PROCEEDINGS OF SCIENCE

Neutrinoless double beta decay search with LEGEND-200 experiment

Nina Burlac[a,*] **for the LEGEND Collaboration**

[a] *University and INFN of Roma Tre, Rome, Italy*

E-mail: nina.burlac@uniroma3.it

The search for neutrinoless double beta decay is a topic of broad and current interest in modern physics. Its discovery would prove unambiguously not only the existence of new lepton-number violating physics but also its connection to the origin of neutrino mass. The LEGEND collaboration follows the GERDA and MAJORANA collaborations and works to develop the largest ^{76}Ge based neutrinoless double beta decay decay experiment. As a first phase, the LEGEND-200 experiment is being installed in the upgraded GERDA infrastructure at Laboratori Nazionali del Gran Sasso of INFN. It is based on 200 kg of high-purity germanium detectors and aims to reach a discovery sensitivity on the neutrinoless double beta decay half-life of 10^{27} years. An overview of the LEGEND-200 setup and its status will be provided.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)602

Contents

1. Double beta decay

The double beta ($\beta\beta$) decay is a second-order weak nuclear decay process with very long lifetime (1.93×10^{21} yr for ^{76}Ge [1]). The two-neutrino mode ($2\nu\beta\beta$) of the $\beta\beta$ decay is a nuclear transition in which two neutrons are simultaneously converted into two protons with the emission of two electrons and two anti-neutrinos. In contrast, the neutrinoless version ($0\nu\beta\beta$) of the decay occurs without the emission of the two anti-neutrinos in the final state. Unlike the $2\nu\beta\beta$ decay, the $0\nu\beta\beta$ decay violates the lepton number conservation and requires the exchange of massive Majorana neutrinos. Thus, finding the $0\nu\beta\beta$ decay would imply the presence of new physics beyond the Standard Model and the Majorana nature of neutrinos.

2. LEGEND Project

The Gerda [2] and Majorana [3] experiments paved the way for a new-generation experiment, the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) [4–6]. The experiment will be phased: LEGEND-200 and LEGEND-1000 will search for $0\nu\beta\beta$ decay in ^{76}Ge using 200 kg and 1000 kg of enriched germanium detectors, respectively.

Thanks to the careful selection of highly radiopure materials surrounding the detectors and of efficient background suppression techniques, the Gerda experiment achieved the lowest background index (6×10^{-4} cts/(keV·kg·yr)) and the highest sensitivity on the half-life (1.8×10^{26} yr at 90% C.L.) in the $0\nu\beta\beta$ decay field [7]; while the Majorana experiment achieved the best energy resolution, FWHM of 2.5 keV in the region of interest (2039 keV) [8]. By combining technological expertise and experience from both previous experiments, LEGEND is expected to reach a design sensitivity two orders of magnitude greater than its predecessors.

In particular, LEGEND-200 aims to reach a sensitivity on the half-life of 10^{27} yr by operating about 200 kg of germanium diodes. The construction of the experiment has already started and LEGEND-200 plans to start data taking by the end of 2022. Together with its scientific purpose, it will also serve as a testing ground for all R&D solutions in view of LEGEND-1000. The latter aims for discovery potential beyond 10^{28} yr.

3. LEGEND-200 experiment

The first stage of the experiment, LEGEND-200, takes place at Laboratori Nazionali del Gran Sasso (LNGS), where the overlying rock removes the hadronic components of cosmic ray showers and reduce the moun flux by six orders of magnitude. In this phase High-Purity germanium (HPGe) detectors are deployed in the slightly modified Gerda infrastructure.

3.1 Experimental set-up

The experimental setup follows a multi-layer approach, as shown in Figure 1, aiming to the minimisation of the backgrounds around the Q-value of the $0\nu\beta\beta$ decay (2039 keV for ^{76}Ge): a 580 m^3 tank with ultra-pure water shields from environmental radioactivity including neutrons and works also as a Cherenkov detector to veto muons passing through the setup; inside the water tank a 64 m^3 cryostat with purified Liquid Argon (LAr) [9] is present, which acts as cooling medium and shielding of the detectors against background radiation; the cryostat contains the LAr

