17th International Conference on Topics in Astroparticle and Underground Physics IOP Publishing
Journal of Physics: Conference Series **2156** (2022) 012216 doi:10.1088/1742-6596/2156/1/012216

The cosmic muon-induced background for the LEGEND-1000 alternative site at LNGS

M. Neuberger(1), **L. Pertoldi**(1), **S. Schönert**(1), **C. Wiesinger**(1,2)
(1)Physik Department, Technische Universität München, Munich, Germany
(2)Max-Planck-Institut für Physik, Munich, Germany

E-mail: `moritz.neuberger@tum.de`

Abstract. The in-situ production of long-lived radio-isotopes by cosmic muon interactions may generate a non-negligible background for rare event searches in the deep subsurface. The delayed decay of $^{77(\mathrm{m})}$Ge has been identified as the dominant in-situ cosmogenic contributor for a neutrinoless double-beta decay search with ^{76}Ge. The future ton-scale LEGEND-1000 experiment requires a total background of $\leq 10^{-5}$ cts/(keV·kg·yr). Dedicated Monte Carlo studies of the $^{77(\mathrm{m})}$Ge background at the alternative LNGS site were performed. The addition of passive neutron moderators, in combination with a delayed coincidence strategy, results in a background contribution of $8.6{\times}10^{-7}$ cts/(keV·kg·yr) with an additional dead time of < 9%.

1. Introduction

The ton-scale Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay (LEGEND-1000) [1] is designed to operate 1000 kg of HPGe detectors with a ^{76}Ge enrichment fraction of $> 90\%$ in a cryostat of liquid argon (LAr) in a deep underground laboratory. LEGEND-1000 aims to probe neutrinoless double beta ($0\nu\beta\beta$) decay up to half-lives of 10^{28} yr and beyond. This requires a background of less than $1 \times 10^{-5}\,\mathrm{cts/(keV \cdot kg \cdot yr)}$.

One source of potential background is the so-called cosmic muon-induced background. When a cosmic ray hits the atmosphere, highly energetic muons are produced. These can penetrate earth down to depths of several kilometers. When such muons cross LEGEND-1000, particle showers can be produced in the various detector and shielding materials. These particles can cause two types of background: the first kind of background are prompt interactions of the shower constituents. Using the water Cherenkov muon detector enclosing the LAr cryostat, it was shown that the prompt muon-induced background can be discriminated with more than 99% efficiency [2]. The second kind of background are delayed decays of in-situ produced nuclei. For germanium-based experiments, the only relevant in-situ produced nucleus is $^{77(\mathrm{m})}$Ge [3]. It has a Q-value of 2.7 MeV and is produced by neutron capture on ^{76}Ge. At the relevant neutron energies ^{77}Ge and $^{77\mathrm{m}}$Ge are produced in about equal proportions [4]. The half-life is 11.2 h for ^{77}Ge and 53.7 s for $^{77\mathrm{m}}$Ge (see Figure 1). While ^{77}Ge decays coincide with a γ cascade of minimum 195 keV, $^{77\mathrm{m}}$Ge decays predominantly via pure ground-state decay, which is not identified by the standard LEGEND-1000 background rejection cuts.

We investigated the influence of the cosmic muon-induced background on LEGEND-1000 using a Geant4 simulation based on existing software [5]. This simulation uses a simplified geometry of LEGEND-1000. A rendering of the setup can be seen in Figure 2. It allows for

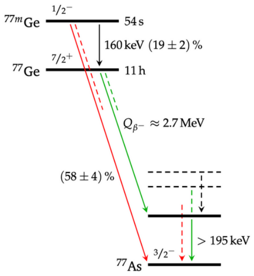

Figure 1. Simplified decay scheme of $^{77(\mathrm{m})}$Ge [4]. ^{77}Ge always coincides with a γ cascade of at least 195 keV, while $^{77\mathrm{m}}$Ge dominantly decays into the groundstate of ^{77}As.

Figure 2. Rendering of the LEGEND-1000 implementation in [5]

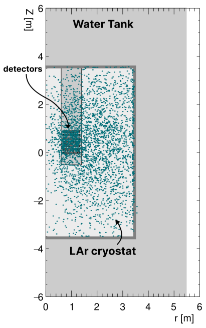

Figure 3. Reaction position of neutrons captured on ^{76}Ge.

easy adjustments and thus investigations of geometry and material dependencies. We validated this simulation against independent frameworks [4, 6] and obtained results consistent with data from the GERDA experiment.

For LEGEND-1000 two different sites are being considered - the so-called *Reference Site* at SNOLAB, with an overburden of 6 km.w.e, and the *Alternative Site* at the Laboratori Nazionali del Gran Sasso (LNGS), with 3.5 km.w.e. Simulations for SNOLAB predict a muon-induced background of 4.2×10^{-7} cts/(keV·kg·yr) [1]. At this site, the cosmic muon-induced background constitutes less than 5% of the total budget. Placing the same baseline setup at LNGS, our simulation predicts a background contribution of 2.7×10^{-5} cts/(keV·kg·yr). As this alone would exceed the total background budget, additional measures have to be taken to reduce this background.

