

Searching for the $0\nu\beta\beta$ with LEGEND

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Summary. — The neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical process which, if observed, would demonstrate the neutrino is a Majorana particle. This process beyond by the Standard Model, and violates lepton number. The LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double beta decay) experiment searches for $0\nu\beta\beta$ in ^{76}Ge , with goals of establishing a discovery sensitivity for a half-life of this nucleus beyond 10^{28} years. The first phase, LEGEND-200, is currently operational in a preliminary configuration at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. In its next phase, LEGEND-1000 aims to achieve its target sensitivity beyond 10^{28} years. To achieve this sensitivity, it is necessary to complete a background-free measurement in the region of interest, through suppression of radiogenic and cosmogenic backgrounds. LEGEND employs many methods to meet this stringent goal including world-class radiopure material fabrication, cutting-edge electronics and signal processing, innovative analysis methods, and an advanced multi-system background veto.

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1. – Description

Double beta decay is a rare decay mode for atomic nuclei that cannot undergo a single beta decay due to energetic constraints, but can transition to a more stable state through two simultaneous beta decays. In a typical double beta decay (Fig. 1 left), two neutrons transform into two protons, releasing two electrons and two electron antineutrinos, conserving lepton number. However, if the neutrino is a Majorana particle [8], a theoretical decay modes exist that resemble the normal double beta decay event topology but without the emission of antineutrinos (Fig. 1 right), resulting in a process known as neutrinoless double beta decay or $0\nu\beta\beta$. Numerous models have been proposed, with the simplest involving the annihilation of the antineutrinos through the exchange of a light Majorana neutrino. Regardless of the model, this results in a lepton-number violating decay mode. If detected, it would confirm the neutrino as the first known Majorana particle and the first observation of lepton number violation, holding significant implications for cosmology and physics beyond the Standard Model. Its experimental signature is a peak at the Q -value of the double beta decay, which is 2039 keV for ^{76}Ge (Fig. 2).

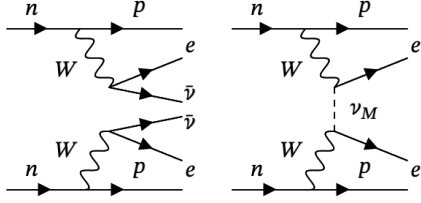


Fig. 1. – Feynman diagrams for the normal double beta decay process (left) vs a potential $0\nu\beta\beta$ process (right).

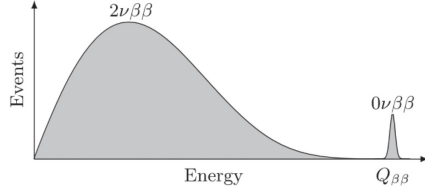


Fig. 2. – An example double beta energy spectrum is shown for both the normal decay mode and the $0\nu\beta\beta$ decay mode, with the $0\nu\beta\beta$ peak on the right. The $0\nu\beta\beta$ branching ratio has been intentionally amplified for better visualization.

Additionally, an observation of $0\nu\beta\beta$ would provide insight into the neutrino mass. In $0\nu\beta\beta$, the half-life of the nuclear isotope ($T_{1/2}^{0\nu}$) is inversely proportional to the effective Majorana neutrino mass ($m_{\beta\beta}$) [6]:

$$(1) \quad (T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2,$$

where $G_{0\nu}(Q_{\beta\beta}, Z)$ representing the phase space factor for the kinematics of the decay, $M_{0\nu}$ is the nuclear matrix element that encompass the nuclear Hamiltonian terms of the double beta decay, and $m_{\beta\beta}$ defined as [5]:

$$(2) \quad \langle m_{\beta\beta} \rangle = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}.$$

Therefore, measuring the half-life of $0\nu\beta\beta$ allows us to estimate the effective Majorana neutrino mass or establish upper limits on the mass by determining lower limits on the half-life.

2. – LEGEND

The Large Enriched Germanium Experiment for Neutrinoless Double beta decay (LEGEND) Collaboration aims to advance the search for $0\nu\beta\beta$ [1] using the isotope ^{76}Ge . This strategy involves a two-phased approach: initially, a 200 kg detector (LEGEND-200) will collect data for several years, paving the way for the full-scale 1 ton experiment (LEGEND-1000).

LEGEND-200 is situated at the *Laboratori Nazionali del Gran Sasso* (LNGS) underground laboratory in Italy. Since March 2023, LEGEND-200 has been operational in a restricted configuration, utilizing a total Germanium detector mass of 140 kg as of March 2024, with an additional installment planned to reach the full 200 kg detector mass in late 2024. The objective of LEGEND-200 is to enhance its capability to detect $0\nu\beta\beta$ with a target sensitivity of $T_{1/2}^{0\nu} \geq 10^{27}$ yr.

