Simulation and verification of the cosmogenic background at the shallow depth GIOVE detector

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Abstract. The GIOVE (Germanium Inner Outer VEto) detector setup is a low level Germanium spectrometer for material screening with elaborated shield located at the shallow depth underground laboratory of the Max-Planck-Institut für Kernphysik in Heidelberg. It is equipped with a double active muon veto with a total muon rejection efficiency of $\sim$99% and there are also passive layers to moderate and capture neutrons. With this setup an integral count rate is achieved comparable to detectors far deeper underground. The detector and shield geometry has been implemented into a Monte Carlo simulation, using the simulation framework MaGe based on Geant4. The Monte Carlo simulation is employed to determine sample efficiencies for $\gamma$ ray screening measurements as well as to reproduce the remaining detector background from cosmic ray muon-induced secondaries. In terms of the background modeling of the unvetoed $\gamma$ ray spectrum an excellent agreement better than 10% in the integral count rate in (40, 2700) keV as well as for the 511 keV line has been found. However, concerning the expected number of neutrons at the diode, the simulation outcome lays 40-80% below the measurement results. Being able to reproduce the detector background in the simulation, the simulation can be used to further optimize the shield design.

1. Introduction of the GIOVE spectrometer
The GIOVE detector ($\sim$2 kg semi-coaxial Germanium (Ge) diode) has been set up for material screening at the shallow depth laboratory (15 meters of water equivalent (m w.e.)) of the Max-Planck-Institut für Kernphysik in Heidelberg (MPIK) (see figure 2). With its passive shield consisting of carefully selected radio-pure materials and the double muon veto system made from plastic scintillator plates GIOVE reaches well the design goal for measurements of radioactive contaminations of $^{232}$Th/$^{238}$U chain daughters in the range of 100 $\mu$Bq/kg. The achieved background rate is comparable to that of instruments at underground sites several 100 m w.e. deeper. Not only the muon-induced background is reduced by $\sim$99% veto efficiency but also background events originating from neutron interactions within the shield are weakened by about 70% compared to another spectrometer at the same shallow depth laboratory. This reduction in the neutron flux is achieved by neutron moderating and absorbing layers made of borated polyethylene (PE) in the shield of GIOVE. To gauge the number of neutrons arriving at the diode, the intensities of the de-excitation lines from the metastable germanium states visible in the vetoed spectrum ($^{71m}$Ge, $^{73m}$Ge and $^{75m}$Ge) are a useful reference.

Figure 1 shows a cut-away view of the GIOVE spectrometer setup with a sample chamber (SC) volume of about 12.4 l. In [1] a detailed description of its layout and performance is reported. In the following the focus is set on the detailed modeling of the detector and shield by
Monte Carlo (MC) simulations. The simulations are employed to determine sample efficiencies for the testing of materials on their radio purity and to model the muon-induced background in the detector.

2. Detector characterization and modeling
Up to the outermost lead (Pb) layer, the GIOVE detector setup has been implemented into a MC simulation, using the simulation framework MaGe [3]. MaGe is based on Geant4 [4, 5] and adapted to low-energy particle physics. For routine detector application a MC simulation is required to determine the efficiency of the measured material samples, i.e. the probability for \( \gamma \) rays to be detected in the full energy peak within the diode. It is the most accurate way to determine the efficiency, especially for samples with complex compositions or shapes. In order to get precise simulation results, there are several parameters to be tuned in the simulation code. Measurements with collimated and uncollimated radioactive sources were carried out and simulated as well. The diode position, dead layer thickness and borehole dimensions of the Ge detector in the simulation were adapted until simulated and measured results became consistent. After the completion of the shield setup the accuracy of the simulation was tested in measurements with several well calibrated (mono) energetic point-like sources. The efficiency of each \( \gamma \) line was determined and plotted against the energy to get an efficiency curve. An excellent agreement between measurements and simulation resulted in a mean absolute deviation of (2±1)% in (90, 1300) keV [1].

