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^{76}Ge Detectors of LEGEND experiment: Production, Characterization, Performance

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The LEGEND Collaboration advances an experimental program to search for the neutrinoless double-beta decay of ^{76}Ge. LEGEND-200, the first stage of this program, recently completed its commissioning process at LNGS in Italy. About 140 kg of ^{76}Ge-enriched high-purity germanium detectors immersed in liquid argon are now continuously taking low background data. The LEGEND experiment integrates the advanced technology of the germanium detectors used in the Gerda and Majorana experiments. They are well suited for γ-rays measurements at the MeV energy scale, yielding high detection efficiency. The crystal growing procedure results in naturally low internal radioactivity and is a well-established technology. A precise understanding of the behavior of the germanium detectors is fundamental to determine their optimal operational parameters and it necessitates extensive detector characterization. This contribution will present the latest state-of-the-art approach to the production chain, the characterization measurements, and the performance of germanium detectors installed in LEGEND-200 so far.

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1. HPGe detectors in LEGEND-200

The observation of neutrinoless double beta ($0\nu\beta\beta$) decay would indicate new physics beyond the standard model of particle physics [1]. It would establish the violation of the lepton number conservation and the Majorana nature of the neutrino. It would also constrain the neutrino mass scale in the picture of light-neutrino exchange. The experimental signature of $0\nu\beta\beta$ decay is a mono-energetic peak in the energy spectrum of the two electrons released in the nuclear decay.

LEGEND is building on the success of GERDA [2] and MAJORANA DEMONSTRATOR [3] collaborations. These two leading experiments bring together their long experience in the field of $0\nu\beta\beta$ search to help build LEGEND. It incorporates also new international institutions to the project comprising one of the most ambitious searches of $0\nu\beta\beta$ decay to this day. The first stage of the experiment, LEGEND-200 [4], has completed its commissioning process and will improve the GERDA and MAJORANA achievements entering a new background regime in the region of interest around $Q_{\beta\beta}$. It aims to achieve a discovery sensitivity $> 10^{27}$ yr within 5 years measurement time and will probe the effective majorana mass down to $m_{\beta\beta} \sim 30$ meV.

The first stage, LEGEND-200, comprises ~200 kg of p-type HPGe detectors arranged in arrays submerged into liquid argon. Germanium detectors provide a superior energy resolution of 0.1% 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 utilized by LEGEND. It presents many advantages w.r.t. the other HPGe detectors (COAX, BEGe, PPC) already used in GERDA and MAJORANA. Fig.1-Left shows the four detector types in LEGEND (the indicated ICPC has the typical geometry produced by the ORTEC company). The particular geometry of ICPC enables it to reach significantly larger detector mass 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. It also provides a better surface to volume ratio.

2. HPGe detector production and characterization

The production of the LEGEND HPGe detectors consists of different steps. Firstly, the enrichment process of the natural germanium is performed by Isotope JSC, at the Electro Chemical Plant (ECP) in Russia, and Urenco in The Netherlands. LEGEND-200 purchased material with 88%-92% enrichment. The enriched Ge is delivered in the form of GeO_2 with a purity of 99.99%. Secondly, established facilities (PPM Pure Metals, IKZ) reduce the oxide to metallic germanium until 6N purity (99.9999%) and purify the material to the level required by the detector manufacturers. Finally, crystals are grown using the Czochralski method and are converted into diodes. The Li atoms are diffused into the outer crystal surface to produce the n+ contact while Boron is implanted for the p+ contact. The n+ contact thickness is determined by the temperature and duration of the lithium diffusion process. The result is a compromise between an efficient absorption of beta particles on the outer surface and the loss of detector active volume. The two contacts are electrically separated on the surface by a groove covered by a passivation layer. The detector geometry and the impurity profile are optimized to maximize the detector mass while maintaining a depletion voltage below 4000 V and a minimal electric field in the detector bulk above 200 V/cm. These two parameters are of particular importance because of their influence on leakage current and charge collection efficiency, respectively. Both contribute to the event topology discrimination performance and energy resolution. After this process, the finished diodes are mounted in vacuum cryostats. Two companies handle the crystal growing and the diode fabrication. Mirion grows germanium crystals in Oak Ridge in the USA and converts them into diodes in Olen, Belgium. ORTEC processes germanium material and produces detectors entirely in Oak Ridge.

Before their implementation in the LEGEND cryostat, the detectors undergo extensive acceptance and characterization tests, which cannot be reproduced once the detectors are installed in the final apparatus of the experiment. 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. Once the nominal bias voltage 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.

