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# Investigation of cosmic-ray induced background of Germanium gamma spectrometer using GEANT4 simulation

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ABSTRACT

In this article, a GEANT4 Monte Carlo simulation toolkit was used to study the response of the cosmic-ray induced background on a High-Purity Germanium (HPGe) gamma spectrometer in the wide energy range, up to 100 MeV. The natural radiation background measurements of the spectrometer were carried out in the energy region from 0.04 to 50 MeV. The simulated cosmic-ray induced background of the Ge detector was evaluated in comparison with the measured data. The contribution of various cosmic-ray components including muons, neutrons, protons, electrons, positrons and photons was investigated. We also analyzed secondary particle showers induced by the muonic component.

## 1. Introduction

Germanium (Ge) gamma spectrometers have been useful tools for analyzing radionuclides in environmental and food samples due to high efficiency and low background. The sensitivity of a Ge spectrometer is influenced by its detection efficiency, energy resolution and the natural radiation background sources at the measurement site. The background spectrum measured by a Germanium detector results from environmental gamma radiation, $^{222}$Rn and its gamma-ray-emitting daughters in the shield, cosmic rays and an intrinsic contamination of Ge detector and shield materials (Heusser, 1986; Heusser, 1993; Heusser, 1994; Vojtyla, 1996). To reduce the environmental gamma radiation, the Ge detector is mounted inside a passive shielding made of low-activity lead, iron or copper that is able to suppress most of the radiation from outside. To reduce a contribution from $^{222}$Rn and its daughters, nitrogen gas has been used to flush the shield. Cosmic rays component can be suppressed in underground laboratories or in ground laboratories if anticoincidence system is used Heusser (1993) and Thomas et al. (2013). More recently Cagniant et al. (2015) used a cosmic veto to design a new versatile ultralow background photon spectrometer installed in a ground laboratory level.

To understand the effect of cosmic rays to the Ge gamma spectrometers, there have been some works experimentally to study the cosmic-ray induced background to the Ge detector (Haines et al., 2011; Solc et al., 2014; Bikit et al., 2014). Cosmic rays can contribute to the background spectrum because of their penetrating power and large number of physical processes leading to background induction. An effective way to understand a contribution of cosmic rays to the Ge detector background is to use a Monte Carlo simulation of the detector background (Vojtyla, 1995; Vojtyla, 1996; Joković et al., 2009; Breier and Povinec, 2010; Solc et al., 2014). However, these studies were mostly compared without measured data (Vojtyla, 1995; Vojtyla, 1996; Joković et al., 2009; Breier and Povinec, 2010) or with the Ge-detector background measured bellow 25 MeV (Solc et al., 2014). The aim of this work was to study the response of cosmic-ray induced background in a High-Purity Germanium (HPGe) gamma spectrometer using GEANT4 simulation toolkit. The background measurements were carried out at ground laboratory level up to 50 MeV and compared with simulation data. We investigate contributions of cosmic-ray components, including muons, neutrons, protons, electrons, positrons and photons on the background spectrum. We also analyzed secondary particle showers induced by the muonic component. The simulations and analysis of the deposited energy in the Ge-detector by cosmic rays were carried out in the wide energy range, up to 100 MeV.

## 2. Materials and methods

### 2.1. Experimental set-up

The HPGe detector (Canberra model GC2018) (Canberra, 2013) is of

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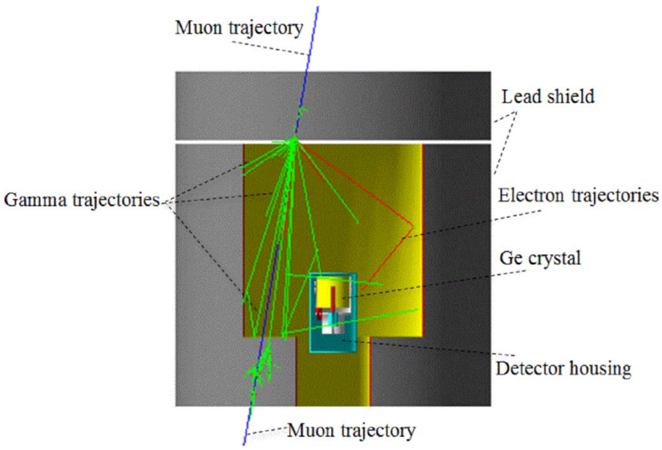


