LEGEND: The future of neutrinoless double-beta decay search with germanium detectors

Anna Julia Zsigmond for the LEGEND Collaboration
Max Planck Institute for Physics, Munich, Germany
E-mail: azsigmon@mpp.mpg.de

Abstract. The observation of neutrinoless double beta (0νββ) decay would establish both the violation of lepton number conservation and the Majorana nature of the neutrino. It will also constrain the neutrino mass hierarchy and scale in the light-neutrino exchange mechanism. The current experiments using 76Ge for 0νββ decay search, the MAJORANA DEMONSTRATOR and GERDA, lead the field in both the ultra-low background and the energy resolution achieved. Building on their success, the LEGEND experiment will conduct an improved search with the goal of reaching a half-life sensitivity beyond 10^{28} years. In order to achieve this goal, the enriched Ge detector mass has to be increased up to tonne-scale and the backgrounds further reduced. LEGEND will pursue a phased approach with the first phase expected to start in 2021 with about 200 kg of 76Ge-enriched detectors operating at LNGS of INFN in Italy.

1. Introduction

Neutrinos are the only known fundamental neutral fermions that allow the origin of their mass to be different from the coupling to the Higgs boson. Such operators violate lepton number conservation that has not been observed so far. Neutrinoless double beta (0νββ) decay would be the first lepton number violating process discovered and would prove that neutrinos have Majorana nature. The prime signature of 0νββ decay is that the sum of the energy of the two electrons is equal to the Q-value of the decay (Qββ).

Germanium detectors provide an excellent opportunity to search for 0νββ decay as they can be enriched in the isotope 76Ge serving as source and detector at the same time. Their pure material and their excellent energy resolution suppress the intrinsic backgrounds at Qββ = 2039 keV. Additionally, their high density allows for background discrimination based on the point-like signature of ββ decay.

Following a long history, currently two experiments are searching for 0νββ decay of 76Ge using enriched germanium detectors: GERDA [1] and MAJORANA DEMONSTRATOR [2]. In their recent results both experiments demonstrated the viability of the technology for a ton-scale experiment. With an analyzed exposure of 26 kg·yr MAJORANA reached a background level of 11.9 cts/FWHM·t·yr and a median sensitivity of 4.8 × 10^{25} yr for the decay half-life [3]. GERDA is the first experiment in the field that reached a half-life sensitivity of more than 10^{26} yr with an exposure of 58.9 kg·yr in its Phase II and a background index of about 1.8 cts/FWHM·t·yr [4].

Based on the success and experience of GERDA and MAJORANA, the Large Enriched Germanium Experiment for Neutrinoless ββ Decay, LEGEND [5] will continue this search in a phased approach. LEGEND aims to increase the sensitivities for 76Ge in the first phase to...
Figure 1. Left: Sensitivity for signal discovery as a function of exposure for different background levels. Right: LEGEND-200 cryostat with the detector strings surrounded by the wavelength shifting fibers of the liquid argon veto.

$10^{27}$ yr and in the second phase up to $10^{28}$ yr both for setting a 90% C.L. half-life limit as well as for discovery of $0\nu\beta\beta$ decay defined as a 50% chance for a signal at $3\sigma$ significance. Fig. 1 shows the sensitivity for signal discovery as a function of exposure for different background levels taking into account a signal efficiency of 0.6. The goal is to perform a ”background-free” measurement, defined as less than one background count expected at the design exposure, in order to gain a linear increase of sensitivity with exposure. In the first phase, LEGEND-200, about 200 kg of enriched Ge detectors will be operated in the existing GERDA infrastructure at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. For an exposure of 1 t·yr and close to background-free conditions, LEGEND-200 is required to reach a background index of 0.6 cts/FWHM·t·yr. The following phase, LEGEND-1000, will be a new facility probably in a new location holding about 1 t of Ge detectors. In order to reach the sensitivity goal with 10 t·yr exposure, a background index better than 0.1 cts/FWHM·t·yr is needed.

2. LEGEND-200 design and backgrounds

LEGEND-200 is designed based on the experience from GERDA and MAJORANA as well as from other LEGEND collaborators with expertise in low-background measurements. The careful selection and control of the radiopurity of all materials surrounding the Ge detectors, like cables and holders, has been proven essential in MAJORANA without an internal active veto system. Additionally, the low noise readout electronics of MAJORANA allow for a low energy threshold and the best resolution in the field. LEGEND-200 has adopted the GERDA design of a low-Z shielding with water and liquid argon (LAr) and an active veto through the detection of argon scintillation light. The clean fabrication techniques and the control of the surface exposure of the enriched Ge material from zone refinement through crystal pulling to detector fabrication and characterisation will be followed as done in the previous experiments.

Fig. 1 shows the schematic view of the upgraded GERDA cryostat that is surrounded by a water tank (not shown) together with a zoom to the Ge detector array with the wavelength shifting fibers of the LAr veto system. The ultra-pure water serves as a Cherenkov detector to veto muons passing through the setup and as shielding against environmental radioactivity including neutrons. The cryostat from GERDA will be modified with a new lock, new cabling and new suspension systems for the detectors and calibration sources. The LAr veto system is based on the latest developments for GERDA using TPB coated wavelength shifting fibers read out by silicon photomultipliers. The enriched Ge detectors will be arranged in strings and mounted
on radiopure low mass holders made from electroformed copper and custom-made polyethylene naphthalate (PEN) parts.

