joutsenvaara²

¹Baltic Scientific Instruments, Ramulu Str. 3, LV-1005, Riga, Latvia

²Kerttu Saalasti Institute, University of Oulu, Pajatie 5, 86800 Nivala, Finland

HIGHLIGHTS

- The measurement results of the gamma-background in underground facility at a depth of 1430 m are presented.
- Two HPGe spectrometers, CdZnTe clustered (6400 mm³) and CeBr₃ (2''x2'') spectrometers were used.
- Gamma-background count rate in the energy range of 40 keV to 2.7 MeV has made to be 0.095 s⁻¹·kg⁻¹.
- The specific activities of walls rock and concrete and minimum detectable activities of some nuclides are determined.

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V. Gostilo^{*1}, A. Sokolov¹, S. Pohuliai¹, J. Joutsenvaara²

¹Baltic Scientific Instruments, Ramulu Str. 3, LV-1005, Riga, Latvia

²Kerttu Saalasti Institute, University of Oulu, Pajatie 5, 86800 Nivala, Finland

Abstract

Herein, we measured the natural gamma-ray background in a new underground laboratory facility within Pyhäsalmi Mine in Finland at a depth of 1430 m (~4100 m.w.e). The radionuclide compositions of the rocks in the walls along with the shotcrete on the walls were investigated. The specific activities of the natural radionuclides in these materials were calculated. The measured spectra of the natural gamma-ray background and calculated minimal detected activities of several natural and artificial radionuclides are presented.

Keywords: HPGe spectrometry; gamma-ray background; underground laboratory

^{*}Corresponding author: Vladimir Gostilo, E-mail: office@bsi.lv

1. Introduction

Modern scientific experiments related to the search for dark matter, double beta decay, the properties and interactions of neutrinos and many other fundamental processes involve the registration of very rare phenomena. Thus, these experiments require extremely low detector background levels (i.e. spurious signals that can mimic the signals being measured) [1-5].

For a semiconductor or scintillation detector used on the Earth's surface, the background is determined by three factors, cosmic radiation, environmental radioactivity (i.e. the natural radioactivity of the uranium and thorium families) and the instrumental background, which is determined by the radioactive contamination of the detector and its surrounding construction materials [5-7]. The most effective strategy to eliminate cosmic radiation is to place the instrument below the Earth's surface at a depth from tens to thousands of meters water equivalent.

Globally, there are over 20 underground laboratories at depths ranging from hundreds of meters up to 2 km [4-7].

With a maximum depth of 1,444 m, Pyhäsalmi Mine, located in Finland, is the deepest base metal mine in Europe [8]. Zinc, copper, gold and silver have been mined in Pyhäsalmi Mine since 1962, and mining activities are projected to end in 2019. Various possibilities for the continued use of the mine are currently being considered while mining operations continue. Pyhäsalmi Mine is an ideal site for an underground nuclear laboratory as its depth would be equal to the average thickness of the mountain above the Gran Sasso National Laboratory (LNGS) (1.4 km) [9].

Pyhäsalmi Mine currently houses Callio Lab, a new laboratory facility for underground research development and innovation. However, to transform the underground mine at a depth of 1430 m into a full-fledged research laboratory, it is necessary to: (1) analyse the mine for radiation that contributes to the background level; (2) provide the required low-background

infrastructure in the underground laboratory; and (3) equip the laboratory with the appropriate nuclear-physical equipment [7,10 -19].

In the framework of the Baltic Sea Underground Innovation Network (BSUIN) [20], the purpose of this study was to characterise the gamma-ray background at the Callio Lab facility to determine the information that can be provided in future nuclear physics experiments.

2. Brief description of the Callio Lab underground facility

The Pyhäsalmi Mine has numerous spaces/caverns at a variety of depths. Callio Lab is a new laboratory space (Fig. 1) at a depth of 1430 m (~ 4100 m.w.e) [21, 22]. The experimental hall has an area of 120 m², and its height ranges from 5.0–7.5 metres. The total volume of Callio Lab is approximately 800 m³. The rock temperature within the lab is around 26°C, and the relative humidity is kept at 50%–55% using dehumidifiers.

Fig. 1. Image of Callio Lab in Pyhäsalmi Mine, Finland.