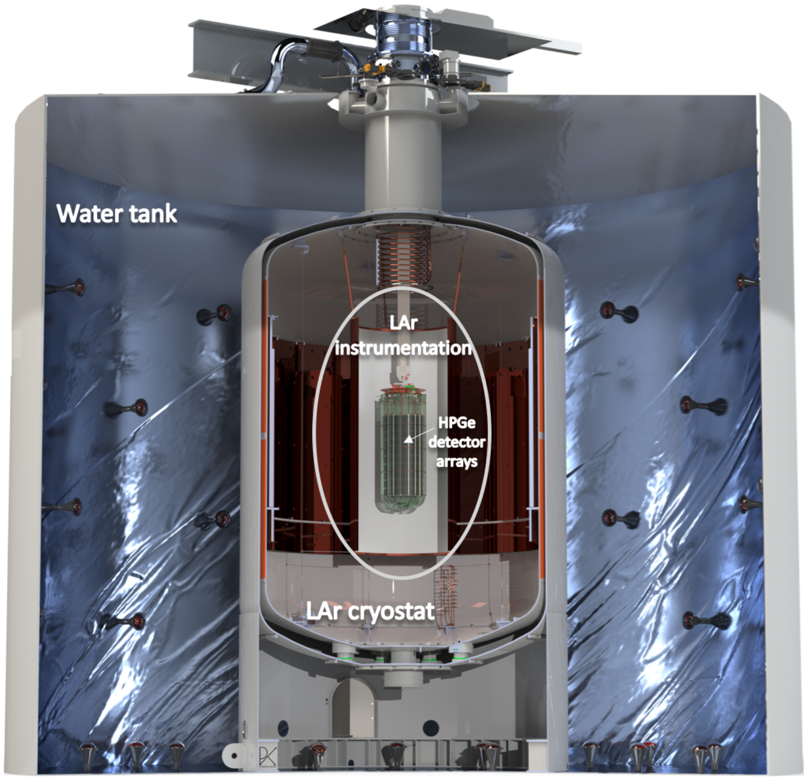

Figure 1: Schematic representation of the LEGEND-200 setup at LNGS.

instrumentation [10] which surrounds the HPGe detectors allowing to detect the background energy deposition in the LAr; the HPGe detectors are arranged in strings and mounted on radiopure low mass holders made from electroformed copper and custom-made polyethylene naphthalate (PEN) parts.

3.2 Germanium detectors

The germanium detectors, semiconductor diodes sensitive to ionizing radiation and γ rays, form the core of the experiment. They show an excellent energy resolution and a high detection efficiency, being simultaneously the source and the detector of the double beta decay. LEGEND-200 is using p-type germanium detectors deployed in previous experiments, Broad Energy Germanium (BEGe) and semi-coaxial detectors from GERDA [11], and P-type Point Contact (PPC) detectors from MAJORANA [12]. In order to reach the 200 kg HPGe array, newly developed detectors will be also incorporate, namely the Inverted Coaxial Point Contact (ICPC) detectors [13], already tested in the last GERDA phase [14]. These new types of detectors combine the high mass (1.5-2 kg) of semi-coaxial and the excellent pulse shape discrimination abilities of BEGe and PPC detectors. 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.

3.3 Active background reduction strategy

The signal due to a $0\nu\beta\beta$ decay is expected to release an energy amounting to $Q_{\beta\beta}$=2039 keV, for ^{76}Ge isotope, in a small volume of the detector ($\sim$ mm^3). The detection of such a rare decay requires the suppression of any kind of background in the region of interest (around $Q_{\beta\beta}$).

In the LEGEND-200 experiment the main background sources are related to the residual contaminations present in the materials used for the experiment construction and located near the detector array. In particular, the γ-rays from ^{214}Bi and ^{208}Tl lines and β-decays from ^{42}K, a daughter nuclide of ^{42}Ar which is a long-lived Ar cosmogenic contaminant, release their energy around $Q_{\beta\beta}$. For these reasons the LEGEND-200 experiment relies on improved active background reduction techniques, such as the LAr veto and Pulse Shape Discrimination (PSD). The complementarity of the two techniques was efficiently demonstrated in the GERDA experiment [7].

3.3.1 LAr instrumentation

The LAr instrumentation of LEGEND-200 experiment builds on its precursor operated in the completed GERDA experiment. Thanks to its efficient background recognition capabilities, it was pivotal to search for $0\nu\beta\beta$ decay of ^{76}Ge quasi-free of background events [7, 15]. An improved LAr instrumentation with better optical coverage and more efficient light readout is deployed in LEGEND-200 to detect the scintillation light in the LAr volume surrounding the HPGe detectors [10, 16]. Upon the interaction with ionizing radiation the liquid argon emits 128 nm Vacuum UltraViolet (VUV) light. LAr instrumentation detects the VUV light created by energy depositions in the LAr that accompanies energy depositions in the HPGe detectors. Such background events originate from α, β, γ or neutron interactions, originating from primordial, anthropogenic radioisotopes or cosmogenic produced unstable isotopes. They must be discriminated from $0\nu\beta\beta$ decay signals, which have energy deposition inside the germanium detectors and no energy deposition in the liquid argon.

