Muon-induced signals and isotope production in the GERDA experiment

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Abstract. Background induced by the interaction of cosmic ray muons can represent a subtiantial contribution for the new generation of experiments searching for neutrinoless double beta decay. The GERmanium Detector Array (GERDA), located at the Gran Sasso Laboratory, in Italy, uses germanium enriched in ^{76}Ge as source and detector material and it aims at a background level of 10^{-3} counts/(kg·keV·y) at the $Q_{\beta\beta}$-value. The prompt background from muon interactions in the setup as well as the delayed background due to the production of radioactive isotopes within the setup have been evaluated by a detailed GEANT4-based Monte Carlo simulation. The results indicate that the background can be reduced to the desired level and that the muon-induced background does not limit the expected GERDA sensitivity.

Keywords: Neutrinoless double beta decay, cosmic ray background
PACS: 23.40.-s, 96.50.S, 24.10.Lx

INTRODUCTION

The GERmanium Detector Array, GERDA [1], is designed to search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge. GERDA will be installed in Hall A of the INFN Gran Sasso National Laboratory (LNGS), Italy. The experiment is designed to collect about 100 kg·y of quasi background-free data in order to explore a possible Majorana neutrino mass in the range 250-500 meV [2]. This leads to the requirement of a background index of the order of 10^{-3} counts/(kg·keV·y) around the $Q_{\beta\beta}$ value of 2039 keV. The main design feature of GERDA is to use a cryogenic liquid (nitrogen or argon) as the shield against the external γ radiation. In the GERDA design high purity germanium detectors are immersed directly in the cryogenic liquid which is also the cooling medium. The cryogenic volume is surrounded by a buffer of ultra-pure water acting as an additional γ and neutron shield (see Fig. 1).

The experiment is foreseen to proceed in two phases. In the first phase detectors, enriched in ^{76}Ge, that were previously operated by the Heidelberg-Moscow [3] and IGEX [4] collaborations will be redeployed. In the second phase new enriched detectors will be installed. These detectors will be segmented. A possible segmentation scheme is 18-fold with 6 segments in the azimuthal angle φ and 3 axial segments.

Cosmic ray muons crossing the setup and the surrounding materials can interact and create an effective flux of γ-rays and neutrons in the detector array. Their interactions can produce a prompt energy deposition faking the signature of a neutrinoless double beta decay, namely a localized energy deposition of approximately 2039 keV. In addition radioactive isotopes can be produced which can cause a delayed background contribution. The prompt component can be reduced effectively by an active muon veto. The reduction factor possibly achievable for the delayed component depends on the life time and the decay scheme of the produced radioactive isotope.

Since the GERDA goal for the total background index in the second phase is 10^{-3} counts/(kg·keV·y), the contribution of each of the background components (muons, external γ-rays, internal contamination, etc.) should not exceed 10^{-4} counts/(kg·keV·y). Thus, the maximum tolerable background from prompt and delayed muon interactions is assumed to be 10^{-4} counts/(kg·keV·y) each.

As discussed in this contribution and in Ref. [5], the muon-induced background can be kept within these specifications making use of the GERDA Cherenkov muon veto and specific delayed-coincidence cuts.

THE MONTE CARLO SIMULATION

The Monte Carlo simulation of the muon-induced background has been carried out using the GEANT4-based [6] MAGE framework [7] which is jointly developed and maintained by the GERDA and Majorana Monte Carlo groups.

