IL NUOVO CIMENTO **45 C** (2022) 136
DOI 10.1393/ncc/i2022-22136-2

Communications: SIF Congress 2021

Detector characterization for LEGEND-200 experiment

V. Biancacci([1])([2]), A. Alexander([3]), for the LEGEND Collaboration

([1]) *Dipartimento di Fisica e Astronomia, Università degli Studi di Padova - Padua, Italy*
([2]) *INFN, Sezione di Padova - Padua, Italy*
([3]) *University College London - London, UK*

received 30 January 2022

Summary. — 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 detectors in an active liquid argon shield and is currently under construction at the Laboratori Nazionali del Gran Sasso (LNGS) of the INFN in Italy. Inverted coaxial point-contact 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, necessitating extensive detector characterization. The acceptance tests aim to verify whether the performance of the delivered detectors meets specifications and to determine their optimal operational parameters. We discuss the first results in the characterization program.

1. – LEGEND experiment

In double-beta ($2\nu\beta\beta$) decay, two neutrons of the same nucleus are transformed into two protons with the emission of two electrons and two anti-electron neutrinos. Theoretically, double-beta decay without the emission of two neutrinos ($0\nu\beta\beta$ decay) is possible [1]. It violates the lepton number by two units. If found, it 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 such as 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, 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 $Q_{\beta\beta}$ (2039 keV). It aims to achieve a discovery sensitivity ($T^{0\nu}_{1/2}$) greater than 10^{27}yr within 5 years of measurement time and will probe the effective Majorana mass ($m_{\beta\beta}$) down to ∼30 meV. LEGEND-200 will operate roughly 200 kg of high-purity germanium (HPGe) detectors immersed in liquid argon (LAr) in an upgrade of the GERDA infrastructure at LNGS.

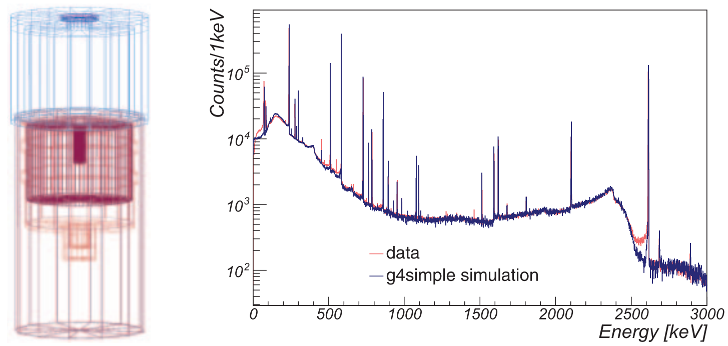
2. – HPGe detectors

The LEGEND experiment uses germanium diodes made from enriched material. Germanium detectors provide a superior energy resolution of 2.21 keV at $Q_{\beta\beta}$ 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. The Inverted Coaxial Point Contact (ICPC) detector is a new type of high purity germanium detector enriched by up to 92% in ^{76}Ge that is utilised by LEGEND. It presents many advantages with respect to the other HPGe detectors already used in GERDA and Majorana. Their particular geometry enables them to reach significantly larger detector masses while preserving excellent energy resolution and pulse shape discrimination (PSD) performance. This increase in mass not only improves the detection efficiency, but allows the total number of read-out channels required to decrease, resulting in fewer nearby components and consequently less background. They also provide a better surface to volume ratio.

Before their implementation in the LEGEND cryostat, the detectors undergo extensive acceptance and characterization tests, some of which are fundamental to estimate the rates of physical processes. In the background-free regime, the sensitivity of the half life of $0\nu\beta\beta$ decay scales with the detection efficiency ϵ, the isotopical abundance a of the $\beta\beta$ emitter, and the total exposure $\mathcal{E}$ given by the product of the total detector mass and data taking run time. Once the nominal bias voltage (<4000 V) has been determined and the homogeneity of the detector's surface has been verified, the best achievable energy resolution is estimated. The ϵ depends on the PSD performance and on the active volume of the detector, whose analysis is explained in the following section. The characterization tests are performed in underground sites to reduce 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 for the surfaces scans or ^{228}Th, ^{60}Co, ^{133}Ba for the static measurements. Special campaigns for prototype detectors are ongoing to better understand surface events or to develop PSD techniques.

