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Neutrinoless double-beta decay search with the LEGEND experiment

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Abstract. Neutrinoless double-beta decay is a nuclear decay, given as (, Z) → (, Z+2)+2e , with deep consequences for the understanding of our universe. A strong experimental program is underway to search for this transition with many proposed experiments using di erent technologies. In this article the LEGEND experiment, which uses ^{76}Ge as the isotope of interest, will be described. We will discuss both the first stage, LEGEND-200, which is now taking data at the Laboratori Nazionali del Gran Sasso of INFN in Italy, and the future stage, LEGEND-1000. LEGEND-200 has analyzed data collected from March 2023 to February 2024 for an exposure of 61 kg·yr with a background index not far away from its goal of 2×10 ^{4} cnts/(keV·kg·yr). Combining the LEGEND-200 data with those of GERD and M JOR N DEMONSTR TOR one obtains an exclusion sensitivity on the half-life of 0ν decay in ^{76}Ge of $T_{1/2} > 2.8 \times 10^{26}$ yr at 90% C.L. and a limit on $T_{1/2} > 1.9 \times 10^{26}$ yr at 90% C.L.

1 Introduction

Neutrinoless double-beta (0ν) decay is a process that violates lepton number conservation by two units. Its observation would have other far-reaching consequences. It would prove that lepton number is not a symmetry of nature, establish that neutrinos are Majorana fermions, possibly constrain the absolute neutrino mass scale, and support theories that leptons contributed to the matter-antimatter asymmetry in the universe.

The isotope candidates for such nuclear transitions are even-even nuclei in which a single beta decay is energetically forbidden. A particularly promising isotope is ^{76}Ge (with a total energy release of Q = 2039.061± 0.007 keV [1]). Many experiments in the past have used this isotope and in recent years the two experiments GERD [2] and M JOR N DEMONSTR - TOR [3] obtained competitive half-life limits of 1.8×10^{26} yr and 0.8×10^{26} yr at 90% C.L., respectively.

Building on the successes of and the best technologies developed by GERD and M JOR N DEMONSTR TOR, the LEGEND [4] collaboration aims to develop a phased 0ν experimental program. LEGEND-200 is its first phase with the aim of reaching a sensitivity[1] of about

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[1]The discovery sensitivity corresponds to the expected number of signal events for which an experiment has a 50% chance to observe an excess of events over the background at 99.73% C.L. The exclusion sensitivity (or sensitivity for setting a limit) corresponds to the expected number of signal events that an experiment has a 50% chance of excluding at 90% C.L. Given that the expected number of signal events depends on $T_{1/2}$, the discovery and exclusion sensitivities on the expected number of events can be directly translated into sensitivities on the 0ν decay half-life. $T_{1/2}$ sensitivities are the most common parameter reported by the experiments [5].

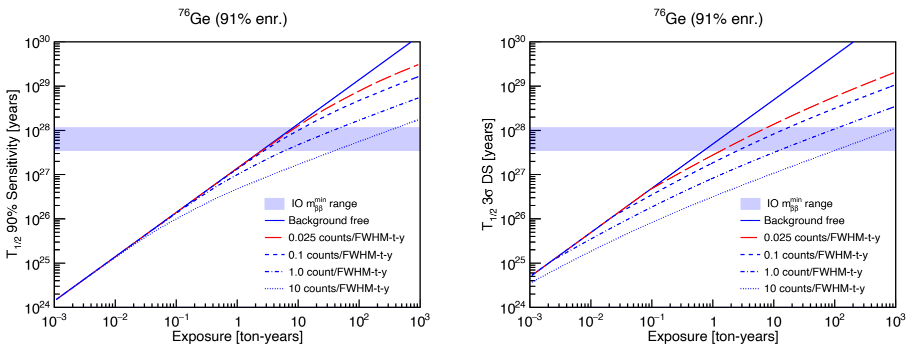

Figure 1. Sensitivity for setting a limit (left) and discovery (right) as a function of the exposure and background. The background rates use a 2.5 keV FWHM energy resolution around the Q of the reaction. The horizontal band corresponds to the range of half-lives, $T_{1/2}$, necessary to cover the lowest value of the e ective Majorana mass, m , permitted by the inverted order hierarchy. It's clear from these figures, that for a discovery to be made, background reduction is as important as exposure.