3. Monte Carlo simulations of the muon-induced background
At the shallow depth of the MPIK laboratory the dominant background contribution comes from cosmic rays. At 15 m w.e. the muon flux is only reduced by a factor of ~2 to 3 [2] meaning that an effective suppression of muon-induced signals is required. This background can be modeled as well in the previously tuned MC simulation. There exist no precise measurements of the muon and neutron flux in the laboratory. Thus, the necessary quantities have been deduced from literature and calculations [6].
Two parameterizations for the muon spectrum at sea level were selected from literature ([7] and [8] adapted by [9] to low energies and expanded to all angles). As the muon flux depends on local conditions, an adaptation to the altitude above sea level of the MPIK has been made according to [10]. Muons traveling through the overburden lose their energy via ionization and radiation with the ionization loss being dominant at shallow depth [11]. They need a certain energy to reach a given depth underground and consequently, the mean muon energy will increase with depth. In the case of our laboratory a shift from 4 GeV at sea level [11] to about 10 GeV in underground occurs according to calculations. This behavior is described by an energy range equation that can be plugged into the parameterizations of the spectrum at sea level to calculate the spectrum underground. To validate this calculation, a comparison to literature values at different depths up to 70 m w.e. has been made. Finally, the spectrum calculated from the Bugaev/Reyna parametrization [8, 9] was found suitable as a starting point for the simulation underground. From the calculation in underground an angular distribution of \( \cos^n(\theta) \) with \( \theta \) the zenith angle and \( n=2 \) averaged over all energies can be derived similar to sea level [11].

For simplicity the simulations were run with an angular distribution of \( \cos^2(\theta) \) at all energies. Positive and negative muons were simulated with the same charge ratio of 1.268 [10] as at sea level. To avoid solid angle corrections, the muons were started from the laboratory walls, taking into account the projection on a flat surface for the angular distribution. For the ceiling at 15 m w.e. the results were normalized to the calculated integral flux of \( 57.0 \text{ m}^{-2}\text{s}^{-1} \) and for the walls at the side a mean depth of 18 m w.e. was assumed, resulting for all walls combined in an integral flux of \( 37.2 \text{ m}^{-2}\text{s}^{-1} \) for normalization.

The cosmic ray hadronic component decreases exponentially with depth and at 15 m w.e. it is suppressed by more than a factor of \( 10^4 \) [2]. Furthermore, muons will produce neutrons in the overburden. Other neutron sources are \((\alpha, n)\) reactions and fission in the walls. However, from measured results at a similar depth and rock composition [12] it could be gauged that there will be a neutron flux of less than \( 1 \text{ m}^{-2}\text{s}^{-1} \) emerging from the walls and the laboratory ceiling. To first order this number of neutrons is considered negligible in comparison to the number of neutrons produced in the GIOVE shield as revealed in the simulations. Therefore only muons are simulated. They are propagated through the shield, where they will produce secondary particles in various processes. As simulation output the \( \gamma \) ray spectrum at the diode as well as the spectrum of muons and neutrons entering into the diode are registered. Furthermore, the spectrum of neutrons traveling through the different shield layers is observed.

### 3.1. Prompt muon-induced spectrum

Figure 3 displays the comparison between the prompt muon-induced Ge spectrum in simulation and the measured result without veto. The SC is empty. Above 80 keV without any adaptation there is an excellent agreement in the form of the Bremsstrahlung induced continuum and also the integral count rate in the (40, 2700) keV interval differs only by (2.0 ± 0.4)%. The measured intensity in the 511 keV line is underestimated by the simulation by (8 ± 3)%. For the SC filled with low-density neutron moderating materials a similar good agreement was found. This means that the electromagnetic physics is implemented very well in the simulation framework.

### 3.2. Neutron spectra and number of neutrons

Next to the \( \gamma \) ray spectrum in Ge, also the energy spectrum of neutrons entering the diode was registered in the simulation output and can be found in figure 4 for an empty SC and normalized to the diode surface. Mostly fast neutrons with energies around a few 100 keV arrive at the diode. Moreover, a significant difference between the number of neutrons entering the diode for the first time and the total number of neutrons entering the diode was found meaning that the backscattering of neutrons in the vicinity of the detector cannot be neglected. Not only the neutrons entering the diode were registered in the simulation output, but also the
neutrons passing from one shield layer to the next. The corresponding energy distributions for
the neutrons in the layers above the diode normalized to the area of the layers (see cut-away
view in figure 1) can be found in figure 5. From the figure it can be observed that in Pb (2-
black, 4-red, 6-purple) fast neutrons are produced. In the plastic scintillator plates (1-gray,
7-turquoise) a moderation to thermal energies takes place. This moderation also happens in
the inserted layers of borated PE (3-green, 5-orange). However, in these layers the thermal
neutrons are captured. Thus, they create no thermal peak and the total number of neutrons
reaches its lowest value. The innermost layer towards the diode is copper (Cu) (8-blue), where,
similar to Pb, many fast neutrons seem to be produced, which will arrive at the diode.

