PROCEEDINGS OF SCIENCE

Background Modeling for LEGEND-200

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LEGEND-200 is the first phase of LEGEND, a ^{76}Ge-based experiment designed to observe a lepton number violating process: neutrinoless double-beta ($0\nu\beta\beta$) decay. Observation of this process would demonstrate neutrinos to be Majorana particles. The first 101 enriched ^{76}Ge detectors, with a total mass of 140 kg, have been installed and are currently taking data at the Laboratori Nazionali del Gran Sasso (LNGS), Italy. A comprehensive simulation campaign is underway to study and model the background contributions from various components in the experimental setup. In this work, we will present the current results of the simulation campaign as well as a preliminary background model for the LEGEND-200 experiment.

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1. Introduction

LEGEND is a ^{76}Ge based $0\nu\beta\beta$ decay experiment [1]. LEGEND-200, the first phase of LEGEND, is operational at Laboratori Nazionali del Gran Sasso (LNGS), Italy in the previously-existing GERDA infrastructure [2]. About 140 kg of detectors enriched in ^{76}Ge have been installed in LEGEND-200, consisting of BEGe and Coaxial detectors previously deployed in GERDA, PPC detectors previously deployed in the MAJORANA DEMONSTRATOR [3], and new large-mass ICPC detectors produced specifically for LEGEND [4]. The ICPC detectors combine the excellent energy resolution and pulse-shape discrimination capabilities of BEGes and PPCs with detector masses in excess of 2 kg. For this analysis, exposure from BEGe and ICPC detectors is considered, totalling 10.10 kg·yr: 2.09 kg·yr from BEGe detectors and 8.00 kg·yr from ICPCs detectors. MJD PPCs and GERDA Coaxial detectors are not included in this work.

2. Background Modeling tools

Background sources for LEGEND include radioactive decays from the array components, $2\nu\beta\beta$ in the Ge detectors, γ and n from the laboratory environment and cosmic ray muons. Modeling the background contribution is essential for LEGEND to reach its background goal of 2×10^{-4} counts/(keV kg yr) for LEGEND-200. Accurately modeling the background contribution will help us in the hardware upgrade for LEGEND-200 and, in future, to optimize the construction and predict the performance of LEGEND-1000 [5], a ton-scale ^{76}Ge based $0\nu\beta\beta$ decay experiment.

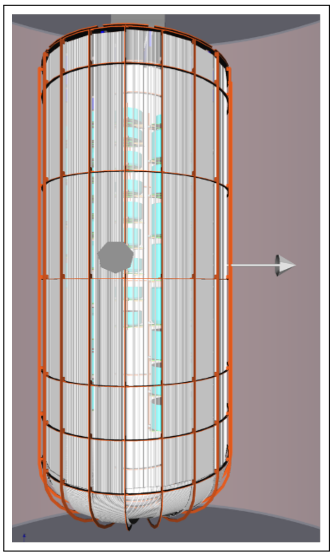
A complex simulation workflow has been developed to be used with LEGEND-200 as well as LEGEND-1000 in the future. To ensure a successful alignment of simulations with the observed data, it is imperative that the simulation geometry closely replicates the precise configuration of the real installation. Construction of geometry and Monte-Carlo simulations of radioactive decay of isotopes are done using an in-house developed, Geant4 based software, called MaGe [6]. An illustration of the geometry created in MaGe is showed in Figure 1.

3. Optical response model

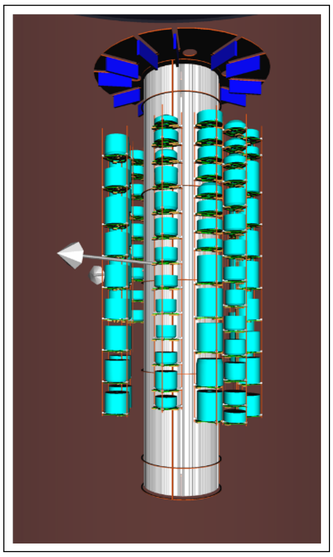
One of the suppression techniques used in LEGEND is Liquid Argon (LAr) active suppression. The scintillation properties of LAr [7] can be used to veto the events that deposit energy in LAr. To model the optical response of the LAr instrumentation used in LEGEND, a set of optical maps have been generated using separate simulations in MaGe. Photons with a Gaussian distributed wavelength centered at 128 nm with a standard deviation of 10 nm are generated in LAr volume and probabilities of them being detected in SiPMs are calculated as seen in the Figure 2. This helps us estimate the number of photo-electrons (NPE) detected from each energy deposition in LAr using the following :