3. HPGe detector performance

The characterization of several standard parameters describing the performance of the HPGe detectors such as depletion voltage, energy resolution, and pulse shape performance can be done with radioactive sources placed at a fixed distance from the detector. Firstly, the depletion voltage measurement with ^{60}Co is executed as a verification of the detector performance. Then, the energy resolution is defined as the FWHM of a characteristic γ-line at a given energy. In HADES tests, it refers to the 1333 keV and 2615 keV lines generated by the crystal irradiation with the ^{60}Co source and the ^{228}Th source, respectively. The resolution curves of the points obtained fitting different peaks of ^{228}Th decay is fitted with the function $\sqrt{a + b \times E}$. The energy-independent term represents the electric noise of the apparatus and it includes the intrinsic equivalent noise charge; the second term is related to the statistics of the charge production and it includes the Fano factor. Some diodes exhibit charge trapping with a release time on the order of the drift time of the charge. As a consequence the reconstructed energy depends on the drift time. Applying a correction improves the energy resolution.

The $0\nu\beta\beta$ is expected to be a single-site events, depositing all the energy in a $\sim$ 1 mm^3 volume inside one HPGe detector. Multiple energy depositions with different charge drift times and surface energy depositions can be discriminated for ICPC detectors using the ratio of the maximum current (A) of the recorded current pulse relative to the total energy (E). The ^{228}Th source produces a broad energy spectrum up to 2.6 MeV with both single-site events (SSE) and multi-site events (MSE) topologies. It is appropriate to study pulse shape discrimination, whose diagnostic relies on the fraction of the surviving ^{228}Th MSEs upon the low A/E cut when accepting 90% of the SSEs from ^{208}Tl double escape peak at 2615 keV. The ^{241}Am source is also used during a fine-grained circular scan on the lateral surface to study the pulse shape response to local surface energy depositions.

Finally, the determination of the active volume (AV) of germanium detectors plays a crucial role in the detector response model, and it is fundamental to define the detection efficiency required for many analyses in LEGEND. The n+ contact has a thickness of $O(1)$ mm and does not contribute to the fully active volume of the detector. 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. The different absorption probability of gammas in the FCCD as a function of energy can be used to measure the FCCD. The gamma spectrum of the detector exposed to a calibration source is compared to Monte Carlo simulations of the measurement in which the FCCD is varied. The inferred FCCD is the one in the simulation spectrum that best describes the measured spectrum [5]. The results from the measurements in HADES with ^{241}Am and ^{133}Ba are shown in Fig.1-Right.

LEGEND-200 has completed its commissioning and stable data has been taking since March 2023. They already report an excellent performance of all detector systems. Most of the HPGe detectors already fulfill LEGEND-200 goals in terms of energy resolution. The energy scale is very stable between calibrations and the pulse shape discrimination shows a very good rejection of multi-site events.

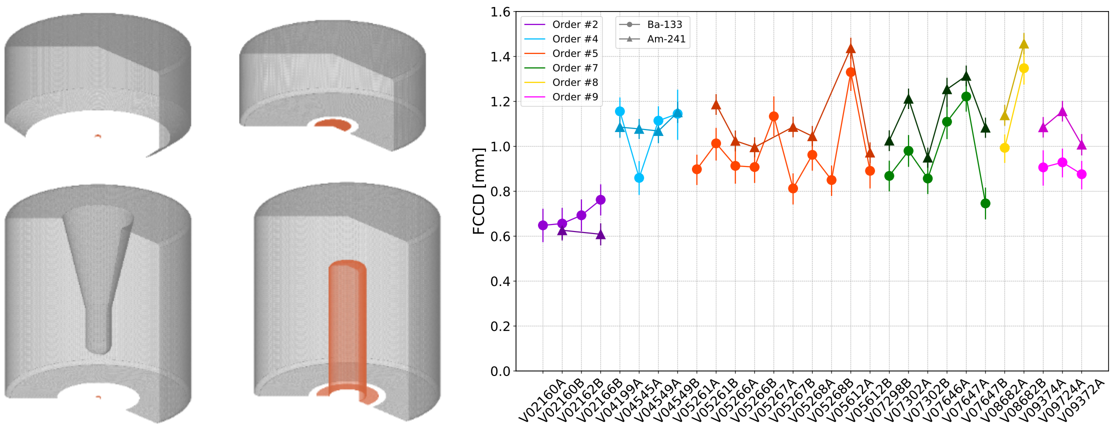

Figure 1: Left. Different detector types used in LEGEND-200: PPC (top-left), BEGe (top-right), ICPC (bottom-left), COAX (bottom-right); the contact geometry is shown in orange and in grey for the p+ and n+ contacts, respectively. **Right**. Best FCCD values estimated by the ^{241}Am and ^{133}Ba analysis.

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