Callio Lab has air conditioning; air extraction and forced ventilation in/from the outside is provided with an intake of 10 m³/s. The floor is reinforced to support heavy shielding. The bare rock that makes up the walls of the lab contains copper–zinc ores [60%–90% pyrite with

inclusions of sphalerite (5%) and chalcopyrite (2.5%)] with an average density of 2.8 g/cm^3 . The walls are covered by shotcrete with a thickness of about 10 cm with a tolerance of a few centimeters. The decline access provides a quick and safe way to transport heavy and/or large objects and bulk materials into and out of the facility.

3. Materials and methods

3.1. Low-background HPGe spectrometer

Possessing own production of HPGe detectors [23], we developed and manufactured a low-background HPGe gamma spectrometer for measurements in Callio Lab (Fig.2). When developing this spectrometer, we pursued two goals: (1) provide the necessary measurements to characterise the gamma-ray background in Callio Lab as part of the BSUIN project; and (2) allow various routine measurements necessary for the production of low-background equipment and scientific research in underground conditions.

The developed HPGe spectrometer is based on a p-type crystal with a 50% detection efficiency (in comparison with NaI 3x3"). The instrument is cooled by a Stirling electric cooler, eliminating the need for the transport of liquid nitrogen to the underground laboratory. The spectrometer provides energy resolutions of 1.20 and 1.95 keV at energies of 122 and 1332 keV, respectively. The HPGe crystal and the detector were transported from the corresponding manufacturers to Callio Lab via ground transportation to reduce activation by cosmic radiation. The cover ($D = 93 \text{ mm}$) and all internal parts of the cryostat are constructed of certified radiation-pure materials. Copper and aluminium were applied (content U+Th has not exceed $1 \text{ } \mu\text{g/kg}$).

Fig. 2. Image of the low-background HPGe gamma spectrometer installed at Callio Lab.

Passive shielding is carried out by a typical industrial lead shield that we produce on a large scale. The shield is made of certified lead with a radiation purity of <10 Bq/kg (Certificate of Berlin The National Metrology Institute). The wall thickness in the lead shield is 100 mm, the thickness of the copper inserts that suppress the shield's own lead lines is 9 mm, and the thickness of the tin coatings on the copper inserts is 0.3 mm. The dimensions of the protective chamber ($D = 210$ mm; $H = 435$ mm) allow Marinelli beakers to be used for measurements with volumes ranging from 1 to 4 L. The lid of the lead shield is opened and closed by an electro-mechanical transfer device. The spectrometer is fully automated and allows access all long-term measurements to be controlled using Spectra Line software [23]. The spectrometer can be remotely operated from an external laboratory over the Internet. The design of the protective chamber allows it to be filled with a radiopure gas for the duration of the measurements to eliminate the effect of radon. Additional passive or active shielding can be installed on the spectrometer body, if necessary.

3.2. Portable spectrometers

In addition to the stationary low-background HPGe spectrometer, we used the following three portable spectrometers in this study which were equipped with software and allowed all necessary analyses of radionuclides to be conducted on-site at Callio Lab (Fig. 3):

a) A portable HPGe spectrometer (NitroSPEC) [22] containing a planar detector with an area of $\sim 1500 \text{ mm}^2$ and a thickness of 19.5 mm. The energy range of registration is 30–2700 keV, the energy resolution is 0.60 keV (122 keV), and the spectrometer mass is 5.9 kg.

b) A Clustered CdZnTe gamma-radiation spectrometer (MultiSPEC-6000) [23]. The total volume of CdZnTe (CZT) detectors in the spectrometer is 6400 mm^3 . The cluster comprises an assembly of four serial $\mu\text{SPEC-1500}$ spectrometers contained by a special holder. All the $\mu\text{SPEC-1500}$ spectrometers work in parallel, creating one common spectrum. The energy resolution (FWHM) is $<1.5\%$ at 662 keV, the energy range is 20 keV to 3.0 MeV, the dimensions are $66 \text{ mm} \times 75 \text{ mm} \times 88 \text{ mm}$, and the mass is 540 g.

c) A scintillation spectrometer (BDEG-51-51-CeBr₃) [23] that contains a CeBr₃ crystal with dimensions of $2'' \times 2''$ (CapeSym, USA), a photomultiplier (R6231; Hamamatsu, Japan), and a removable electronics unit (Baltic Scientific Instruments, Latvia). The energy range and energy resolution of the spectrometer are 30–3000 keV and $\sim 4.0\%$ (662 keV), respectively. The dimensions of the spectrometer are $\varnothing 75 \text{ mm} \times 250 \text{ mm}$, and the mass is 1350 g.