$$\langle NPE \rangle = \sum_{i}^{\text{steps}} E_i \times P_i(x, y, z) \times Y \times Q.E. \tag{1}$$

where $\langle NPE \rangle$ is the estimated number of photo-electrons detected in SiPMs following an energy deposition in LAr, E_i is the energy deposited in each step in LAr, $P_i(x, y, z)$ is the probability of photons being detected from that location, Y is the yield of LAr taken to be about $20,000$ photons/MeV,



(a)



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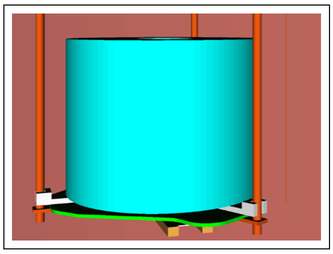

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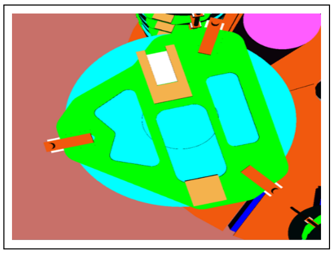


(d)

Figure 1: Visualization of LEGEND-200 geometry created in MaGe. (a) A complete view of the LEGEND-200 array with optical fiber shroud covering the detector strings. (b) A view of the detector strings suspended from the copper plate and the inner optical fiber shroud. (c) Side view of an individual detector unit. (d) Bottom view of a detector unit showing the PEN tile, HV and signal readout.

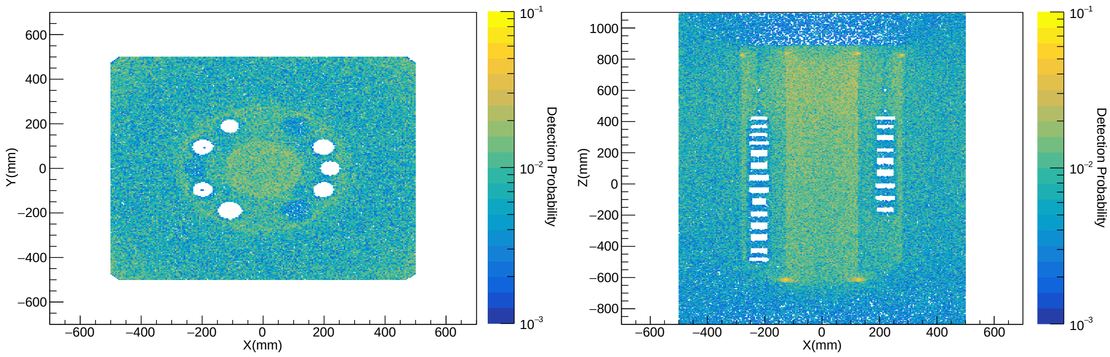
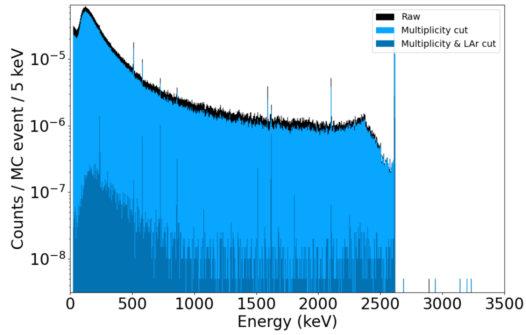


Figure 2: XY and XZ slice of the probability distribution map of LAr. Color axis denotes the photon detection probability for a photon generated at that location

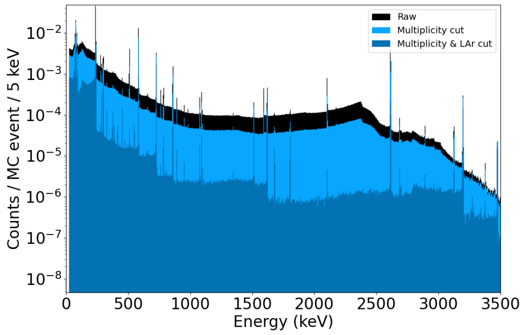
$Q.E.$ is the quantum efficiency of the SiPMs supplied by the manufacturer. $\langle NPE \rangle$ is then used to emulate the veto performance of the LAr shield.