3.3.2 Pulse Shape Discrimination

The LEGEND-200 background in the region of interest is further reduced by the application of the PSD cuts [17]. The pulse shape of the output signals from HPGe detectors allows to identify background events from γ-rays, which mainly interact via Compton scattering, producing events with multiple energy depositions (multiple site events), and events on the detector surface due to α or β decays, respectively on p^+ or n^+ contact. The PSD is used to discriminate these type of events against highly localized events (single site events), such as those produced by $0\nu\beta\beta$ and $2\nu\beta\beta$ decays.

4. Conclusions

Among numerous experiments in the field, the GERDA and MAJORANA experiments have achieved the lowest backgrounds and the best energy resolution of all neutrinoless double-beta decay searches. Taking the best of these experiments, the LEGEND collaboration will proceed in a phased approach towards a tonne-scale experiment with neutrinoless double-beta decay discovery potential at a half-life beyond 10^{28} years.

The LEGEND-200 experiment is the first phase of a next-generation experiment designed in the search of the lepton number violating $0\nu\beta\beta$ decay of the ^{76}Ge isotope. The goal of LEGEND-200 is to reach a half-life sensitivity of 10^{27} yr within about five years. This requires additional mass of HPGe detectors, compared to previous experiments, and more rigorous active background reduction techniques, based on powerful pulse shape discrimination and improved LAr instrumentation for the detection of the Ar scintillation light.

The upgrade and stand-alone commissioning of the LEGEND-200 LAr instrumentation was completed in April 2022. In May the LEGEND-200 experiment began the first integrated commissioning with 4 strings of HPGe detectors (~60 kg), operated with full LAr instrumentation. The follow-up commissioning and first physics runs with 10 strings (~140 kg) will start by the end of this year. While the LEGEND-200 final goal with 12 HPGe detector strings (~200 kg) will take place in 2023.

References

[1] GERDA collaboration, *Results on $\beta\beta$ decay with emission of two neutrinos or majorons in ^{76}Ge from GERDA Phase II*, European Physical Journal C (2015) 416.

[2] GERDA collaboration, *Results on neutrinoless double-β decay of* ^{76}Ge *from Phase I of the GERDA experiment*, Phys. Rev. Lett. **111** (2013) 122503.

[3] MAJORANA collaboration, *Search for neutrinoless double-β decay in* ^{76}Ge *with 26 kg yr of exposure from the MAJORANA demonstrator*, Phys. Rev. C **100** (2019) 025501.

[4] LEGEND collaboration, *The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND)*, AIP Conf. Proc. **1894** (2017) 020027 [1709.01980].

[5] LEGEND collaboration, *The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay: LEGEND-1000 Preconceptual Design Report*, 2107.11462.

[6] N. Burlac and G. Salamanna, *Present and Future of 0ν2β Searches with Germanium*, *Universe* **7** (2021) 386.

[7] GERDA collaboration, *Final results of GERDA on the search for neutrinoless double-β decay*, *Phys. Rev. Lett.* **125** (2020) 252502.

[8] MAJORANA collaboration, *Final result of the MAJORANA demonstrator's search for neutrinoless double-β decay in* ^{76}*Ge*, 2207.07638.

[9] M. Haranczyk et al., *Purification of large volume of liquid argon for LEGEND-200*, *PoS* **PANIC2021** (2022) 102.

[10] N. Burlac, *The LEGEND-200 LAr instrumentation: From design to commissioning*, June, 2022. 10.5281/zenodo.6781226.

[11] GERDA collaboration, *Characterization of 30* ^{76}*Ge enriched broad energy ge detectors for GERDA Phase II*, *The European Physical Journal C* **79** (2019) 1.

[12] MAJORANA collaboration, *Characteristics of signals originating near the lithium-diffused n+ contact of high purity germanium p-type point contact detectors*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **701** (2013) 176.

[13] R. Cooper, D. Radford, P. Hausladen and K. Lagergren, *A novel hpge detector for gamma-ray tracking and imaging*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **665** (2011) 25.

[14] GERDA collaboration, *Characterization of inverted coaxial* ^{76}*Ge detectors in GERDA for future double-β decay experiments*, *The European Physical Journal C* **81** (2021) 1.

[15] N. Burlac, GERDA *final results on neutrinoless double beta decay search*, *Nuovo Cim. C* **44** (2021) 9.

[16] M. Schwarz et al., *Liquid argon instrumentation and monitoring in legend-200*, *EPJ Web Conf.* **253** (2021) 11014.

[17] GERDA collaboration, *Pulse shape analysis in GERDA Phase II*, *The European Physical Journal C* **82** (2022) 1.