Mitigation Strategies for ^{42}Ar/^{42}K Background Reduction using Encapsulation with Ultra-Pure Plastic for the LEGEND Experiment

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Abstract. Neutrinoless double-beta ($0\nu\beta\beta$) decay is the most compelling approach to determine the Majorana nature of the neutrino and measure the effective Majorana neutrino mass. The LEGEND collaboration is aiming to look for $0\nu\beta\beta$ decay of ^{76}Ge with unprecedented sensitivity. If underground-sourced argon is not available, ^{42}K, the decay progeny of the cosmogenically-induced isotope ^{42}Ar in the liquid-argon active veto, could create a challenging background for the $0\nu\beta\beta$ signal. We are studying methodologies to mitigate this background. Encapsulation of germanium detectors with 3D-printed technologies using low-background material is currently under investigation. Simulation results of Poly(ethylene 2,6- naphthalate) (PEN) encapsulation of germanium detectors and plans to study other potential materials are presented. The simulation shows that 8 mm of PEN material around the Ge detector sufficiently quench the energy of the decay electron, though the amount of the extraneous material can potentially be lowered if additional mitigation strategies are employed. The simulation also shows that scintillation in 2 mm of PEN can be used to tag the ^{42}K background events.

INTRODUCTION

The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay (LEGEND) is an ultra-low-radioactive-background experiment designed to detect the $0\nu\beta\beta$ decay signal in ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV) [1]. Performance parameters of the 200-kg and 1000-kg phases of the LEGEND are listed in Table I. Backgrounds in the region of interest (ROI) can be produced by detector components such as the detector mounts, front-end electronics, cables, optical fibers, the re-entrant tube, liquid argon, and cryostat, among other sources.

The work presented here is focused on the concepts and techniques to mitigate the background caused by argon, i.e. the small concentration of ^{42}Ar via its daughter isotope ^{42}K in atmospheric argon.

^{42}Ar / ^{42}K Background in LEGEND

Ge detectors are immersed in liquid argon in the LEGEND cryostat. For LEGEND, liquid argon serves as (i) coolant: because Ge detectors cannot be fully depleted at room temperature, they must operate at cryogenic temperature, (ii) a veto for background events: liquid argon is a scintillator; therefore, by detecting scintillation light near Ge detectors, many background signals can be effectively suppressed. However, natural argon contains a small amount of ^{42}Ar,

Experiment	**LEGEND-200**	**LEGEND-1000**
Status	In commissioning	Planned
Location	LNGS	LNGS / SNOLAB
Isotope	^{76}Ge	^{76}Ge
Total mass	200 kg	1000 kg
Exposure	1 t yr	10 t yr
Background Index	2×10^{-4} cts / (keV kg yr)	$< 1\times10^{-5}$ cts / (keV kg yr)
Discovery Sensitivity	10^{27} yr	1.3×10^{28} yr
Live time	5 yr	10 yr
Majorana neutrino mass (discovery sensitivity)	< 34 – 78 meV	< 9 – 21 meV

TABLE I. The specifications for the two experimental phases of the LEGEND program.

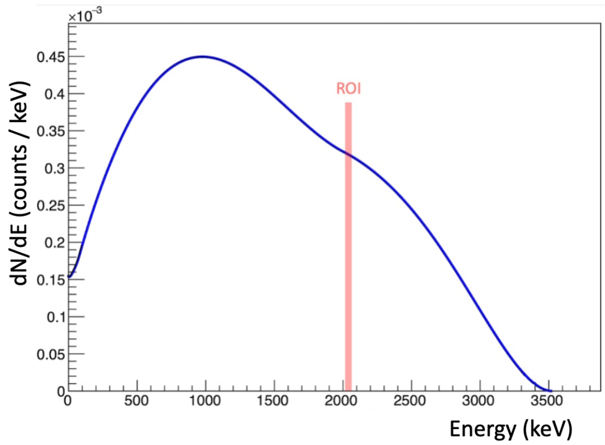


FIGURE 1. The energy distribution of ^{42}K β^- decay. The vertical band depicts the ROI. Data is taken from Ref. [5].

which in turn produces ^{42}K, a source of background. GERDA Phase II [2] and DEAP-3600 [3] reported the presence of ^{42}K in liquid argon. nEXO [4] also reported the study of ^{42}K in liquid xenon.

