PROCEEDINGS OF SCIENCE

Detector characterization for LEGEND-200 experiment

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The LEGEND collaboration is developing an experimental search for the neutrinoless double-beta ($0\nu\beta\beta$) decay of the ^{76}Ge isotope. Its first phase, LEGEND-200, uses 200 kg of ^{76}Ge-enriched high-purity germanium (HPGe) detectors in an active liquid argon shield and is currently under construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Inverted coaxial point-contact (ICPC) detectors are deployed in the experiment. Their unique geometry provides an excellent energy resolution in a broad energy range and impressive discrimination of signal against background events. LEGEND's search for $0\nu\beta\beta$ requires a precise understanding of the behavior of germanium detectors, requiring extensive detector characterization. The acceptance tests aim to verify the performance of the delivered detectors meets specifications and to determine their optimal operational parameters. A review and the first results of the detector characterization program are discussed.

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1. LEGEND experiment

In double-beta ($2\nu\beta\beta$) decay, two neutrons of the same nucleus are transformed to two protons with the emission of two electrons and two anti-electron neutrinos. Theoretically, double-beta decay without the emission of the two neutrinos ($0\nu\beta\beta$ decay) is possible [1]. It violates the lepton number by two units and, if found, would indicate new physics beyond the standard model of particle physics. The search for $0\nu\beta\beta$ decay is appealing as its existence would constrain properties of neutrinos like their nature (Dirac or Majorana) and mass.

LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) [2] will conduct a $0\nu\beta\beta$ decay search using the candidate isotope ^{76}Ge. LEGEND is building on the success of the Gerda [3] and Majorana Demonstrator [4] collaborations. The first stage of the experiment, LEGEND-200, will improve the latest achievements by entering a new background regime in the region of interest around $Q_{\beta\beta}$. It aims to achieve a discovery sensitivity ($T^{0\nu}_{1/2}$) greater than 10^{27} yr within 5 years measurement time and will probe the effective Majorana mass ($m_{\beta\beta}$) down to $\sim$ 50 meV. The LEGEND-200 experiment operates germanium detectors immersed in liquid argon (LAr) in an upgrade of the Gerda infrastructure at LNGS. Fig.1 shows a schematic view of

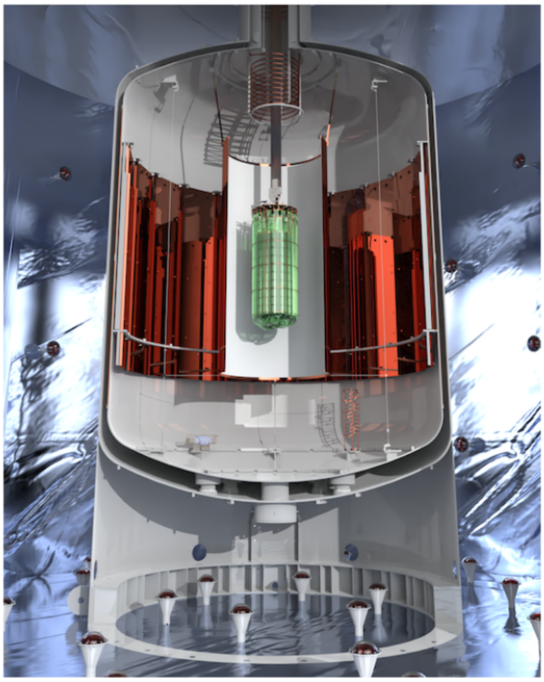

Figure 1: Detector systems positioned in the center of the LAr cryostat equipped with wavelength-shifting reflectors. The cryostat is placed in a water tank instrumented with photomultipliers and used as a Cherenkov muon detector.

the experiment. LEGEND-200 will have about 200 kg of detector mass, using the existing 65 kg of enriched detectors from the Majorana Demonstrator and Gerda, and an additional 140 kg of newly produced ICPC (inverted coaxial point contact) detectors. To remain nearly background-free, LEGEND-200 requires the reduction of background by a factor of 2.5 w.r.t. what has already been achieved by Gerda. This improvement is easily obtained due to the larger average detector mass. Consequently, the number of nearby components, cables, and holder materials per kilogram is reduced. The radiopurity of these near-detector components is essential, as well. This can be reduced by using low-mass MAJORANA DEMONSTRATOR style components. The detector supports are made of scintillating plastic such as active Polyethylene naphtalate (PEN) that has replaced the optically inactive silicon plates used in GERDA. Low-noise electronics have been achieved combining the Liquid Argon-operated preamplifier of GERDA with the ultra-clean Low Mass Front-End of MAJORANA. Finally, a new reflector surrounding the detector array has been implemented to improve the scintillation light collection, and higher-purity LAr with better light transmission and light yield has been utilized.