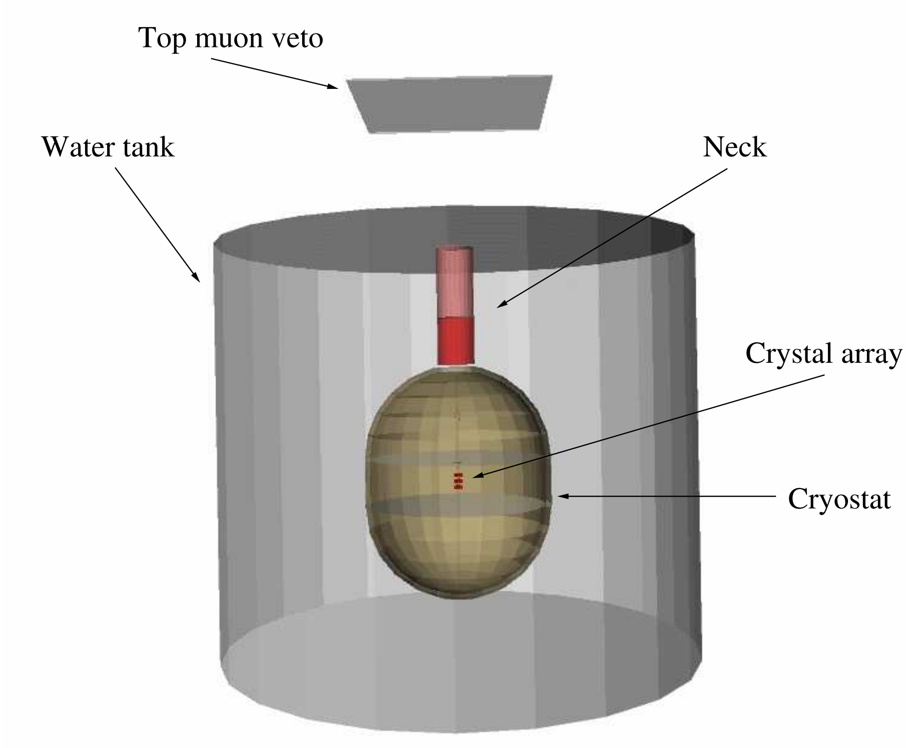

FIGURE 1. Geometry implemented in the simulation of the GERDA setup.

GERDA setup

The geometry implemented in the simulation is shown in Fig. 1. It includes a cryogenic volume of about 45 m^3 filled with either liquid nitrogen and liquid argon, contained in a copper cryostat. The total thickness of the cryostat walls is 3 cm. The cryostat is immersed in a water volume of about 700 m^3, acting as additional shielding against γ-rays and neutrons. The water is contained by a cylindrical stainless-steel tank of radius 5 m and height 8.9 m. The array of germanium detectors is located in the center of the cryogenic volume. Each detector is assumed to have mass of 2 kg. For this study we use a "nominal" setup with 21 segmented detectors arranged in a hexagonal package of 7×3 (see Ref. [5]).

Two muon vetoes are incorporated in the GERDA design: (1) the water buffer is operated as a Cherenkov detector; (2) a plane of plastic scintillator is placed on the top of the setup to detect vertical muons.

Primary muon spectrum

The Gran Sasso overburden of 3400 m.w.e. suppresses the cosmic muon flux by six orders of magnitude to 1.1 muons/(m^2·h) and shifts the mean energy to 270 GeV. The energy spectrum of cosmic ray muons in Hall A of the laboratory is calculated according to the analytical parametrization of Ref. [8]. The energy range spans from 1 GeV to 10 TeV, as shown in Fig. 2. The angular distribution is determined by the profile of the Gran Sasso mountain and it has been precisely measured by the MACRO experiment [9]. The distribution used for the simulation is hence calculated from this measurement. The average zenith angle is $\langle\theta\rangle \sim 35$ degrees. The distribution of the azimuth angle φ is not uniform, but follows the profile of the mountain. Separate projections of the distribution in $\cos\theta$ and φ are shown in Fig. 3.

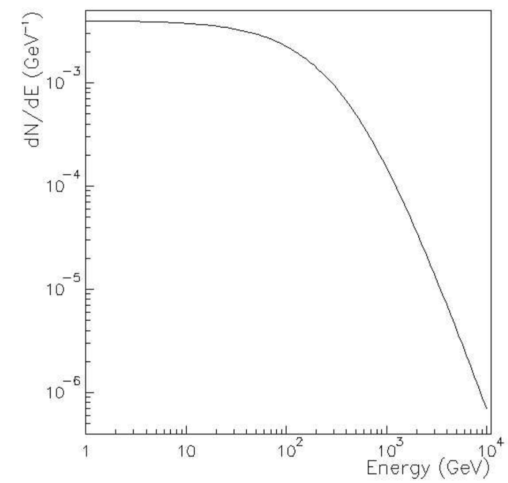

FIGURE 2. Energy spectrum of cosmic ray muons in the Gran Sasso underground laboratory according to the parametrization of Ref. [8].