Fig.3. The set of portable gamma spectrometers used for measurements in Callio Lab: a) portable HPGe spectrometer (NitroSPEC); b) clustered CdZnTe spectrometer (MultiSPEC-

6000); and c) scintillation spectrometer (BDEG-51-51-CeBr₃). The relative size ratios between the different spectrometers are preserved.

4. Results and discussion

4.1. Background measurement using the portable spectrometers

As a first step, the background radiation level in Callio Lab was examined using the NitroSPEC, MultiSPEC-6000 and BDEG-51-51-CeBr₃ portable spectrometers. Both HPGe [7, 10–15] and scintillation [17,19] detectors have been used to characterise the background levels in underground facilities. We used CZT detectors in this study for two reasons: (1) increased efficiency of registration of clustered CZT detectors; and (2) improved resolution. The detectors of all spectrometers were non-collimated. The spectrometers were installed side by side at the height of 1 m from the floor. The measurement time ranged from 16 to 24 h. The measurements were carried out sequentially at four locations in the laboratory (MP1-MP4 in Fig.4).

Fig. 4. Positions of measurement points (MP) in the Callio Lab (top view): MP1–MP4: NitroSPEC, MultiSPEC-6000 and BDEG-51-51-CeBr₃ spectrometers; MP5: LB HPGe spectrometer; MP6: NitroSPEC spectrometer (rock); and MP7: NitroSPEC spectrometer (shotcrete).

Fig.5 shows the natural gamma-ray background spectra, reduced to count rate, measured

at points MP1–MP4 (Fig.4) in Callio Lab using the NitroSPEC, MultiSPEC-6000 and BDEG-

51-51-CeBr₃ portable spectrometers.

Fig.5. In situ gamma-spectra at different locations in Callio Lab. Vertical axis – counts per day per keV, horizontal axis – energy, keV. (— NitroSpec, — CZT, — CeBr₃).

The measured background spectra can be attributed to the lines of natural uranium-radium, thorium, potassium, and their daughters. Table 1 shows the integral count rates for all three spectrometers at the different measurement points. The integral counting rates differed slightly from point to point, which is largely attributed to the fact that the detectors were not collimated, and radiation was recorded from all directions (practically from the solid angle 4π).

Table 1. Integral counting rates of the three portable spectrometers

	HPGe Count rate, s ⁻¹ 30-2700 keV	CZT Count rate, s ⁻¹ 30-2700 keV	CeBr₃ Count rate, s ⁻¹ 30-3000 keV
MP1	135	61	365
MP2	134	59	366
MP3	136	64	374
MP4	138	64	394

Comparing the FWHM lines of the ⁴⁰K recorded with CZT and scintillation detectors indicates that the CZT detector has better resolution than scintillation detector spectrometer. However, the detection efficiency of the CZT detector was obviously lower than that of the scintillator; thus, the scintillator resulted in a higher counting rate (approximately six times higher; Table 1) in almost the entire energy range.

4.2. Background measurement using the low-background HPGe spectrometer

A low-background HPGe spectrometer was installed at point MP5 (Fig. 4). The background spectra were first collected with the lid of the HPGe detector's lead shield open (acquisition time: 21 h) and then with it closed (150 h). The background spectra collected with the lid

open and closed are shown in Fig. 6, and the count rates of the main lines of the background spectra are shown in Table 2.

Fig. 6. Gamma-ray background spectra measured using a HPGe spectrometer with the shield lid open and closed.

The counting rates of the background lines (Fig.6 and Table 2) clearly depend on the efficiency of detection of the HPGe detector and the quality of protection. Typically, the

integral background count rate in the energy range from 40 keV to 2.7 MeV normalised to the HPGe crystal mass is used to compare data collected using different detectors [11,16]. In Ref. [11], the normalised integral background count rate was $0.034 \text{ s}^{-1} \cdot \text{kg}^{-1}$; in this study, for a detector with a mass of 1.0 kg, the value was $0.095 \text{ s}^{-1} \cdot \text{kg}^{-1}$. It should be underlined that the device of [11] is Ultra-low background and the device of the present work is only Low-background with typical industrial shielding

Table 2. Counting rates of the main lines in the background gamma-spectra with the shield lid open and closed