2. HPGe detectors

The LEGEND experiment operates germanium diodes made from enriched material. Germanium detectors provide the superior energy resolution of 0.2% at $Q_{\beta\beta}$ = 2039.061 ± 0.007 keV compared to other searches with different isotopes. The crystal growing procedure results in naturally low internal radioactivity and is a well-established technology. The source itself acts as a detector as well, yielding high detection efficiency. On the other hand, since the $Q_{\beta\beta}$ value is relatively low it is more challenging to reach a sufficiently low background, and an enrichment is required due to the small abundance of $0\nu\beta\beta$ isotope in nature.

The ICPC detectors present many advantages w.r.t. the other high purity germanium (HPGe) detectors already used in GERDA and MAJORANA. They are enriched up to 92% in ^{76}Ge and provide an excellent energy resolution and pulse shape discrimination (PSD) performance. Since they are significantly larger, the required total amount of channels decreases, resulting in fewer nearby components and hence less background. Finally, their particular geometry provides a better surface to volume ratio. The characterization of the detectors before their implementation in the LEGEND cryostat is fundamental not only because it is strongly connected with the background index, but also to provide high discovery sensitivity with negligible contribution from $2\nu\beta\beta$ decays, and finally to better probe $T^{0\nu}_{1/2}$. In the background-free regime, the sensitivity of the half life of $0\nu\beta\beta$ decay scales with

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot a \cdot \epsilon \tag{1}$$

where ε is the detection efficiency, a is the isotopical abundance of the $\beta\beta$ emitter and ϵ is the total exposure given by the product of the total detector mass and the run time of the data taking. Once the nominal bias voltage (< 4000 V) has been determined and the homogeneity of the detector's surface has been scanned, the best achievable energy resolution is estimated. Also the determinations of the total detector mass and the material enrichment are essential. The PSD performance needs to be evaluated since it impacts ε. The latter depends also on the amount of active volume of the detector, whose analysis is explained in the following section. The characterization tests of the detectors are performed in underground sites to reduce the cosmic activation. The European facility is the HADES laboratory in Belgium while the SURF laboratory is the site used in the USA. During the standard campaigns the detectors are exposed to different radioactive sources such as ^{241}Am source for the surfaces scans or ^{228}Th, ^{60}Co, ^{133}Ba sources used in static measurements. Special campaigns for prototype detectors are ongoing to better understand the surface events or to develop pulse-shape discrimination.

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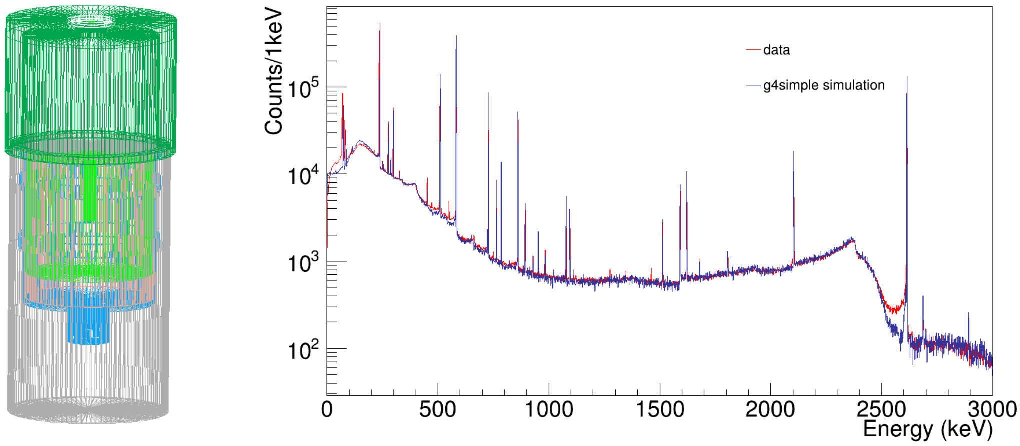