**Fig. 1.** Geometry of Ge gamma spectrometer modeling by Geant4 simulation toolkit. Visualization of a simulated event of muon interacting with the spectrometer.

coaxial p-type (SEGe) with a relative efficiency of 20%, an active volume of 104 cm$^3$ and a resolution of 1.8 keV at the 1332.5 keV gamma rays of $^{60}$Co. The Ge detector was mounted inside a cylindrical shield (Canberra model 747E) (Canberra, 2013) with 10 cm thick low-background lead. Energy range of measurements was setup from 0.04 to 50 MeV. The background counting rates measured during 5 days were 100 counts/min and 75 counts/min at the full energy interval (0.04–50MeV) and at energies below 2.4 MeV, respectively.

### 2.2. Monte Carlo simulation

A model of the Ge gamma spectrometer was developed using the Monte Carlo code GEANT4 in version 9.6.p04 (Agostinelli et al., 2003). The Ge detector and the lead shielding parameters were taken from Canberra and from measurements at the experimental site. The Ge detector was of a cylindrical shape with 5.2 cm in diameter and 4.95 cm in length. The lead shielding was made of 10 cm of lead, 1 mm of tin and 1.6 mm of copper and its outer dimensions were 50.8 cm in diameter and 63.5 cm in length. Fig. 1 shows the geometry of the Ge spectrometer modeled by the GEANT4 simulation toolkit.

Cosmic rays for GEANT4 input were taken from the Cosmic-ray Shower Library (CRY) generator, version 1.7 (Hagmann et al., 2012). This simulation code library generates the momentum, energy, direction and angular distribution of cosmic rays at sea level at given time and geographic location (Hagmann et al., 2007). The components of incident cosmic rays consisted of muon, neutron, photon, electron, positron and proton particles.

**Table 1**
Relative contribution of components of cosmic rays into the total detector count rate.

| Component of cosmic rays | Relative detector count rate [%] |
|---|---|
| Muon | 86.0 |
| Neutron | 8.6 |
| Photon | 3.0 |
| Electron | 0.6 |
| Positron | 0.5 |
| Proton | 1.2 |

The aim was to study contributions of various cosmic-ray components to the Ge detector background, and also to study secondary particle showers caused by the muons itself. To separate cosmic-ray components, simulated data about the particle tracking information include the primary particle name and its energy deposited in the Ge detector per an event. For studying the secondary particle showers caused by muons, the simulation took into account the production of secondary particles as the result of interactions of cosmic rays with lead shielding and the Ge detector. Fig. 1 shows trajectories of an incident cosmic-ray muon, interacting with lead chamber causing the secondary particle shower.

## 3. Results and discussion

### 3.1. Comparison of experimental and simulated spectra

Fig. 2 shows measured and simulated deposited energy spectra of the Ge detector of radiation background (blue curve) and cosmic-ray induced background (black cure), respectively. In the high-energy region (above 3 MeV), there is a good agreement between the measured and simulated data. A peak in the region of 30–42 MeV, resulted from direct hits of comic-ray particles with the Ge material. In the low-energy region (below 3 MeV), the measured spectrum is higher than the simulated spectra because it includes, in addition to the cosmic rays component, also the terrestrial component of natural radiation background. The terrestrial component is induced by $^{212}$Pb (0.239 MeV), $^{214}$Pb (0.352 MeV), $^{214}$Bi (0.609 MeV, $^{40}$K (1.461 MeV) and $^{208}$Tl (2.615 MeV), etc. The simulated data show that the cosmic-ray induced background to the measured background describing a continuous spectrum characterized by an annihilation peak at 0.511 MeV.