2. Neutron Flux Reduction

The production rate of $^{77(\mathrm{m})}$Ge can be reduced by dedicated neutron shielding. The reaction positions of neutrons captured on ^{76}Ge are displayed in Figure 3. The majority of those neutrons originate from inside the LAr cryostat. Reducing the size of the LAr cryostat would reduce the neutron flux at the germanium detectors and thus the $^{77(\mathrm{m})}$Ge production rate. With the baseline cryostat of LEGEND-1000 (7 m diameter), the $^{77(\mathrm{m})}$Ge production rate at LNGS is (0.33 ± 0.01) nuclei/(kg·yr). When using a cryostat of the size used in LEGEND-200 (4 m diameter), the $^{77(\mathrm{m})}$Ge production rate decreases to (0.17 ± 0.01) nuclei/(kg·yr)[1]. Reducing the size of the cryostat would lower the muon-induced background by almost a factor of two, but results in a weaker shielding of γ radiation from the cryostat steel and thus is not pursued further here.

Another approach is to capture or slow down neutrons on their path to the germanium, e.g. by polyethylene (PE) structures[2]. The large amount of hydrogen effectively moderates neutrons. One can also introduce other nuclei into the PE that can capture the neutrons like boron. Boron has a relatively high capture cross section and coincides with the emission of an α particle and a γ of 478 keV, well below $0\nu\beta\beta$-relevant energies. In our investigation we chose to use 5% borated PE as well as pure PE. Another issue one has to consider is the additional γ radiation from impurities in the shielding material. It has been shown that PE can be fabricated with about 0.1 mBq/kg ^{232}Th and 0.4 mBq/kg $^{238}\mathrm{U}_{\mathrm{lower}}$ [7], though with a mass of several tonnes of PE in

---

[1] Production uncertainties quoted are statistical only. The systematic uncertainty are approximately 35% [4].

[2] Thanks to the surrounding LAr, the ^{77}Ge production appears dominant at high neutron energies [4].

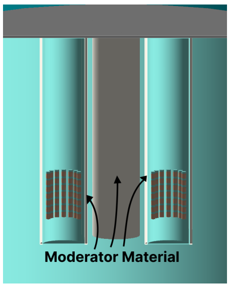

Figure 4. Design 1 - close-by enclosure

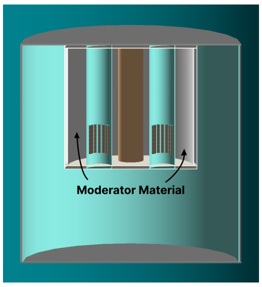

Figure 5. Design 2 - far enclosure

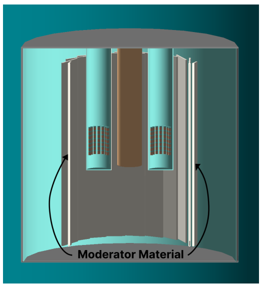

Figure 6. Design 3 - close-by panels

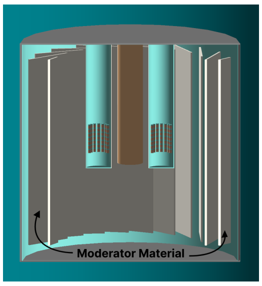

Figure 7. Design 4 - far panels

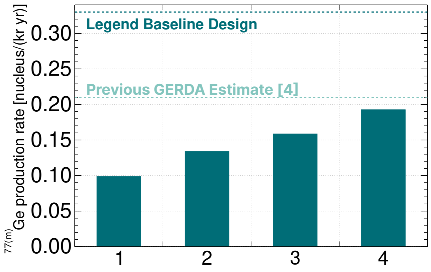

Figure 8. Design Dependence (using 5% borated PE). The Designs are displayed in Figs. 4-7.

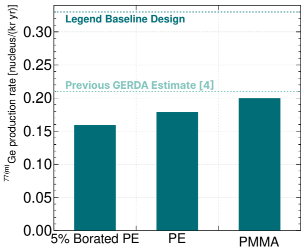

Figure 9. Material Dependence (using Design 3)

the cryostat, this woube be a considerable background source. It is also expected that 5% borated PE would have an even higher level of impurities. It is also of interest to look for alternative materials with very high radio purity. Such a material would be e.g. polymethylmethacrylat (PMMA). In comparison to PE it has a larger mass ratio of oxygen which reduces its neutron moderation. Radio purities of < 0.5 mBq/kg ^{232}Th and < 0.1 mBq/kg ^{238}U (^{226}Ra) have been reported [7].