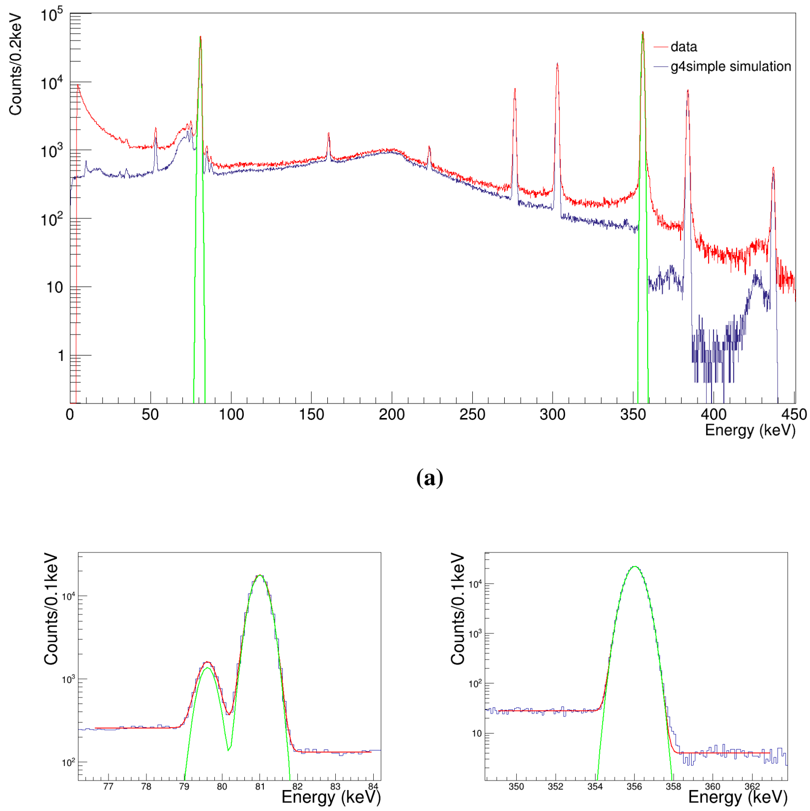
(a) **(b)**

Figure 2: Tests on G4simple simulation. (a) Visualization of the inner components in the lead castle. (b) Comparison between data and simulation using ^{228}Th source.

3. Active volume characterization

The ICPC detectors have typically a cylindrical geometry with a bore-hole in the upper side. The p+ contact is a point contact on the bottom surface of the crystal. The detectors are read out via their grounded p+ contact, while the depletion voltage is applied to the n+ contact. A groove separates the two electrodes. The p+ contact is boron doped, and has a negligible thickness. The n+ contact is generated by the thermal diffusion of lithium atoms, and has a thickness of $O(1)$ mm. Since n+ layer does not contribute to the fully active volume of the detector, a high precision measurement is needed to reduce its systematic uncertainty for all analyses. Its thickness is called full charge collection depth (FCCD) and it consists of a dead layer (DL) where the charge collection is negligible and a transition layer (TL) where the charges are partially collected. In this analysis the TL is ignored and the FCCD and DL are fully equivalent. The FCCD is determined through gamma spectroscopy, comparing the gamma spectrum of a calibration source with MC simulations of the measurement in which the FCCD of the detector is varied. The inferred FCCD of the detector is the FCCD in the simulation spectrum that best describes the measured spectrum. In the HADES laboratory, the detector is mounted in an aluminum cryostat during the acceptance test. The relevant interior components include an aluminum detector holder and a HD1000 wrap. The acrylic source is placed in a source holder which defines the distance between the source and the cryostat. All the components are set inside a lead castle.

The LEGEND collaboration has developed a simulation suite based on Geant4 called G4simple which is appropriate for these simple geometries. First, the ^{228}Th source is used to validate the simulation comparing the resulted energy spectrum with the data. Figure 2 shows some mismatches between the histograms at the left tails of the gamma energy peaks and at lower energy. They are due to the absence of TL implementation into the simulations, which is not relevant for the FCCD determination.