### 3.2. Contributions of cosmic-ray components to the Ge detector backgrounds

These components of cosmic rays were considered: muons, neutrons, photons, electrons, positrons and protons. Table 1 shows the

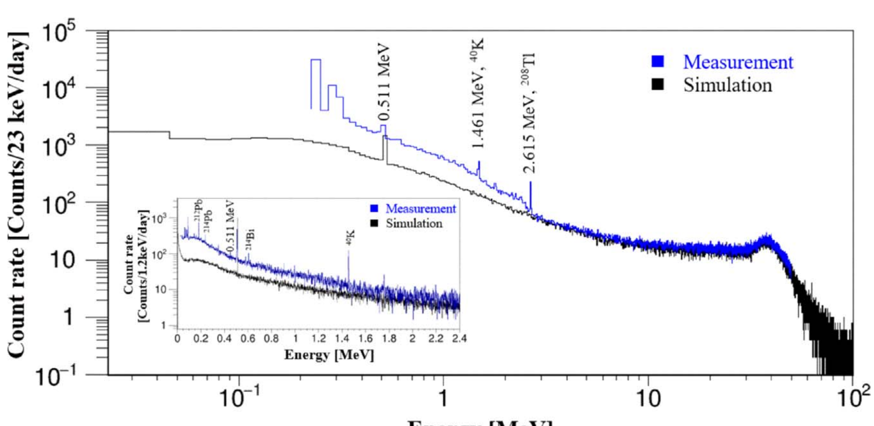


**Fig. 2.** Measured (blue curve) and simulated (black curve) deposited energy spectra of the Ge detector of radiation background and cosmic-ray induced background, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

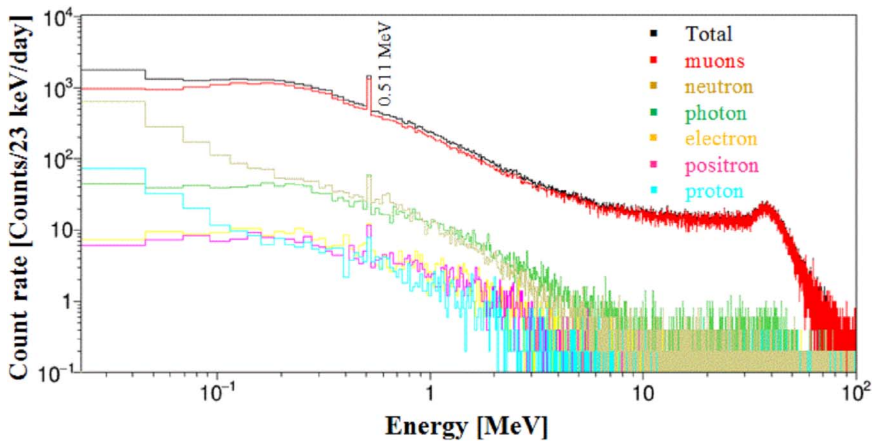


**Fig. 3.** Simulated deposited energy spectra of various components of cosmic rays recorded by the Ge detector. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

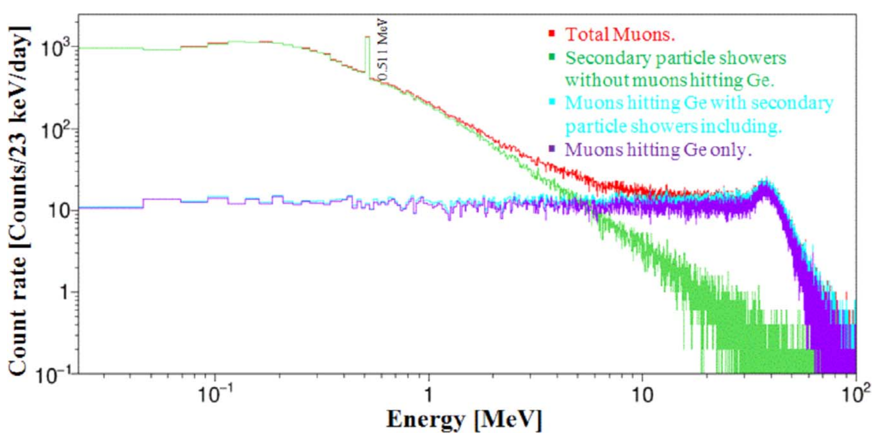


**Fig. 4.** Simulated deposited energy spectra of the Ge detector induced by cosmic muons hitting the Ge spectrometer. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