		Open		Closed	
Nuclide	Energy, keV	Count rate, s^{-1}	Uncertainty, %	Count rate, s^{-1}	Uncertainty, %
^{212}Pb	238.19	0.23	2.2	0.011	3
^{214}Pb	296	0.09	3.9	0.013	3
^{214}Pb	351.96	0.17	2.6	0.022	1.9
^{208}Tl	510.77	0.09	3.7	0.004	6.1
^{208}Tl	583.35	0.12	2.5	0.003	5.8
^{214}Bi	609.47	0.18	2.1	0.018	2.1
^{214}Bi	768.26	0.02	9.2	0.002	8.6
^{228}Ac	911.07	0.09	2.9	0.0003	37
^{214}Bi	1119.96	0.06	3.7	0.004	5
^{40}K	1460.97	0.47	1.2	0.008	3.3
^{214}Bi	1764.02	0.06	3.2	0.005	3.8
^{208}Tl	2614	0.1	2.4	0.005	3.54
	Total	1.67	2.4	0.095	3.2

The effectiveness of passive shielding depends on the task at hand. If ultra-low background levels are required, it is possible to suppress the background by 4–5 orders of magnitude [7,18]. As shown in Fig. 6 and Table 2, our typical industrial lead shield reduced the total count rate by 17 times compared to the spectrum collected with the shield lid open. Estimating the counting rates with the lid open and closed, we actually estimate the effectiveness of not the entire protection, but only parts of it in a solid angle 0.47π steradians, to which the lid opens the detector inside the protection. Rough estimation shows that if we expand the solid angle to 4π and estimate the background counting rate along the reduced lines (column 3), we obtain a total counting rate on the order of $20 \text{ s}^{-1} \cdot \text{kg}^{-1}$. Thus,

the typical industrial shield used in this study reduced the background by more than 200 times in the energy range of 40 keV to 2.7 MeV.

4.3. Radon effect

Numerous experiments [7,16,18,19] have shown that the gamma-ray background in underground laboratories depends on the level of radon in the air. Radon penetrates into all parts of the equipment, resulting in worse background characteristics. To eliminate this issue, we designed the spectrometer to allow the lead shield chamber around the detector to be filled with radiopure gas, thereby displacing radon and its decay products. In this study, we filled the chamber volume with pure nitrogen evaporated from a Dewar vessel. Table 3 shows the effect of nitrogen purging on the count rate for the peaks in the gamma-ray spectra at different energies.

Table 3. Counting rates of peaks with different energies with and without nitrogen purging

	Without purging Count rate, s ⁻¹	With purging Count rate, s ⁻¹	decreasing %
296 keV (²¹⁴ Pb)	0.013	0.012	7.7
351.96 keV (²¹⁴ Pb)	0.022	0.021	4.5
1119.9 keV (²¹⁴ Bi)	0.044	0.041	6.8
1764.02 keV (²¹⁴ Bi)	0.005	0.005	0

Purging with nitrogen reduced the count rate of the lines associated with radon/thoron by an average of several percents (up to 7.7%). The minimum detectable activities (MDA) [25], at measurement time 150 h, of natural and artificial nuclides calculated from the background spectra were also reduced by approximately the same amount (Table 4).

Table 4. Minimum detected activities (MDA) of natural and artificial nuclides

Nuclide	MDA, Bq/kg without purging	MDA, Bq/kg with purging,
⁶⁰ Co	0.019	0.018
¹³⁷ Cs	0.013	0.012
⁵⁴ Mn	0.013	0.013

^{226}Ra	0.072	0.071
^{232}Th	0.033	0.032
^{134}Cs	0.011	0.011
^{152}Eu	0.025	0.024
^{241}Am	0.067	0.067
^{40}K	0.8	0.77

Taking into account the high radon level (50–300 Bq/m³) in Callio Lab [224], we expected a more significant decrease in gamma-ray background level after purging the spectrometer with pure nitrogen. However, the flow of nitrogen during the purge was only 12.5 L/day (natural evaporation from the dewar vessel), and the volume of the filled chamber was 9 L. Thus, this low flow rate was not sufficient to properly ventilate the protective chamber. The purge rate in Ref. [7] was much higher -2 L/h; however, the authors did not discuss the effect of nitrogen purging on the count rate. In future experiments, we will more thoroughly investigate the effects of gas purging at higher flow rates, including pulsed blowing.