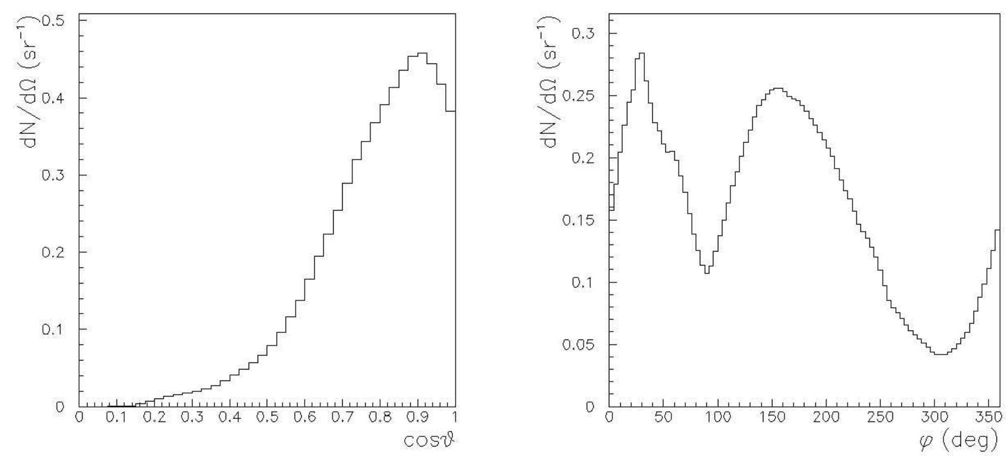

FIGURE 3. Marginal distributions of the muon direction ($\cos\theta$ and φ) from the MACRO measurements [9].

PROMPT BACKGROUND

Both γ-rays and neutrons contribute to the prompt background, in addition to the direct interaction of muons. γ-rays deposit energy in the crystals through electromagnetic interactions. The neutron-induced prompt background is due to the photons emitted in (n,n'γ) or (n,γ) interactions[1].

Since most $0\nu\beta\beta$-decay events are single-site events, i.e. the energy is released locally by the two electrons in the final state, background from γ-rays and muons can be rejected by requiring that only one crystal or segment shows an energy deposition, as discussed in Ref. [1, 10]. An energy threshold of 50 keV has been assumed for each segment. As

[1] Nuclear recoils from neutron elastic scattering do not contribute at $Q_{\beta\beta}$ for two reasons: (1) the ionization yield for nuclear recoils in germanium is a factor of three smaller than for electrons. Therefore a 2-MeV electron-equivalent energy deposition corresponds to a 6-MeV nuclear recoil; (2) the mass of germanium nuclei is large with respect to the neutron mass. Therefore only a small fraction of energy can be transferred in elastic interactions.

TABLE 1. Background index in the range from 1.5 to 2.5 MeV, for different veto scenarios. Only statistical errors are quoted.

Condition	Background index counts/(kg·keV·y)	
	Nitrogen	Argon
No cuts	$(1.42 \pm 0.04) \cdot 10^{-2}$	$(1.90 \pm 0.04) \cdot 10^{-2}$
Crystal anticoincidence	$(5.6 \pm 0.6) \cdot 10^{-4}$	$(9.0 \pm 0.6) \cdot 10^{-4}$
Segment anticoincidence	$(2.9 \pm 0.4) \cdot 10^{-4}$	$(4.0 \pm 0.4) \cdot 10^{-4}$
Anticoincidence + ideal muon veto (above 120 MeV)	$< 1 \cdot 10^{-5}$ (95% CL)	

shown in Table. 1, the crystal anticoincidence cuts suppress the background by a factor of 25 at $Q_{\beta\beta}$. An other factor of two can be gained with the segment anticoincidence requirement. The muon veto is required to lower the prompt background index below 10^{-4} counts/(kg·keV·y).
Table 1 shows that an "ideal" muon veto with 100% efficiency above 120 MeV would reduce the background index below 10^{-5} counts/(kg·keV·y). In fact the simulation shows that in all events with energy deposition in the germanium crystals, at least 120 MeV are released in the water. The final background index which is achievable for prompt muon-induced interactions depends on the veto efficiency. It can be reduced below 10^{-4} counts/(kg·keV·y), provided the efficiency of the Cherenkov veto above 120 MeV is not smaller than about 70% for the nitrogen setup and 80% for the argon setup. Dedicated simulations of the Cherekov light indicate that an efficiency higher than 90% for muon tracks that release energy in the crystals can be achieved with about 80 PMTs, provided that the walls of the water tank are covered with light-reflecting foils.