percentage of each component of cosmic rays contributing to the total cosmic-ray induced background. Fig. 3 shows simulated deposited energy spectra of various components of cosmic rays recorded by the Ge detector. The results show that, muons (red curve) is the main contributing component in the total deposited energy spectrum of cosmic-ray induced background with 86% of events. In the high-energy region (above 3 MeV), muons represent the dominating component. A so-called muon peak at the region of 36 MeV is confirmed as the direct hits of muons passing through the Ge detector material, as the energy losses of a minimum ionizing particle in Ge material is 7.3 MeV $cm^{-1}$ (Groom et al., 2001). In the low-energy region (below 3 MeV), the contributions of neutrons (brown), photons (green), and protons (aqua) are visualized. The neutrons contribute by about 8.6%, mostly in the very low-energy region of several tens of keV. Because neutrons are able to penetrate through the lead shield, nuclear reactions with materials of the spectrometer can occur generating secondary gammas and charged particles. Electron, positron and proton components do not contribute much to the total background.

The deposited energy spectra caused by muons, photons, electrons and positrons in the low- energy region have the broad spectrum with maximum around 0.2 MeV. The 0.511 MeV peak is caused by the annihilation photons created by electron-positron pairs originated from the bremsstrahlung radiation generated by cosmic rays interacting with the lead shielding.

### 3.3. Secondary particle showers induced by cosmic muons

For a low-background Ge gamma spectrometer, lead shield is used to suppress the environmental gamma radiation around the Ge detector. Muons hit the lead material and generate secondary particle showers, which may reach the sensitive volume of the Ge detector. Fig. 4 shows the simulations of muon-induced background of the Ge detector (the red curve). The green curve describes the deposited energy spectrum caused by the secondary particle showers induced by muons. Aqua and magenta curves describe muons hitting the Ge volume including its secondary particle shower, and muons hitting Ge not including its secondary particle shower, respectively. In the high-energy region (above 10 MeV), almost all events come from the direct muon events which strike directly the Ge detector. However, the events in the energy region below 3 MeV mostly come from secondary particle showers induced by muons. The continuum peak at 0.2 MeV results from the secondary particle showers as well.

The simulation results clearly show that the secondary particle showers which originated in the lead shield mostly contributed to the background spectrum in the energy region below 3 MeV. The muons directly hitting the Ge detector were not depending on the lead shielding.

## 4. Summary

The cosmic-ray induced background of the HPGe gamma spectrometer was investigated using the GEANT4 Monte Carlo simulation and measured background data. The simulated deposited energy spectrum of the Ge detector showed a good agreement with the measured background spectrum in the energy region from 3 to 50 MeV. The so-called muon peak at about 36 MeV resulted from the direct hits of comic-ray muons with the Ge detector. In the low energy-region (below 3 MeV), the simulated data showed cosmic-ray induced background to the measured radiation background. It is a continuous gamma spectrum characterized by an annihilation peak at 0.511 MeV and a continuum peaking at around 0.2 MeV. Muonic component is the main contributing component in the total deposited energy spectrum of the cosmic-ray induced background with 86% of events. The contributions of neutrons, photons, and protons can be taken into account in the energy region below 3 MeV. The secondary particle showers induced by muons mostly contributed to the background spectrum in the low-energy region (below 3 MeV). In the high-energy region (above 10 MeV), almost events come from the direct muon events which strike directly the Ge detector.

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