The origin of ^{42}Ar and ^{42}K in atmospheric argon occurs as follows. Gaseous argon in the upper atmosphere is constantly bombarded with cosmic rays. When a cosmogenically produced α particle interacts with atmospheric argon, it produces a small concentration of ^{42}Ar via the reaction, $^{40}\mathrm{Ar} + \alpha \rightarrow {}^{42}\mathrm{Ar} + \mathrm{p} + \mathrm{p}$. Liquid argon is normally extracted from the atmosphere, so ^{42}Ar is present. ^{42}Ar is a long-lived radioactive isotope, with a half-life of 32.9 y. It undergoes β^- decay via $^{42}\mathrm{Ar} \rightarrow {}^{42}\mathrm{K}^+ + \beta^- + \overline{\nu_e}$ with Q_β = 0.599 MeV. Since $Q_\beta < Q_{\beta\beta}$, ^{42}Ar does not cause background in the ROI for LEGEND.

However, the daughter isotope of ^{42}Ar is ^{42}K, which is also radioactive, with a short half-life of 12.36 h. It undergoes β^- decay via $^{42}\mathrm{K}^+ \rightarrow {}^{42}\mathrm{Ca}^{++} + \beta^- + \overline{\nu_e}$ with Q_β = 3.525 MeV. The β-decay spectrum is shown in Figure 1. Since $Q_\beta > Q_{\beta\beta}$, the β emitted in the ^{42}K decay causes background in the ROI.

In particular, $^{42}\mathrm{K}^+$ can be attracted by the electric field of the detectors and as a result accumulate on the Ge surface. Thermally driven convection in liquid argon also affects the dynamics of both neutral (^{42}Ar) and charged ($^{42}\mathrm{K}^+$, β^-) particles. Backgrounds from ^{42}K decay are expected to comprise 30–40% of LEGEND backgrounds in both phases of the experiment. Therefore, it is essential to reduce the concentration of ^{42}Ar in the argon veto, or otherwise mitigate this background.

The most promising approach to dramatically reduce ^{42}Ar backgrounds is the use of underground argon (UGLAr), i.e. argon extracted from deep underground sources. UGLAr is exposed to a much lower flux of cosmic particles, with no mechanism for ^{42}Ar production by high-energy α particles. We plan to coordinate with the DarkSide-20k effort [6] to use the URANIA plant to produce UGLAr extracted from CO_2 wells in Colorado, which will then be transferred to the ARIA plant or other facilities for additional chemical purification. The LEGEND-1000 project is in negotiations to obtain approximately 18 tonnes of UGLAr. However, given the high risk associated with this background, the collaboration is investigating additional strategies to suppress the ^{42}Ar background. These additional techniques include (i) encapsulation of Ge detectors, (ii) slightly depleting atmospheric sourced argon of ^{42}Ar, (iii) enclosing the detector strings with an ultra-pure nylon shroud surrounding a reduced volume of argon as in LEGEND-200, (iv) fabricating Ge detectors with thicker n+ dead layers, (v) doping liquid argon with non-quenching impurities to neutralize ^{42}K ions, (vi) better pulse-shape discrimination of β-induced events. Many of these techniques can be used to reduce backgrounds whether or not UGLAr is available. In the following, we focus on the encapsulation of the Ge detectors with low-radioactivity scintillating material.

ENCAPSULATION OF THE GERMANIUM DETECTOR

GERDA Phase II data show the viability of encapsulation for ^{42}K background suppression [2, 7]. GERDA used transparent nylon mini-shrouds to limit the volume of argon that could drift into the vicinity of the Ge detectors. However, to completely eliminate the possibility for ions to drift to the Ge detectors, we need to provide complete