(a) **(b)** **(c)**

Figure 3: ^{133}Ba source. (a) Energy spectra of data and simulation using ^{133}Ba source. (b) Zoom in on the fit of the double peak around 80 keV. (c) Zoom in on the fit of the γ peak at 356 keV.

Then, the ^{133}Ba source is placed at the top of the detector and the data are acquired for typically 30 minutes. The Ba simulations are processed setting different values of FCCD thickness. The analysis method [5] uses the count ratio of the double peak around 80 keV and the γ-line peak at 356 keV as the FCCD sensitive observable:

$$R = \frac{I_{79.6keV} + I_{81keV}}{I_{356keV}}. \tag{2}$$

The peaks counts are determined through the fitting on the peaks. In Figure 4 the black line is the exponential fit of the MC count ratios. The systematics uncertainty are taken into account by the red lines. The intersection with the data count ratio returns the estimation of the FCCD value and its uncertainty for the current detector. This process is repeated automatically for many detectors.

4. Conclusion

The results obtained are comparable to the vendor specifications and to the FCCDs values determined for the inverted coaxial detectors used in the GERDA experiment.

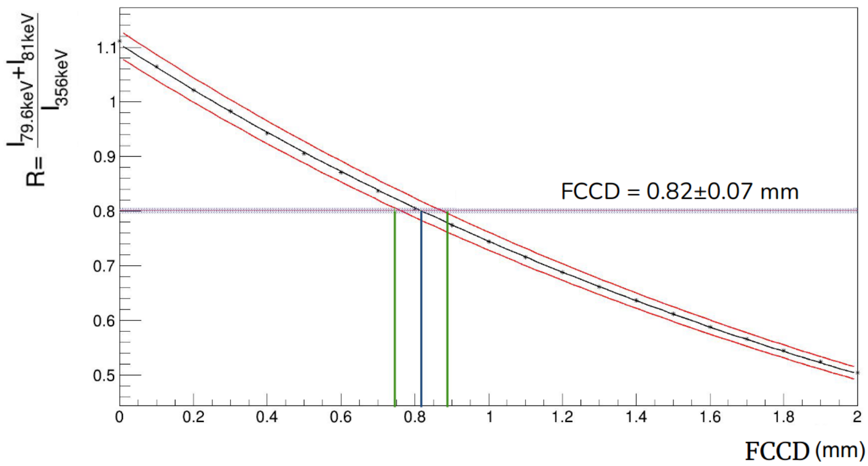


Figure 4: Finding the FCCD with fitting the experimental observable to the set of MC observables.

The next step will be the TL implementation in the simulations for a complete estimation of the FCCD thickness. Figure 5 shows a preliminary plot which compares the spectra setting a simple linear model for the transition layer in the simulation.

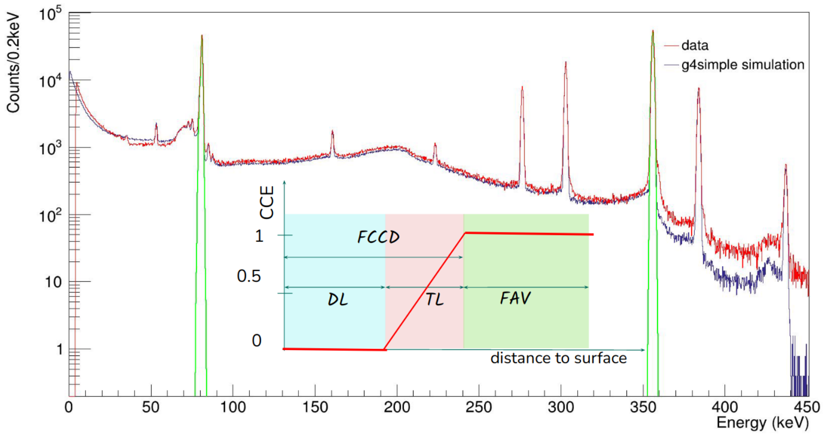


Figure 5: Comparison between data and preliminary MC simulation processed including linear model for the transition layer.

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