4. Pulse Shape Analysis

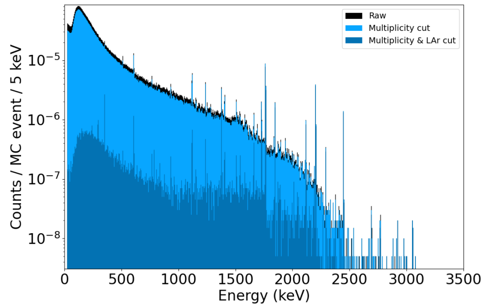
$0\nu\beta\beta$ is a single-site event (SSE). All of the energy from the decay is deposited in a very small volume. Most of the backgrounds in LEGEND are multi-site events (MSE)[8]. LEGEND detectors are capable of discriminating between SSE and MSE and thus reject the multi-site energy



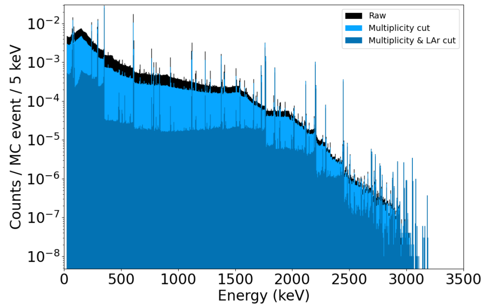
(a) ^{232}Th chain decay from a far component



(b) ^{232}Th chain decay from a near component



(c) ^{238}U chain decay from a far component



(d) ^{238}U chain decay from a near component

Figure 3: Typical PDFs produced from Monte Carlo simulations. The histograms top (bottom) row denote the ^{232}Th (^{238}U) decay chains and the left (right) columns are from contamination in the far (near) components in the detector array.

depositions. To model this behaviour in our background model, drift times for the holes to reach the point contact are calculated for each detector. A drift time cut-off is set to match the detector response to identify and reject multi-site events from our simulation.

5. Monte Carlo simulations and probability density functions

Monte Carlo simulations are performed in MaGe to produce the probability density functions (PDFs). $2\nu\beta\beta$ decay of ^{76}Ge in the interior of the detectors as well as radioactive decay background simulations of the known contaminants from within and around the detectors are simulated. Detector properties such as energy resolution, dead layer correction and individual detector exposure during the data taking period are taken into account during post-processing in mage-post-proc [9] before producing PDFs. Figure 3 has some example PDFs from ^{232}Th and ^{238}U decay chains at a near and far component of the array. As it can be seen from the figure, LAr active veto is extremely successful in suppressing background radiation particularly from far away components.

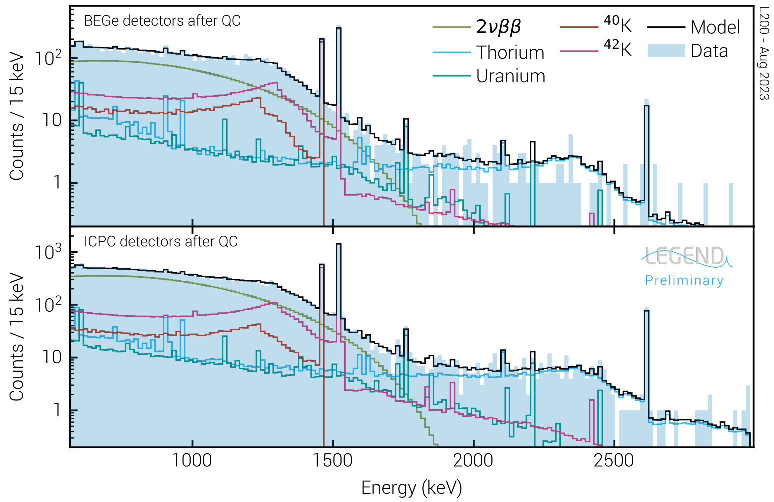


Figure 4: Background decomposition of the LEGEND-200 data for ICPC and BEGe detectors using BAT.

