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Development of an underground low background instrument for high sensitivity measurements

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Abstract.
The Center for Underground Physics has developed in collaboration with CANBERRA a low background instrument composed of 14 HPGe detectors divided in two arrays facing each other. The performance and the background of a single detector of the array have been studied in order to improve the array final configuration. An accurate material selection, through the measurements of building material samples and Monte Carlo simulations based on Geant4, has been performed to reach the lowest possible intrinsic background. Alternative materials and configurations have been considered for the final design of the array simulating the expected intrinsic background of the instrument considering the needed changes. The expected sensitivity of the improved array configuration, concerning the low background material selection for rare events physics experiments, has been evaluated through Monte Carlo simulations considering ^{232}Th concentration in a Copper sample. Since the array can also be used for rare decays searches, the expected sensitivity on the ^{156}Dy resonant double electron capture has thus been calculated.

1. Introduction

Ultra low background gamma spectroscopy is continuously under development with the goal of reaching very high sensitivity and detection limits. High Purity Germanium detectors have a very good energy resolution and can be built using highly radio-pure materials achieving low intrinsic background, which consists of the count rate due to contaminations in the building materials. These features make the HPGe detectors suitable for the selection of materials with the lowest possible contaminations used for rare events physics experiments, furthermore the improvement in their development can be exploited also for rare decay searches. The detection efficiency can be increased using more detectors with the possibility to perform also measurements in coincidence when the isotope under study decays through gamma ray cascade, this is a very sensitive background reduction method. To further enhance the instrument sensitivity it is mandatory to place it underground.

2. The Array design

The gamma spectrometer that has been developed is an array of 14 HPGe detectors with 70% of relative efficiency arranged on two opposite plates, 7 for each plate, with a relative distance of 2.5 cm from each other. The two plates can move along the vertical axis in order to put

samples of various dimensions between the detectors. The Array will be placed at the YangYang underground Laboratory in South Korea: this facility is composed of two main tunnels, A6 and A5, located in the underground facility of a Pumped Storage Power Plant; it has a coverage of about 700 m which corresponds to 2000 m.w.e.. In the A5 tunnel, recently constructed and provided with a Radon free system, rare events physics experiments are also placed: AMoRE [1] searching for the neutrinoless double beta decay and KIMS [2] for the Dark Matter detection.
The design process of the Array started from an initial configuration with the following specifics:

- Copper plates holding the detectors;
- The external canister (End Cap) of each detector made of low background Aluminum;
- The inner layer closer to the crystal (Holder) made of low background Aluminum;
- An inner shielding for the contamination of the electronics parts;
- O-rings to seal the detectors on the plate;
- A shielding outside the End Cap to prevent the possible O-rings contamination to affect the background

Starting from this configuration the first work concerned the study of the intrinsic background of a single element of the array, a 70% HPGe detector provided by the manufacturer for this purpose. The intrinsic background, due to the contaminations of the materials composing the detector, has been studied paying particular attention to the primordial radionuclides: ^{232}Th chain, ^{238}U chain and ^{40}K.

2.1. HPGe detectors
In the A6 laboratory of the YangYang underground facility two HPGe detectors are installed: the single element of the array and a 100% HPGe, both p-type in coaxial configuration. The 100% HPGe has a dedicated shielding composed of 10 cm of Lead and an inner 10 cm thick layer of Copper. To further improve the instrument background a layer of 5 cm of Ancient Lead has been placed close to the detector; a Nitrogen fluxing system is also present to avoid Radon contamination when samples are changed. Its background between 30 and 2700 keV shows a rate of 25 counts/h/kg (Fig. 1). The 70% HPGe shielding is composed of a 10 cm external layer of Lead, a 777B CANBERRA shielding composed of 15 cm low background Lead and 4 cm of Copper closer to the detector. The instrument is equipped with a Nitrogen fluxing system; the background rate in the energy range 30-3300 keV is of about 24 counts/h/kg (Fig. 2).
The 100% HPGe has been used to perform the measurements of the 70% HPGe building materials in order to evaluate their internal contaminations. Samples of each part of the detector have been provided by CANBERRA and for each measurement the detection efficiency for the energy of the gamma lines under study has been evaluated through Monte Carlo simulations, based on Geant 4, in which the detector-sample configuration has been described in detail.

The most important materials, considering mass, quantity and distance from the crystal, and their measured contaminations are summarize in table 1.

It was possibile to evaluate a specific activity only for O-rings and the ^{232}Th contamination of the Aluminum sample; for the other materials and concentrations, the detection limits have been set with 90% of Confidence Level.