Simultaneously, research and development for LEGEND-1000 is underway, focusing on various components detailed later. The current baseline design for LEGEND-1000 is to construct the detector at LNGS, with alternative sites being considered.

3. – LEGEND-200

The LEGEND-200 detector utilizes GERDA's infrastructure and comprises the following components:

- Fourteen strings of detectors including ICPC, BEGe, Coax, and PPC types. These detectors are enriched up to 92% in ^{76}Ge and are housed within a single cylindrical volume surrounded by Liquid Argon (LAr). The detectors have high detection efficiency, as they also serve as the source of double beta decay. They also feature excellent energy resolution, with a resolution (FWHM) at the Q-value of double beta decay around 0.13%.
- A 64 m³ cryostat containing LAr, serves as both a cryogen and a scintillator for the active veto system. This functionality is facilitated by an optical readout system comprised of fibers and silicon photomultipliers. The light collection has significantly increased since GERDA thanks to: a higher purity of the LAr, the presence of wavelength shifters inside the cryostat, and a greater optical coverage of the instrumentation system.
- Surrounding the cryostat is a 10 m diameter water tank with a capacity of 590 m³, acting as a muon veto. Photomultiplier tubes (PMTs) detect Cherenkov radiation generated by cosmic rays entering the tank.

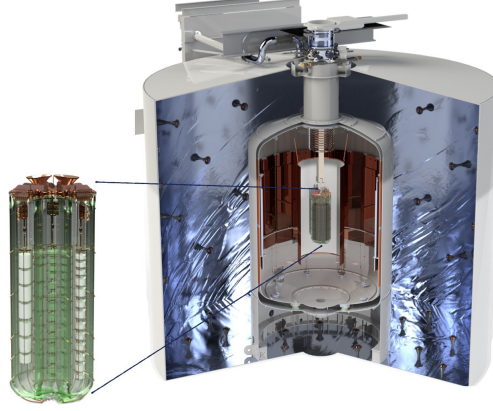


Fig. 3. – The LEGEND-200 structure, shown with a detailed view of the central part, features a water Cherenkov muon veto surrounding a steel cryostat. The cryostat encloses a volume of LAr and houses the detector array structure. The detector array structure is surrounded by optical fibers that shift the wavelength and guide scintillation light to silicon photomultiplier arrays.

A representative drawing of LEGEND-200 can be seen in Fig. 3.

The first dataset released from LEGEND-200 includes 10.1 kg yr of stable and viable detector data suitable for $0\nu\beta\beta$ analysis. This constitutes approximately 8% of GERDA's [4, 3] total exposure and 1% of the experiment's targeted total exposure during its runtime, suggesting that no signal events are likely. As can be seen in Fig. 3, it is evident that the majority of detectors already meet the resolution goal for LEGEND-200 of 2.5 keV at $Q_{\beta\beta}$.

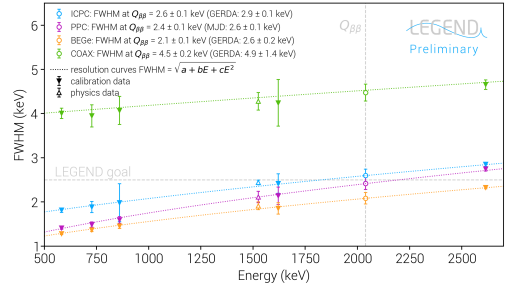


Fig. 4. – Full Width at Half Maximum (FWHM) resolution for different detector types (ICPC, PPC, BEGe, COAX) as a function of energy (keV). FWHM values at $Q_{\beta\beta}$ (2039 keV) are listed in the legend for each detector. The gray dashed line indicates the target resolution for LEGEND-200. Most detectors satisfy the goal resolution and have improved compared to their performance in Majorana (MJD) or GERDA. The lower resolution of COAX detectors was expected, and they will not be used in the future.

The Pulse Shape Discrimination (PSD), developed by the LEGEND collaboration exploits the different topology of $0\nu\beta\beta$ and background events in the detector to reduce the latter. Its performance can be seen in Fig. 5. This technique is based on the time evolution of the classifier $\frac{A}{E}$, where A is the amplitude of the current and E is the energy release, related to the signal integral in the detector. A good discussion on the PSD for $0\nu\beta\beta$ experiments can be found in [7, 2]. The PSD can discriminate between background-induced events, such as multi-site events within the same detector and surface events, primarily induced by external α s and β s. The double escape peak (DEP) of the ^{208}Tl is used as single-site event proxy.