6. Background Fitting

Background decomposition for the simulation result and LEGEND-200 dataset is done using Bayesian Analysis Toolkit [10][11] using a Poissonian likelihood function which is defined as :

$$\mathcal{L}(p_1, p_2 \ldots p_m \mid \text{data}) = \prod_i^{\text{data set}} \prod_j^{\text{bins}} \text{Poisson}[n_{ij} \mid \sum_k p_k \nu_{ij}] \tag{2}$$

where $n_{ij}(\nu_{ij})$ is the number of counts in the j^{th} bin of the i^{th} data set (pdf), $p_1, p_2 \ldots p_m$ are the weights of the linear combination of the histograms on which statistical inference is performed.

Screening measurements that were conducted for Majorana Demonstrator [12] and GERDA Experiment, along with updated measurements for LEGEND, used to assess the radio-contamination of the components used in LEGEND-200 have been used as priors with 1σ uncertainty associated with the measurements. In cases where the measurements only have a 90% C.L. upper limit available, an exponential prior distribution with 90% area covering the 0-90% upper limit C.L. is used. For components for which radio assay measurements are unavailable, a uniform prior distribution has been employed.

7. Conclusions

We have presented a background decomposition for LEGEND-200 initial data before any application of active suppression techniques using a multivariate Bayesian fitting method. Given the low statistics of the data, the results of the background fitting are able to describe the data collected for ICPC and BEGe type of detectors as seen in Figure 4. We anticipate a refinement of the background index after the implementation of LAr active suppression and pulse shape analysis into our background model. Additionally, it will help us to pinpoint the major sources of contamination, offering valuable insights for upcoming hardware upgrades and enhanced predictive capabilities for background assessment in the LEGEND-1000 experiment.

References

[1] N. Abgrall et al., *The large enriched germanium experiment for neutrinoless double beta decay (LEGEND)*, in *AIP Conference Proceedings*, vol. 1894, AIP Publishing, 2017.

[2] M. Agostini et al., *Upgrade for Phase 2 of the Gerda experiment*, *The European Physical Journal C* **78** (2018) 388.

[3] M. Collaboration, S.R. Elliott, N. Abgrall, E. Aguayo, F.T.A.I. au2, A.S. Barabash et al., *The majorana demonstrator: A search for neutrinoless double-beta decay of germanium-76*, 2013.

[4] R.J. Cooper, D.C. Radford, P.A. Hausladen and K. Lagergren, *A novel hpge detector for gamma-ray tracking and imaging*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **665** (2011) 25.

[5] N. Abgrall et al., *LEGEND-1000 preconceptual design report*, *arXiv:2107.11462* (2021) .

[6] M. Boswell et al., *MaGe-a Geant4-based Monte Carlo application framework for low-background germanium experiments*, *IEEE Transactions on Nuclear Science* **58** (2011) 1212.

[7] T. Heindl et al., *The scintillation of liquid argon*, *Europhysics Letters* **91** (2010) 62002.

[8] S. Alvis et al., *Multisite event discrimination for the MAJORANA DEMONSTRATOR*, *Physical Review C* **99** (2019) 065501.

[9] "MAGE Post-Processing: Analysis tools for the LEGEND Experiment." https://github.com/legend-exp/mage-post-proc.

[10] A. Caldwell, D. Kollar and K. Kröninger, *BAT–The Bayesian analysis toolkit*, *Computer Physics Communications* **180** (2009) 2197.

[11] "Hmixfit: Fit linear mixtures of histograms to data with Bayesian statistics." https://github.com/gipert/hmixfit.

[12] N. Abgrall et al., *The MAJORANA DEMONSTRATOR radioassay program*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **828** (2016) 22.