Neutrons cannot be registered directly with a Ge spectrometer. However, there are two
indirect ways to compare the number of neutrons in simulation and measurement. One possibility
is to fill the SC with materials, where the neutrons are captured in nuclei which become excited.
The $\gamma$ rays from the following de-excitation are registered in the diode and the count rates in
simulation and measurement can be compared. This procedure has been carried out for a SC
filled with pure and borated PE. For the 478 keV (borated PE) and 2223 keV (pure PE) the
count rate in the simulation lies $\sim 40\%$ and $\sim 60\%$ below the measurement.

The second way to access the neutrons works over the neutron-induced isomeric Ge states.
There are two techniques. Both require knowledge of the cross section for the creation of these
states not only at thermal energies, but up to fast neutron energies (in the energy range of
figure 4). However, literature data on these cross sections is limited and therefore we decided
to focus on $^{75m}$Ge produced from $^{74}$Ge with a de-excitation line at 140 keV, for which the most
information is available. From the count rate in this line, the detection efficiency, the form of
the simulated neutron flux and the energy-dependent cross section, it is possible to calculate
the number of neutrons required to produce this line (formula from [13], adapted to an energy
dependent cross section [6]). The result can be compared to the number of neutrons arriving at
the diode from the simulation of muons outside the shield. This has been done for an empty SC
and a SC filled with pure as well as with borated PE. It turns out that in the simulation 40-80%
less neutrons arrive at the diode than expected from the measurement based calculations.

Vice versa, it is possible to do this comparison by simulating the 140 keV line directly, but
there are two drawbacks. First, in Geant4.9 no metastable states are created. Thus, it is required
to hard-code the cross section for the production of the line (like described in [14]). Second, there
is no muon veto in the simulation. This problem can be overcome by running two simulations.
In the first one, the spectrum of neutrons arriving at the diode is registered. This spectrum is
used as starting point for a second simulation, where the 140 keV line is created, while there is no
disturbing background from muon-induced secondaries. Following this procedure and comparing
the resulting count rate with measured data for an empty and filled SC (like described above)
leads again to an underestimation in the number of neutrons in the simulation of 40-80%.
Figure 4. Spectrum of muon-induced neutrons entering the Ge diode (for the first time) with empty SC, normalized to the diode surface.

Figure 5. Spectrum of muon-induced neutrons leaving the different layers of the shield above the diode, normalized to the area of the layers. The order of the layers in the legend corresponds to the order of the layers in the shield from outside towards the diode.

4. Summary and outlook

The GIOVE detector is a Ge detector setup for material screening at the shallow depth of 15 m w.e. at the MPIK. It is equipped with an active muon veto and there are also layers to moderate and absorb neutrons. The resulting background is comparable to detectors operated at several 100 m w.e. depth underground.

A MC simulation is employed to model the remaining detector background. For the prompt muon-induced spectrum an excellent agreement between simulation and measurement has been found, while for muon-induced neutrons an underestimation of 40-80% in the simulation depending on the filling of the SC has been observed. This might indicate an underestimation of the production of neutrons by muons and/or a problem of the simulation in the propagation of neutrons through the shield. To further investigate this discrepancy measurements with an external $^{252}$Cf source and a comparison to the respective simulations are ongoing.

After full validation, the shield design can be modified in the simulation and it can be tried to find the optimum shield configuration for the lowest background at a given underground site.

References

[1] Heusser G et al 2015 Eur. Phys. J. C 75 531
[2] Heusser G 1993 Nucl. Instrum. Methods B 83 223-228
[3] Boswell M et al 2011 IEEE Trans. Nucl. Sci. 58 1212-1220
[4] Agostinelli S et al 2003 Nucl. Instrum. Meth. A 506 250-303
[5] Allison J et al 2006 IEEE Trans. Nucl. Sci. 53 270-278
[6] Hakenmüller J 2015 Master Thesis University of Heidelberg
[7] Bogdanova L N et al 2006 Phys. Atom. Nucl. 69 1293-1298
[8] Bugaev E V et al 1998 Phys. Rev. D 58 054001
[9] Reyna D 2006 arXiv:hep-ph/0604145
[10] Hebbeker T and Timmermans C 2002 Astroparticle Physics 18 107-127
[11] Olive K A et al (PDG) 2014 Chin. Phys. C 38 090001
[12] Da Silva A et al 1995 Nucl. Instrum. Meth. A 354 553-559
[13] Škoro G P et al 1992 Nucl. Instrum. Meth. A 316 333-336
[14] Pandola L and Lui J 2008 A quick fix of Geant4 bug #956 (http://bugzilla-geant4.kek.jp/)