2.2. Intrinsic background evaluation
A long measurement of the single element background has been accurately analyzed to understand the origin of the visible gamma peaks: intrinsic contaminations, environmental radioactivity and neutron activation. To evaluate the contribution of the materials contamination to the measured background it is necessary to perform Monte Carlo simulations using a detailed reconstruction of the detector geometry. Combining the simulated detection

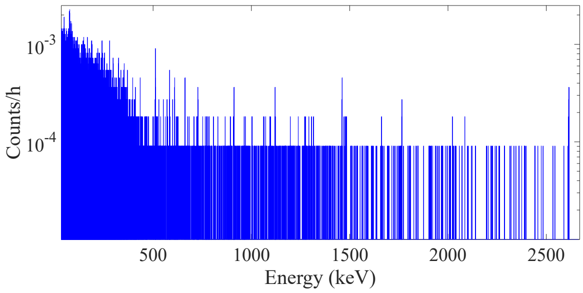

Figure 1. Background spectrum of the 100% HPGe.

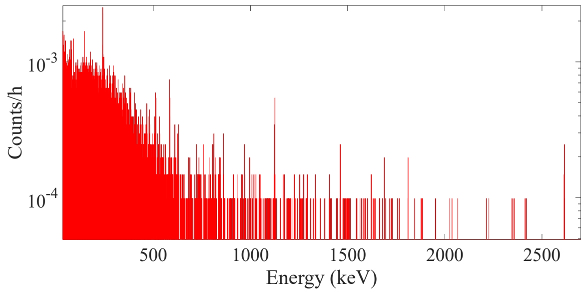

Figure 2. Background spectrum of the 70% HPGe.

Table 1. Measured contaminations of some materials.

Material	^{238}U(mBq/kg)	^{232}Th (mBq/kg)	^{40}K (mBq/kg)
O-ring	2536 ± 60	411 ± 27	2132 ± 307
Copper	< 0.57	< 0.55	< 5.87
Aluminum	< 0.52	1.94 ± 0.40	< 6
Lead	< 1.6	< 2.7	< 7.7

efficiency and the measured contamination it is possible to calculate the count rate of the considered gamma peaks due to each material activity. Considering the most prominent gamma line of the ^{232}Th chain, the comparison between the measured and the expected background counting rates shows that the intrinsic background is almost completely explained by Aluminum and O-ring contaminations as shown in Figure 3. The measured counts per day at the 2615 keV peak of ^{208}Tl are higher than expected: this gamma is indeed difficult to shield since it has a quite high energy and thus can be also ascribed to external radioactivity. Made exception for the O-rings, the concentration of Uranium was given as a detection limit, making the overall simulated count rate overestimated. Despite that, O-rings and Aluminum parts can be considered as the main contributors to the intrinsic background of the instrument also for this radioisotope (Fig 4).

3. Material Selection

In the initial configuration both the End Cap and the Holder were made of Aluminum, but since this material is one of the main sources of background two alternative configurations have been considered: one with the End Cap in Aluminum and the Holder in Copper and the other in which both End Cap and Holder are made of Copper. The former, thanks to the Aluminum lower density and the possibility to machine it in thin layers, would guarantee a lower detection threshold, the latter would provide a lower background having Copper a lower radioactive contamination. These two options have been compared through Monte Carlo simulations considering not only the expected count rate due to their contaminations but also the efficiency.

In order to perform the simulations the different geometries of the array has been accurately described, as shown in Figure 5, and the contribution from all the detectors, from each material and the overall background have been taken into account. The intrinsic background due to Copper is overestimated since the measured upper limits has been used for its evaluation. Despite the overestimation, the configuration using Copper for both the canisters is not showing a higher

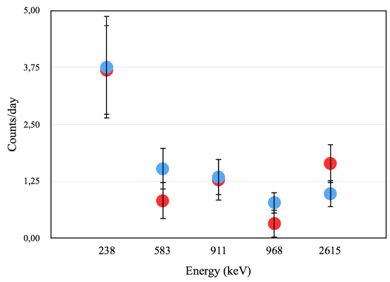

Figure 3. Comparison between the counts/day in the background measurement (red) and the expected from simulation (blue) for the most intense gamma lines of the ^{232}Th chain.