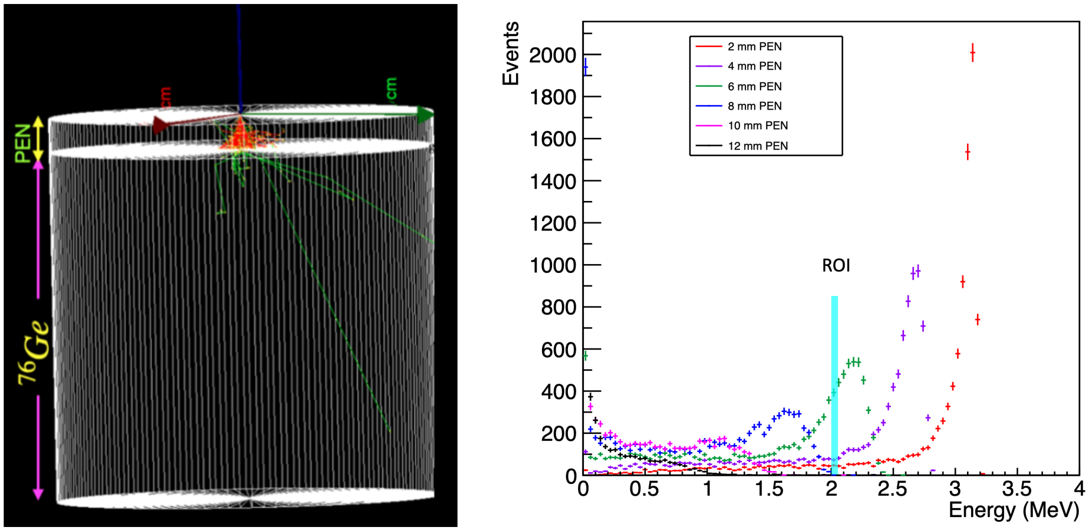


FIGURE 2. Left: Simulation of the detector geometry, with the trajectories of the electrons shown in the PEN layer and the resulting gamma trajectories shown in Ge. **Right:** Simulation results of energy deposition in Ge for six different thicknesses of PEN. The histograms peak below the ROI (vertical band) for PEN thicknesses $\geq$ 8 mm.

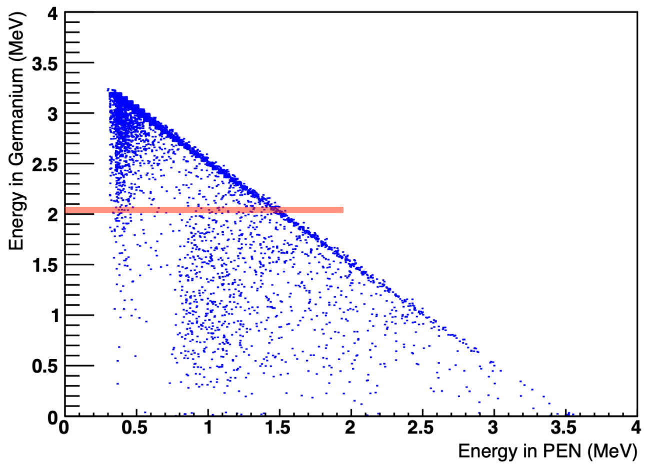
encapsulation. 392 Ge detectors with a total mass of 1000 kg of ^{76}Ge will be deployed in the LEGEND-1000 cryostat. The detectors will be of different sizes and shapes, so capsules would need to be custom-built for each detector. 3D printing is a viable solution for encapsulation to meet these demands, and Oak Ridge National Laboratory (ORNL) facilities are equipped with state-of-the-art 3D printers well-suited for Research and Development (R&D) studies. Custom-produced Poly(ethylene 2,6- naphthalate) (PEN) is one of the materials considered for the encapsulation. PEN is transparent plastic scintillator that has proven its capability as a wavelength shifter from vacuum ultraviolet (VUV) into the blue region of the visible spectrum [8, 9]. PEN has the same mechanical stability as copper at cryogenic temperature, and LEGEND-200 employs PEN as a baseplate to support each Ge detector. Due to its favorable characteristics, we consider an encapsulation design made entirely of PEN.

Simulation Results of Encapsulation

GEANT4 [10] is used to simulate the geometry of PEN-encapsulated Ge. A layer of PEN is deposited over the top cross-section of the Ge detector and surrounded with liquid argon, as shown in Figure 2 (left). At the center of the PEN disk, a source of electrons with energy of 3.525 MeV, equal to Q_β of ^{42}K, is simulated. We select the direction of the particle momenta to be towards the PEN. We calculate the energy deposition by the electrons in Ge for several PEN thicknesses, as shown in Figure 3 (right). The simulation shows that 8 mm of PEN are required to reduce the energy of 3.525-MeV electrons to below the ROI. So much passive material next to the Ge detector can create another source of radioactive background. This simulation, however, does not take into account the dead layer present on the surface of the Ge detectors (1–2 mm thick) or the role of pulse-shape rejection of near-surface events. Figure 3 (right) shows the deposited energy correlation in a 9-cm-thick Ge detector versus 2-mm-thick PEN plate, from the incident electron. From this simulation we can conclude that 2 mm of scintillation material next to the Ge detector can efficiently tag products of ^{42}K decay if we achieve the threshold of 0.3 MeV in PEN. We show this simulation as an illustrative example and not necessarily viable encapsulation design.