Muons not crossing the setup

In the previous section only muons interacting in the setup are accounted for. There is the additional possibility that muons interacting in the surrounding rock create high-energy neutrons that are entering the experimental setup. They can penetrate the shield and contribute to the background around $Q_{\beta\beta}$. Since the explicit Monte Carlo tracking of muons and neutrons in thick layers of rock is extremely CPU-intensive, a simplified approach is chosen. High-energy neutrons from the rock are generated according to the energy and angular distributions obtained in the simulation of Ref. [11] and are tracked into the GERDA setup. The integral flux above 1 MeV is assumed to be 300 neutrons/(m^2·y), according to Ref. [11]. The mean energy is about 100 MeV.
The resulting background index is $6 \cdot 10^{-5}$ counts/(kg·keV·y). It can be reduced below 10^{-5} counts/(kg·keV·y) (90% CL) with the segment anticoincidence cut. High-energy external neutrons represent a limiting background in the calculations of Ref. [12]. However, they are effectively absorbed by the thick layer of water in the GERDA design.

DELAYED BACKGROUND

The production of unstable isotopes inside the setup can be induced either by neutrons, via capture or other inelastic interactions as (n,p) and (n,α), or by γ-rays via photo-nuclear reactions.
The delayed decay of these nuclei can mimic $0\nu\beta\beta$-events and thus they represent an additional background source. They cannot be identified by the muon veto if their half-life exceeds a few hundreds of ms. In fact the expected rate of the Cherenkov muon veto is about 2.5 events/min; a one-second-long veto window after each veto trigger would yield an overall 4% dead time. Long-lived unstable isotopes hence form an irreducible background contribution which eventually limits the achievable background index for the given setup. The isotopes that are potential background sources for GERDA are those emitting γ and/or β-rays above $Q_{\beta\beta}$. The β-rays are only relevant if the unstable isotope is located inside the detector crystals themselves[2]. The total production rate in the crystal depends on the cryogenic liquid because of the different fluxes of neutrons and γ-rays. Results are presented in Table 2. The only isotope produced outside the detectors which gives a contribution larger than 10^{-6} counts/(kg·keV·y) is ^{38}Cl in liquid argon.

[2] External β-rays are absorbed by a few millimeters of the cryogenic liquid.

TABLE 2. Muon-induced isotope production. Segment anticoincidence has been taken into account. Isotopes giving a background index below 10^{-6} counts/(kg·keV·y) are not reported. Only statistical errors are quoted. Upper limits are quoted at 90% CL.

	Nitrogen		Argon	
	nuclei/(kg·y)	counts/(kg·keV·y)	nuclei/(kg·y)	counts/(kg·keV·y)
Isotopes produced in crystals				
^{74}Ga/^{75}Ga/^{76}Ga	< 0.08	$< 3 \cdot 10^{-5}$	< 0.1	$< 4 \cdot 10^{-5}$
^{68}Ge	0.07±0.03	$(2 \pm 1) \cdot 10^{-6}$	0.08±0.03	$(2 \pm 1) \cdot 10^{-6}$
^{69}Ge	0.38±0.08	$(4.0 \pm 0.8) \cdot 10^{-7}$	1.8±0.2	$(2.0 \pm 0.2) \cdot 10^{-6}$
^{77}Ge/^{77m}Ge	0.05±0.03	$(0.9 \pm 0.6) \cdot 10^{-5}$	0.51±0.09	$(1.0 \pm 0.2) \cdot 10^{-4}$
Isotopes produced in cryogenic liquid				
^{38}Cl	-	-	46±1 nucl/day	$(1.3 \pm 0.1) \cdot 10^{-5}$

The production of radioactive isotopes induced by muons in the GERDA setup gives a contribution to the background index at $Q_{\beta\beta}$ of the order of 10^{-4} counts/(kg·keV·y) in the liquid argon setup and of 10^{-5} counts/(kg·keV·y) in the liquid nitrogen one. Therefore the delayed muon-induced background is relevant if liquid argon is used as the cryogenic liquid. In the present design of the GERDA experiment the setup is filled with liquid argon because it can shield better than liquid nitrogen the γ-rays produced by radioactive decays in the cryostat.