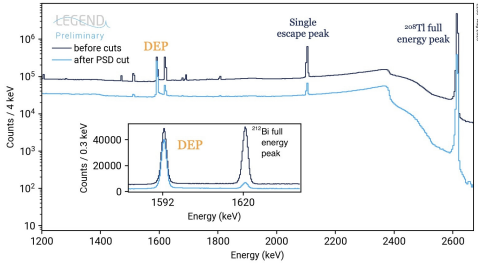


Fig. 5. – LEGEND-200 background spectrum before (deep blue) and after PSD cuts (light blue). The PSD performance in discriminating multi-site from single-site events is shown by the different reductions in the ^{208}Tl DEP and the ^{212}Bi full energy peak, in the image inset.

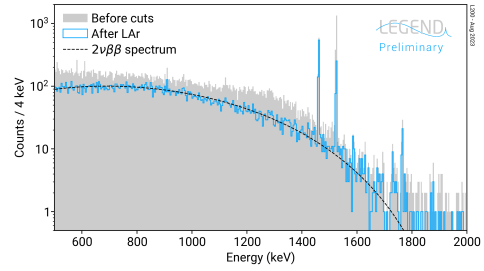


Fig. 6. – Background spectrum before cuts and after the PSD cut plus the LAr cut (blue). The 1461 keV and 1525 keV peaks are γ -lines from ^{40}K and ^{42}K respectively. The ^{40}K is present in the materials near the detectors, while ^{42}K comes from the ^{42}Ar decay present in the LAr.

Inside the cryostat, energy depositions in the LAr near the germanium detectors generate scintillation light. This light is detected by optical fibers connected to silicon photomultipliers that encircle the detector array. Signals coinciding with LAr activity can be identified and rejected as background using the LAr analysis cut. The impact on the background spectrum is illustrated in Fig. 6.

Finally, the most important region, around the Q -value, is shown in Fig 7. The background goal for LEGEND-200 in the analysis window of $(-90, +150)$ keV around $Q_{\beta\beta}$ is 2×10^{-4} cts/(keV kg yr). For the 10.1 kg yr exposure we expect a value of 0.48 background events that pass all cuts. As Fig. 7 show one event passes all cuts in the analysis window, outside of the expected $Q_{\beta\beta}$ region. This results in a background level of $4.1^{+7.3}_{-2.6} \times 10^{-4}$ cts/(keV kg yr) at 68% CL. Therefore this result remains in LEGEND-200 background goal confidence interval.

4. – Outlooks

The LEGEND collaboration has outlined ambitious goals in its pursuit to investigate $0\nu\beta\beta$. The first phase, LEGEND-200, commenced data collection in March 2023 with a

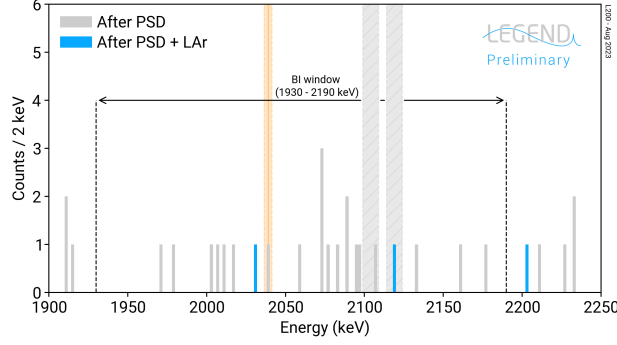


Fig. 7. – A detailed view of the background spectrum of LEGEND-200 around the Q -value, with known gamma lines (shaded in light grey) excluded from the analysis window, and with the $Q_{\beta\beta}$ shaded in light orange.

setup involving 140 kg of ^{76}Ge . This phase aims to achieve a background goal of $\leq 2 \times 10^{-4}$ cts/(keV kg yr), targeting a sensitivity of 1.5×10^{27} yr and an equivalent mass range of 27 to 63 meV. Following this, the LEGEND-1000 phase is planned, with data collection expected to start around 2030. This phase will significantly scale up the experiment to 1000 kg of ^{76}Ge , with a more stringent background goal of $\leq 1 \times 10^{-5}$ cts/(keV kg yr). It aims for a sensitivity of 1.3×10^{28} yr and an equivalent mass range of 9 to 21 meV. These phases represent a significant advancement in the search for $0\nu\beta\beta$, potentially providing deeper insights into the fundamental properties of neutrinos.

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