3. – Active volume characterization

The ICPC detectors typically have a cylindrical geometry with a bore-hole in the top face. 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 a voltage exceeding 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 $\mathcal{O}(1)$ mm. Since the 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 the 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 such that the FCCD and DL are equivalent. The FCCD is determined through gamma spectroscopy, comparing the



(a) (b)

Fig. 1. – Validations tests of G4simple. (a) Visualization of the inner components in the lead castle. (b) Comparison between data and simulation using ^{228}Th source.

gamma spectrum of detectors exposed to a calibration source with Monte Carlo 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 tests (fig. 1(a)). The relevant interior components include an aluminum detector holder and a polyethylene wrap. The 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 Geant4-based simulation suite, G4simple, which is appropriate for modelling simple geometries such as detector characterisation test stands. Firstly, the setup of the G4simple simulation is validated by comparing the simulated energy spectrum against data for detectors exposed to a ^{228}Th source. Figure 1(b) shows the agreement of these spectra. Note that the mismatches in the low energy tails of the gamma lines are only due to the absence of TL modelling in the simulations, which is not relevant for the FCCD determination. Next, a flood ^{133}Ba source is placed above the detector for 30 minutes and the acquired data is compared against multiple ^{133}Ba simulations processed with different values for the FCCD thickness. Following the analysis method [5], the count ratio of the double γ-line peak at 80 keV and the γ-line peak at 356 keV (see eq. (1)) is selected as the FCCD sensitive observable and computed for all processed simulations and data:

$$R = \frac{I_{79.6\,\mathrm{keV}} + I_{81\,\mathrm{keV}}}{I_{356\,\mathrm{keV}}}. \tag{1}$$

The peak counts, I, are determined through the fitting on the peaks, as shown in fig. 2. Figure 3 shows this count ratio as a function of simulated FCCD, which is fitted with an exponential (black line). The red lines illustrate the systematic uncertainties for the simulations. The intersection of the exponential fit with the count ratio for the data (blue line) returns an estimation of the FCCD and its uncertainty for the current detector. This process is repeated automatically for many detectors.

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

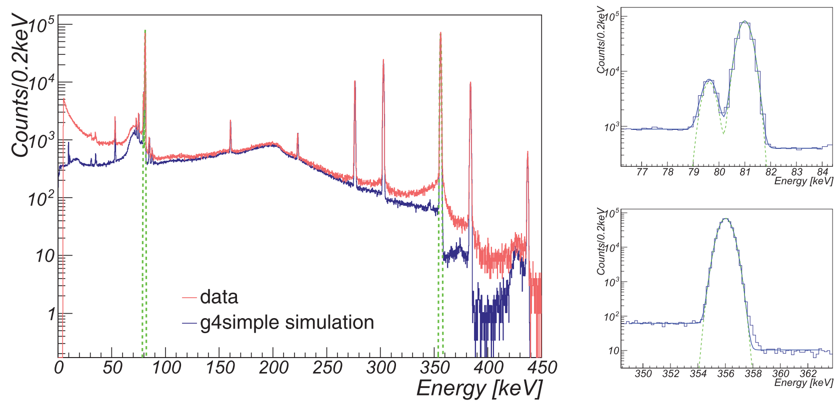


Fig. 2. – Left: real and simulated energy spectra for a detector exposed to ^{133}Ba. Right: the top and bottom plots show the fits of the double γ-peak at 80 keV and the single γ-peak at 356 keV, respectively. The fit functions consist of a Gaussian (signal) and a step function (background).

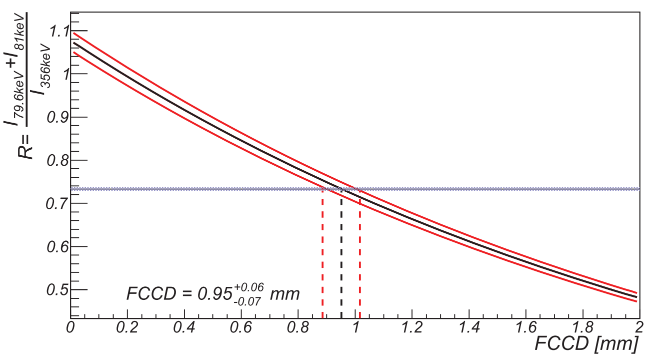


Fig. 3. – Count ratio as a function of the simulated FCCD (see text).

step will be the TL implementation in the simulations for a complete estimation of the active volume.

* * *

The authors acknowledge Yoann Kermaïdic for the support to this work.

REFERENCES

[1] Avignone III F. T., Elliott S. R. and Engel J., *Rev. Mod. Phys.*, **80** (2008) 481.
[2] LEGEND Collaboration, *AIP Conf. Proc.*, **1894** (2017) 020027.
[3] GERDA Collaboration, *Phys. Rev. Lett.*, **125** (2020) 252502.
[4] MAJORANA Collaboration, *Phys. Rev. Lett.*, **120** (2018) 132502.
[5] Lehnert B., *Search for 2nbb Excited State Transitions and HPGe Characterization for Surface Events in GERDA Phase II*, PhD Thesis (2015).