R&D FOR ENCAPSULATION

R&D for encapsulation of Ge detectors is currently ongoing at ORNL. The selection of material for encapsulation is under investigation. An ideal material for encapsulation should be (i) radiopure, (ii) 3D printable, (iii) transparent, (iv) scintillating, (v) mechanically stable at cryogenic temperature, and should not contaminate liquid argon by outgassing.



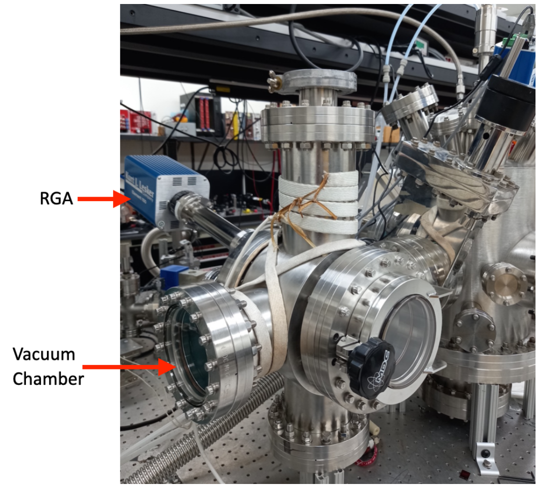


FIGURE 3. Left: Simulated energy deposition in 9-cm-thick Ge versus energy deposition in 2-mm-thick PEN. The horizontal band shows the region of the ROI. A detection threshold in PEN of 0.3 MeV would allow tagging of all events in Ge that can produce background in the ROI. **Right:** Recently assembled residual gas analyzer mounted on the outgassing vacuum chamber in the Physics Division at ORNL.

In an attempt to choose the appropriate material for encapsulation, we have compiled a database of resins based on their physical properties. We are also considering tests of resins used for medical and dental purposes, as such resins have relatively high tensile strength compared to the resins used for engineering designs.

As part of our R&D plan, we will perform the outgassing, radiopurity, optical, mechanical and cryogenic tests for the encapsulation material, which are described as follows:

1. Outgassing measurements– contamination of the material can be determined by outgassing, where the molecular species present inside the encapsulation sample can be identified. UTK-ORNL jointly commissioned a setup for outgassing measurements at ORNL. We have assembled a residual gas analyzer (RGA) connected to a vacuum chamber, as shown in Figure 3. The encapsulation materials are placed in the vacuum chamber. Prior to the outgassing measurements, a chamber pressure of around 5×10^{-7} Torr is maintained by the combination of roughing and turbo pumps. Gaseous molecules present in the encapsulation sample are released quickly in vacuum and are detected in the RGA.

2. Radiopurity measurements– we plan to evaluate radioactive impurities in the sample after the outgassing measurements. In an attempt to meet LEGEND background goal, any supplementary materials used in the detector must have an ultra-low concentration of the U-238 and Th-232 decay chains and must not introduce impurities into the liquid argon, which can quench scintillation light. We will perform ICP-MS and gamma ray spectrometry. The material having the highest level of radiopurity will be selected as a potential candidate for encapsulation tests of Ge detectors.

3. Optical measurements– each material used for encapsulation will undergo optical testing. The light produced from scintillation in encapsulation will be detected by the same optical readout that used for argon veto and therefore enhance total veto performance. We intend to perform several measurements of the optical response, including photon yield, refractive index, attenuation length, peak emission wavelength and reflectivity. Existing equipment for optical reflectivity measurements at ORNL will be used, and we will establish an extensive optical test setup.

4. Mechanical measurements– the encapsulation material will remain in the cryogenic environment of LEGEND-1000 for at least 10 years. Therefore, the structural integrity of the material is crucial, and every material under considerations will also undergo extensive mechanical testing after the optical measurements. Measurement of the tensile strength of each sample will be determined. For this purpose we intend to establish a mechanical testing setup. We are planning to perform initial mechanical measurement at liquid nitrogen temperature. We plan to perform measurement in liquid argon for the final product.

5. Cryogenic measurements– Ge detectors with completed encapsulation will be immersed in liquid argon in the LEGEND-1000 cryostat. We are currently planning to custom-build a cryostat with a VUV optical readout at ORNL. We will test the encapsulated Ge detector performance and ^{42}K signal suppression in atmospheric argon, enriched with ^{42}Ar.

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