10^{27} yr in terms of both setting a 90% C.L. limit and achieving a 50% chance to make a 3 σ discovery, thanks to a projected background index of 0.6 cnts/(FWHM·t·yr), or $2\times10^{\ 4}$ cnts/(keV·kg·yr), and an exposure of 1 t·yr. The second phase, LEGEND-1000, aims for a sensitivity of beyond 10^{28} yr by operating 1 tonne of enriched germanium detectors for an exposure of more than 10 t·yr at a background index of about 0.025 cnts/(FWHM·t·yr), or $10^{\ 5}$ cnts/(keV·kg·yr). Figure 1 shows the sensitivities for setting limits and for discovery potential for a ^{76}Ge experiment as a function of the exposure for di erent background indices.

2 LEGEND-200

The LEGEND-200 experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, where a rock overburden of 3500 m water equivalent reduces the cosmic muon flux by 6 orders of magnitude. The figure 2 shows an artists view of the experiment: going from outside to inside we have the tank filled with 590 m^3 of pure water to moderate and absorb neutrons and attenuate the flux of external γ radiation and thanks to 66 photomultipliers to serve as a Cherenkov medium for the detection of muons crossing the experiment, the cryostat holding 64 m^3 of liquid argon (LAr) which serves as thermal bath for the cryogenic operation of the bare Ge diodes, as a shield against the radioactivity of the cryostat itself and as a scintillation medium, finally inside the cryostat the strings of enriched Germanium detectors with the wavelength shifting fibers coupled to SiPMs.

During the first data taking period of LEGEND-200, begun in March 2023 and ended in February 2024, 142.5 kg of Germanium detectors of di erent types were deployed into the cryostat: 86.7 kg of inverted-coaxial (IC) detectors, 22.1 kg of p-type point-contact (PPC) detectors from the M JOR N DEMONSTR TOR, 14.7 kg of semicoaxial (Coax) plus 19 kg of Broad Energy Germanium (BEGe) detectors from GERD . The detectors are organized in 10 strings and are made from isotopically modified material with ^{76}Ge enriched up to 92%.

A total of 85.5 kg·yr of exposure was collected of which 61 kg·yr were selected for the following 0ν analysis [6]. During the entire period of data taking a strict blinded analysis was adopted: events with a reconstructed energy within ± 25 keV of Q were hidden until the entire data selection was finalized. The figure 3 shows on the left the energy resolution of

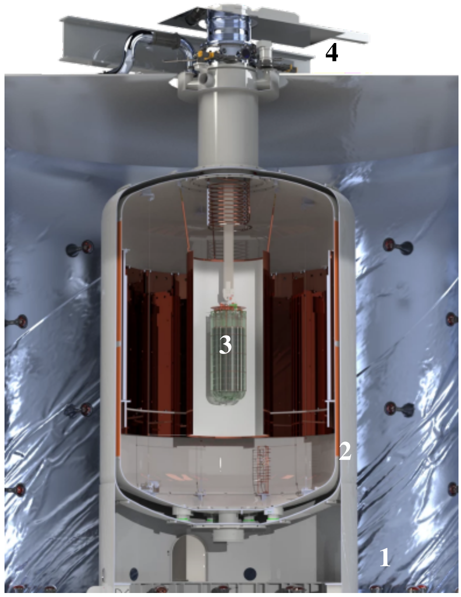

Figure 2. Artists view of the LEGEND-200 experiment showing: the water tank housing the Cherenkov muon veto (1), the cryostat filled with liquid argon (2), the strings of enriched Germanium detectors with the wavelength shifting fibers coupled to SiPMs (3), the lock system for the deployment of the array of Germanium detectors (4).

the Ge detectors: for the entire data taking the energy resolution of all types of Ge detectors remained stable at 0.1% FWHM at the Q value. The energy scale also remained very stable, as can be deduced from the plot on the right of figure 3, which shows the weekly variation in energy of three γ calibration peaks.

Signal-like events release energy in a very narrow region in a single Germanium detector; for this reason they are called single-site events. In contrast, background events release energy either in more than one detector (eliminated by requiring energy release in a single detector, multiplicity cut), or in many di erent sites (multi-site events) of a single detector or on its surfaces (both these two last classes of events are eliminated using dedicated pulse shape discrimination PSD techniques), or they are accompanied by energy release in the LAr (detected by reading the LAr scintillation light). The total histogram in figure 4 shows the energy spectrum after quality cuts, muon veto and multiplicity cut. The light gray and red histograms show the remaining events after PSD cut is applied and finally after PSD and argon anti-coincidence cuts. These active rejection tools are particularly e ective in eliminating background events around the Q region.