Using PMMA, pure and 5% borated PE, we investigated the $^{77(\mathrm{m})}$Ge production rate. Overall four different designs were investigated, displayed in Figure 4 to Figure 7. Design 1 consists of neutron moderators right around the copper reentrant tubes of LEGEND-1000 with a thickness of 5 cm. For this design, the radiopurity of the moderator is most critical. Design 2 has a cylindrical shape with a radius of 2 m, same height as the reentrant tubes and a thickness of 10 cm. This design is similar to one used in a previous investigation in [6]. Design 3 represents a turbine-like geometry. The idea is that neutrons produced at larger radii are moderated and captured close to their production location. Thus, the required moderator mass would be located further away from the germanium detectors and backgrounds from the moderator material would be strongly attenuated. That is also the idea behind Design 4 which has longer panels that extend also further out from the center.

Using 5% borated PE as neutron moderator material, we found production rates for $^{77(\mathrm{m})}$Ge displayed in Figure 8. Also shown in dashed lines is the production rate of the baseline design without any moderators as well as the result of previous GERDA simulations, which feature a smaller LAr volume. As expected Design 1 performs best, followed by Design 2 due to its high mass of neutron moderator. Design 3 is slightly less efficient but still reduces the production rate by a factor of two. Design 4 is least efficient, but still has a significant impact.

In Figure 9 the production rates for Design 3 are shown for pure PE, 5% borated PE and PMMA, which highlights the moderator material dependence. The 5% borated PE results in the lowest production rate, however, the pure PE and the PMMA also show significant reductions.

3. Delayed Coincidence Rejection

$^{77(\mathrm{m})}$Ge is predominantly produced in high-energy neutron captures during muon-induced showers with high neutron multiplicity. Identification (tagging) of such production events allows delayed coincidence rejection of the subsequent short lived $^{77\mathrm{m}}$Ge decay. The long-lived ^{77}Ge decays are discriminated efficiently thanks to their gamma de-excitation, which lead to mulit-site interactions and/or signals in the liquid argon detector.

There are two types of observable one can use to identify high neutron multiplicity muon showers and/or $^{77(\mathrm{m})}$Ge production: First, one can use the germanium signal to identify high energy depositions by shower particles or γ emission from neutron capture. Second, one can use the coincidence signal in LAr instrumentation and the water tank to tag capture of neutron siblings in the respective volumes.

Showering muons may trigger many germanium detectors. Neutron captures that appear prompt ($<10\,\mu$s) within such showers may hide within all the other energy depositions, whereas γs emitted in later captures are a smoking gun for neutron production within the shower. We find no strong topological correlation between shower-induced Ge triggers and the production position of the $^{77(\mathrm{m})}$Ge. However for the neutron capture γs, there is a strong correlation between triggered detectors and the neutron capture site. When investigating the distance of the $^{77(\mathrm{m})}$Ge to the closest triggered detector, a strong position dependence is found. By vetoing detectors around those that triggered, $>95\%$ of $^{77\mathrm{m}}$Ge decays can be removed with $<8\%$ dead time.

In a high neutron multiplicity muon shower the capture on ^{76}Ge is typically only one member of a much larger family of captures appearing all over the setup, mostly in the LAr and the surrounding water tank. Most neutron captures on LAr occur after neutron thermalization and with a characteristic capture time of $270\,\mu$s [4]. Such captures can be detected, with e.g. chose a tagging threshold of $>200\,$keV on the delayed LAr signal. To detect those neutrons that escape into the water tank, we suggest to dope water with gadolinium. This would boost the capture cross section and allow for a bright signal that can be seen with a dedicated Cherenkov instrumentation. In this analysis, we assumed that all neutron captures 1 m away from the cryostat are detectable. We chose a conservative multiplicity of 50 and more neutron captures in this volume as tagging condition. The combination of this set of measures - germanium detector signal, delayed captures in the LAr and neutron siblings in the Gd neutron tagger - results in a $^{77\mathrm{m}}$Ge cut efficiency of 97.7% with less than 9% dead time.

4. Conclusions

Combining passive neutron flux moderation of using 5% borated PE in Design 3 (turbine-like structure with shorter panels) with active delayed coincidence approach we obtain a $^{77(\mathrm{m})}$Ge background index of 8.6×10^{-7} cts/(keV·kg·yr). This contributes with less than 10% to the total projected background index for LEGEND-1000, establishing LNGS as a potential site for the next generation experiments.

References

[1] N. Abgrall et al. (LEGEND Collaboration) `arXiv:2107.11462` (2021)
[2] K. Freund et al., *Eur. Phys. J. C 76 (2016) 5, 298*
[3] L. Pandola et al., *Nucl. Instr. Methods A 570 (2007) 149*
[4] C. Wiesinger et al., *Eur. Phys. J. C (2018) 78:597*
[5] Y. Ramachers and B. Morgan of Warwick University (`https://github.com/drbenmorgan/warwick-legend`)
[6] C. J. Barton, *Proceedings of Science (ICHEP2020) 195*
[7] P. Amaudruz et al., *Astropart. Phys. 108 (2019) 1-23*