More detailed studies on the radon concentration in Callio Lab are also needed since the reported radon level (50– 300 Bq/m³) [22] is at least 10–15 times higher than that in LNGS [26]. It is known as well that the radon-level in a lab generally varies quite a lot. It is very different in different locations. Therefore a (long) time-series of the radon-concentration is important. All these issues will be studied in our future research.

5. Underground materials measurements and discussion

Initial measurements were carried out using the NitroSpec spectrometer. The planar HPGe detector was applied in these measurements to obtain the low-energy-range spectra of the wall rock and coating. Two measurements were done. First, the spectrometer was installed at a shotcrete-free recess section of the wall (point MP6, Fig. 4). Second, the detector was mounted close to the wall in an area lined with shotcrete (point MP7, Fig. 4). The low-energy part of the rock spectrum (10 to 200 keV) is shown in Fig. 7. This spectrum was acquired over at least 18 h.

Fig. 7. Gamma-ray spectrum of the rock wall in Callio Lab without shotcrete coating.

As shown in Fig. 7, the background has a clear hump with an apex in the energy range of 80–95 keV. Peaks with energies of 74.8, 77.14, 84.37 and 87.35 keV are located at the top of the hump. These peaks are attributed to the presence of radionuclides of natural origin (i.e. thorium, radium, and their daughter decay products). Peaks with energies of 46.64 and 63.23 keV are visible on the left side of the hump and can be quantified if necessary. Peaks with lower energies are not visible due to the total level of Compton scattering.

A more precise radionuclide analysis of the wall materials in Callio Lab was carried out using a low-background HPGe spectrometer. Pieces of wall rock were crushed to sizes of approximately 5 mm and placed in a 1.5 L Marinelli beaker. Subsequently, they were kept in a sealed package for approximately one month to obtain a balance between the decay products of radon and thoron. The shotcrete covering the walls of Callio Lab was analysed in the same way. To measure the activities of the rock and covering material, the spectrometer efficiency curve was calibrated against a reference material representing a mixture of the radionuclides ^{241}Am and ^{152}Eu (OMACH N2/2003, density = 1 g/cm^{-3} , uncertainty = 3%). The measured spectra are shown in Fig. 8. Table 5 lists the resulting specific activities.

Fig. 8. Spectra of shotcrete and rock acquired by a low-background spectrometer

Table 5. Specific activities of radionuclides in shotcrete and rock

Nuclide	Shotcrete, Bq/kg	Rock, Bq/kg
Ra-226	162±14.5	83±7.47
Th-232	100±11	47.6±5.2
K-40	1171±257	1513±333

The specific activities of natural nuclides in the shotcrete covering were higher than those of the wall rock. ^{232}Th and ^{226}Ra in shotcrete exceeded those in rock by a factor of 2, while the specific activity of ^{40}K in shotcrete was a 23% less than that in rock. These results are supported by the findings of Ref. [21], which reported that cement with relatively high

additive activities was used to coat the walls of Callio Lab (^{40}K - 140 Bq/kg; ^{226}Ra - 160 Bq/kg; ^{232}Th - 240 Bq/kg). A similar finding was reported in Ref. [16], where shotcrete was the main source of the environmental gamma-ray background.

6. Conclusions

Based on measurements made with a low-background HPGe spectrometer in the underground Callio Lab facility, we determined the integral gamma-ray background count rate in the energy range of 40 keV to 2.7 MeV to be $0.095 \text{ s}^{-1} \cdot \text{kg}^{-1}$. The minimum detectable activities of some natural and artificial nuclides were less than 0.071 Bq/kg (^{226}Ra), 0.77 Bq/kg (^{40}K) and 0.012 Bq/kg (^{137}Cs).

The specific activities of natural nuclides in the shotcrete covering the walls of the hall were higher than those in the rock: 100.3 Bq/kg (^{232}Th), 161.7 Bq/kg (^{226}Ra) and 1171 Bq/kg (^{40}K) in the shotcrete covering and 47.6 Bq/kg (^{232}Th), 83.1 Bq/kg (^{226}Ra) and 1513 Bq/kg (^{40}K) in the rock.

In general, the results of this study confirm that the level and energy spectrum of background gamma radiation in the underground Callio Lab facility within the studied energy range is defined mainly by the composition of the walls of the laboratory.

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Vladimir Gostilo, Alexander Sokolov, Serhii Pohuliai, Jari Joutsenvaara

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