Rejection of ^{77}Ge/^{77m}Ge background

The largest contribution to the delayed background comes from ^{77}Ge and ^{77m}Ge produced by thermal neutron capture of ^{76}Ge. Neutron capture on ^{76}Ge (0^+) can eventually populate the ground state of ^{77}Ge ($7/2^+$) and the excited isomeric state ^{77m}Ge ($1/2^-$) at 159 keV. The cross section of the reaction is about 0.14 barn. Given the spin of the nuclear levels involved, about 95% of the neutron captures end up in the isomeric ^{77m}Ge state [13].
The Q-value of the ^{77}Ge β-decay is 2.861 MeV (half-life: 11.3 h). The isomeric state ^{77m}Ge can de-excite to the ground state ^{77}Ge (21% of the cases) with the emission of a 159-keV γ-ray, or β-decay to ^{77}As with half-life 52.9 s and Q-value of 2.702 keV [14]. The β-decays of ^{77}Ge and ^{77m}Ge can produce a localized energy deposition at $Q_{\beta\beta}$, faking the $0\nu\beta\beta$-event signature. It is important to notice that the production rate of ^{77}Ge scales with the ^{76}Ge enrichment: such a background would not show up in non-enriched ("control") germanium crystals. While the β-decay of ^{77}Ge ($7/2^+$) to ^{77}As ($3/2^-$) is associated with a complex γ-ray cascade due to the difference in the nuclear spins, the decay of ^{77m}Ge ($1/2^-$) to ^{77}As ($3/2^-$) is dominantely a pure β-decay, without emission of further γ-rays (see Fig. 4). The decay of ^{77m}Ge (which is most probable product of the neutron capture) is particularly dangerous because it produces a single β-ray, namely a localized energy deposition, and the rejection tools based on anticoincidence are not effective[3].

It is hence necessary a dedicated delayed-coincidence cut to reduce the background from ^{77m}Ge below 10^{-4} counts/(kg·keV·y) also in the liquid argon scenario. It is not possible to introduce a 4-$T_{1/2}$ dead time after each muon trigger, because $T_{1/2} = 53$ s and the trigger rate of the veto is about 2.5 events/minute. The ^{77m}Ge background can instead be reduced using a 4-$T_{1/2}$ dead time after each triple delayed coincidence between the muon veto, the prompt γ-rays emitted in the capture and the following β decay. Since the efficiency of the muon veto is expected to be $> 90\%$, the overall cut efficiency depends on the probability to detect the prompt γ-rays from the neutron capture. Although the prompt γ-ray cascade is poorly known, the total energy amounts to 6.07 MeV [15]. Even in the most pessimistic case (namely, all the energy is emitted in a single photon) the efficiency of the rejection cut is larger than 50%, and possibly much better if more than one photon is emitted. Therefore the ^{77m}Ge background can be suppressed by at least a factor of two, to $5 \cdot 10^{-5}$ counts/(kg·keV·y) or less, for liquid argon.

[3] On the contrary, the ^{77}Ge background can be reduced by a factor of three using the segment anticoincidence.

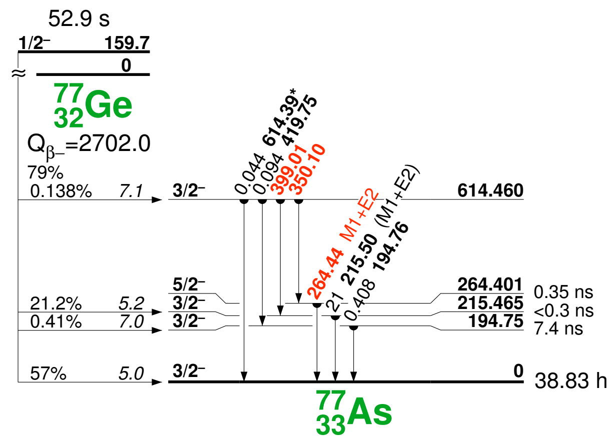

FIGURE 4. Decay scheme of the isomeric state ^{77m}Ge. The β-decay to ^{77}As has a branching ratio of 79% [14].

CONCLUSIONS

The muon-induced background of the GERDA experiment has been extensively simulated using the GEANT4-based MAGE framework. The results of the simulations show that the prompt background at the $Q_{\beta\beta}$ energy can be kept within the 10^{-4} counts/(kg·keV·y) specifications, provided that the efficiency of the Cherenkov muon veto is larger than 75%. The delayed muon-induced background is about 10^{-5} counts/(kg·keV·y) if the setup is filled with liquid nitrogen. For liquid argon filling, the delayed background is 10^{-4} counts/(kg·keV·y) because of the increased production of ^{77m}Ge by neutron capture. Since the ^{77m}Ge β-decay mostly gives single-site events, it is necessary a dedicated rejection cut based on triple coincidence with the muon veto and the capture γ-rays. Such a cut allows to reduce the delayed muon-induced background well below the 10^{-4} counts/(kg·keV·y) specification, even with liquid argon filling.

The GERDA design fulfills the background specifications with respect to muon-induced radiation at the depth of the Gran Sasso Laboratory, namely the muon-induced background does not limit the expected GERDA sensitivity.

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