The detector array will be built up from the 30 enriched broad energy germanium (BEGe) and 7 semi-coaxial detectors from GERDA corresponding to 35.6 kg, from the 35 enriched p-type point contact (PPC) detectors from MAJORANA with an overall weight of 29.7 kg and from new inverted coaxial (IC) type detectors [6]. These new type of detectors combine the high mass (1.5-2 kg) of semi-coaxial and the excellent pulse shape discrimination (PSD) abilities of BEGe and PPC detectors [7]. The higher mass is necessary to reduce the number of detectors and with that the amount of nearby parts, like holders and cables that contribute significantly to the background. Recently, 5 new enriched IC detectors corresponding to 9 kg have been deployed in GERDA and show good stability and PSD properties. Another 150 kg of enriched detectors is under procurement and production for LEGEND-200.

The LEGEND-200 readout electronics will conflate the integral elements of the GERDA and MAJORANA designs. The charges collected at a detector’s $p^+$ electrode are fed to the gate of a junction gate field-effect transistor (JFET) on a low mass front-end (LMFE) board and then transmitted to the charge sensitive preamplifier (CSA) mounted about 40 cm away from the top detector in a string. LEGEND-200 will deploy a system that comprises improved versions of the MAJORANA LMFE and the GERDA CSA with new interconnects. Investigations and integration tests are ongoing including LMFE operation in LAr, improvements of LMFE fabrication, modification of the CSA design with 7 instead of 4 channels, improvements of LMFE-CSA interconnects to reduce noise, and the design and selection of cables from the CSA to the feedthrough flange.

LEGEND will follow the successful background reduction scheme of the previous experiments based on the single-site nature of the $\beta\beta$ decay signal. Multiple scatterings of gammas from radioactivity in the setup are suppressed by anti-coincidence cuts within the Ge detector array and between the LAr light sensors and the Ge detectors. Additionally, pulse shape analysis provides a handle on multi-site events within one Ge detector, where the small contact of BEGe, PPC and IC detectors is essential for an effective identification of backgrounds. The effect of these cuts is demonstrated in the left-hand side of Fig. 2 on simulated background expectations of gammas from $^{238}$U-chain, $^{232}$Th-chain and $^{40}$K. The active rejection methods are expected to reduce the backgrounds from environmental gammas by about 3 orders of magnitude at $Q_{\beta\beta}$.

The projected background composition from different sources in the setup is shown in the right-hand side of Fig. 2 based on material screening measurements. The dominant background contributions at $Q_{\beta\beta}$ are expected to come from $^{42}$K beta decays and alpha decays near the

![Figure 2. Left: Expected total contribution from $^{238}$U-chain, $^{232}$Th-chain and $^{40}$K from all components of the setup after the various background rejection cuts. Right: Projected background contributions from different parts of the setup at $Q_{\beta\beta}$.](image)
detector surfaces. Such alpha or beta particles have to penetrate the inactive layer of the detector where they lose part of their energy and so can end up at 2039 keV in the spectrum. There is a considerable effort ongoing to perform surface scans of the different detector types to better understand the signal shapes of these type of events. For example, the GALATEA [8] and TUBE [9] facilities are designed to scan Ge detector surfaces with alpha and beta sources without any material between the source and the detector. Other test stands for surface scans are currently being designed or constructed.

3. Status and prospects

LEGEND-200 will take over the infrastructure at LNGS in the beginning of 2020 and should be able to start physics data taking in 2021 with the goal to reach a half-life sensitivity of $10^{27}$ yr within about five years. The new lock system for the cryostat, the fibers and SiPMs for the LAr veto and the new enriched Ge detectors are currently being produced. Tests of the electronics system together with the new detector holders and cables is ongoing.

LEGEND-1000 is planned to run for 10 years with about 1000 kg of enriched Ge detectors deployed in individual payloads. In order to achieve background-free conditions and $10^{28}$ yr half-life sensitivity, a background at least six times lower than LEGEND-200 is needed. Current background models have large uncertainties due to the very low background, thus LEGEND-200 will provide more informed estimates for LEGEND-1000. Radioactivity from U and Th-chains needs to be reduced by optimizing array spacing, minimizing inactive materials, larger detectors, better LAr light collection and cleaner materials. The $^{42}$Ar needs to be eliminated by using Ar from underground sources near the detectors and surface alpha contamination should get reduced by improved process control. The site for the new LEGEND-1000 infrastructure is still to be selected and then the earliest start is projected to be in 2026-2027 after the funding is secured.

In summary, the current experiments searching for neutrinoless double beta decay with germanium detectors have achieved the best resolution in the field and background-free conditions, that are important for a future signal discovery. LEGEND will continue a background-free search in a phased approach with its first phase, LEGEND-200, starting construction next year.

References

[1] Ackermann K H et al. (GERDA Collaboration) 2013 Eur. Phys. J. C 73 2330 (Preprint 1212.4067)
[2] Abgrall N et al. (MAJORANA Collaboration) 2014 Adv. High Energy Phys. 2014 365432 (Preprint 1308.1633)
[3] Alvis S I et al. (MAJORANA Collaboration) 2019 Phys. Rev. C 100 025501 (Preprint 1902.02299)
[4] Agostini M et al. (GERDA Collaboration) 2019 Science 365 1445 (Preprint 1909.02726)
[5] Abgrall N et al. (LEGEND Collaboration) 2017 AIP Conf. Proc. 1894 020027 (Preprint 1709.01980)
[6] Cooper R J et al. 2011 Nucl. Instrum. Meth. A 665 25
[7] Domula A et al. 2018 Nucl. Instrum. Meth. A 891 106 (Preprint 1711.01433)
[8] Abt I et al. 2015 Nucl. Instrum. Meth. A 782 56 (Preprint 1409.0493)
[9] Gruszko J 2017 Surface Alpha Interactions in P-Type Point-Contact HPGe Detectors: Maximizing Sensitivity of $^{76}$Ge Neutrinoless Double-Beta Decay Searches Ph.D. thesis University of Washington