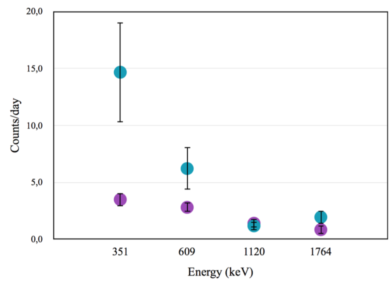

Figure 4. Comparison between the counts/day in the background measurement (purple) and the expected from simulation (green) for the most intense gamma lines of the ^{238}U chain.

background compared to the other one. To overcome the lower efficiency, in particular at low energy, we asked the manufacturer to make the Copper layers lying on the top of the crystal as thin as possible for both End Cap and Holder.

To reduce the background due to the Viton O-rings an accurate material selection has been

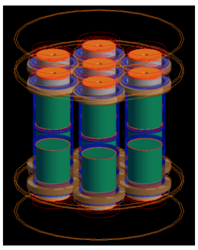

Figure 5. Array simulated geometry.

done measuring various kind of O-rings in order to replace them with a material with a lower radioactive background, but satisfying the same physical constraint. All the alternative samples have been measured on both the HPGe detectors at YangYang laboratory. Most of the O-rings showed quite high contamination in all the considered isotopes. On the other hand EPDM O-rings have the lowest measured activity values for ^{232}Th and ^{238}U, 38 $\pm$ 5 mBq/kg and 68 $\pm$ 12 mBq/kg respectively, although the ^{40}K activity is quite high. In the final configuration the EPDM O-rings will be used not only to seal each of the 14 detectors on the Copper Plate but also for the Plate itself. The expected intrinsic radioactive background has been evaluated simulating all the different considered configurations.
In the final modified configuration a change in the vacuum system has been requested replacing the UHV inside the canister connected with the cryostat with single vacuum for each detector. The two parts of the array will have two separated cooling lines.

3.1. Shielding
To reduce the background due to the environmental radioactivity a preliminary dedicated shielding has been designed; it will consist of 10 cm of Copper as inner layer, 25cm of Lead on the outside and a layer of borate polyethylene as neutrons shielding. The structure and the opening are currently being designed, the shielding in fact needs to have openings on both sides to allow an easy placement of the sample in the Array. The sample can be placed not only

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between the two plates but also between the detectors on the same plate to increase the mass and the detection efficiency. The Array will be placed at the YangYang underground laboratory in one of the new laboratory which is provided with a Radon free system preventing the use of an acrylic box with Nitrogen flux.

4. Expected sensitivity

The ultra low background array has been designed for high sensitivity measurements, the main applications are the material selection for rare events physics experiments and rare decays searches. Regarding material selection, Copper is generally a very pure material and can be used as reference for the instrument performance, in particular for its ^{232}Th concentration. To evaluate the reachable detection limit of this radioisotope in copper, simulations of a sample surrounding all the detectors and with a layer between the two halves of the array have been performed, for a total sample mass of 36 kg. The instrument background has been considered during the sensitivity evaluation using the measured concentration, including the detection limits. Exploiting the array geometry it is possible to perform coincidence measurements. The gammas with the highest branching ratios from the ^{208}Tl decay of ^{232}Th chain have been analyzed considering the most probable coincidences between them. Assuming two months of measurement and 90% of C.L. the reachable detection limit on ^{232}Th in Copper would be < 14 μBq/kg.

Concerning the rare decays the first isotope under study has been the ^{156}Dy which decays on ^{156}Gd through resonant neutrino-less double electron capture. A measurement of a sample of natural Dy_2O_3 has already been performed in LNGS with one HPGe detector reaching a limit on the half life time $> 3 \times 10^{14}$ years [3]. The array sensitivity on this decay has been evaluated simulating a 32 kg sample of natural Dy_2O_3 in the same configuration as the Copper sample. ^{156}Dy has a very low isotopic abundance (0.056%) but most of the excited state from the R-0νECEC emit gamma cascade during the de-excitation process, thus the analysis has been performed in coincidence. The Monte Carlo simulation are based on DECAY0 [4] event generator choosing the 2004 keV level which is expected to have the most significant resonance leading to the highest enhancement in the decay rate. Assuming zero coincidence background in the energy range of the analyzed gammas and two months of measurements the preliminary limit on the half life time is $T_{1/2} > 10^{17}$ years. This result can be improved using an enriched sample and combining results on other excited levels.

5. Conclusion

The HPGe array has been developed in collaboration with CANBERRA concerning the selection of the building materials and the configuration. Monte Carlo simulations have been performed to evaluate the reachable sensitivity for various measurements, from very low background material selection to rare decays measurements. The performance of the instrument which will be delivered this year will be improved with a dedicated shielding and placing the facility in the Y2L underground laboratory.

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