The two plots in figure 5 provide further information on how the liquid argon instrumentation works. The top right plot of figure 5 shows the energy spectrum from 565 keV to 1620 keV after quality cuts, muon veto and multiplicity cuts and then after the argon anti-coincidence cut (blue histogram). After this cut the spectrum is strongly dominated by 2ν events with only a small percentage of residual background events as shown by the red curve representing its predicted contribution using the 2ν half-life measured by GERD [7]. The inset shows the photo-electrons detected by the LAr instrumentation in the energy region around the two potassium γ lines and helps to understand how the LAr cut works: the internal conversion of ^{40}K releases only a small amount of energy in the liquid argon and for that reason it is not suppressed by the LAr cut, while the -decay of ^{42}K releases a lot of energy in the liquid argon and as consequence this γ peak is highly suppressed. The plot on the left shows the light yield distribution registered by the LAr instrumentation of the LEGEND experiment compared with the same distribution registered in Gerd . A sizeable improvement is visible in LEGEND respect to the Gerd result, which comes from a larger fibers coverage, improved electronics, better quality of the liquid argon and minor shadowing of the Germanium detectors thanks to an optimized arrangement of the detectors and the use of scintillating polyethylene naphthalate plates as structural pieces of the detectors strings.

Figure 6 shows the energy distribution of the eleven events surviving all the cuts in the analysis region going from 1930 to 2130 keV. Events in the regions of expected γ lines (marked by gray areas) are not included in the analysis. A frequentist analysis using a two-sided profile likelihood ratio test statistics gives no evidence of a 0ν signal and places a 90% confidence level (C.L.) lower limit of $T_{1/2} > 0.5 \times 10^{26}$ yr. The background index is $0.5^{+0.3}_{\;0.2}$ cts/(keV·t·yr) at 68% C.L. for the *golden* data set made by the best performing detectors (BEGe and large part of the IC detectors) and $1.3^{+0.8}_{\;0.5}$ cts/(keV·t·yr) for the *silver* data set largely made by Coax detectors.

A frequentist fit combining the present LEGEND-200 data with the final data from Gerd [2] (127.2 kg·yr of exposure) and from M jor n Demonstr tor [3] (64.5 kg·yr of exposure) gives a lower limit on $T_{1/2}$ of 1.9×10^{26} yr (90% C.L.) and a median exclusion sensitivity of 2.8×10^{26} yr (90% C.L.). This median sensitivity is, at the moment, the best one between all the present 0ν searching experiments. A Bayesian analysis obtains identical lower limit under uniform signal and background priors.

The $T_{1/2}$ limit can be converted into an upper limit on the e ective Majorana mass, m ,
under the assumption that the decay proceeds by the exchange of light Majorana neutrinos. Using a set of nuclear matrix elements calculations spanning the interval 2.35-6.34, the range for the upper limit on m is 75 - 200 meV in the frequentist framework. The large spread in the values of m arises directly from the uncertainties of the nuclear matrix elements.

Data taking was interrupted in February 2024 because a higher than expected level of background events was discovered in the analysis of the data around the Q value. Most of 2024 was spent understanding the origin of these events through dedicated data taking and radio-assay campaigns of pieces of material placed near the Ge detectors. Data taking will be resumed in 2025 with an apparatus with enhanced performances.

3 LEGEND-1000

The next phase, LEGEND-1000 [8], will consist of 1000 kg of IC detectors enriched to more than 90% in ^{76}Ge operated in a liquid argon active shield at an underground laboratory. The baseline design assumes LNGS as host site. Its goal is to fully explore the neutrino inverted order hierarchy down to m in the range 9-21 meV, in 10 years of live time, with a background index of $10^{\;5}$ cnts/(keV·kg·yr) and a discovery sensitivity beyond 10^{28} years. The figure 7 shows a conceptual design of the experiment. The general design reflects the Gerd layout with the Germanium detectors deployed naked into a liquid argon bath contained in a super-insulated cryostat, the cryostat is inside a large tank filled with pure water and equipped with photomultipliers for the cosmic muons tagging. Several new features are planned to achieve the ambitious goals of the experiment. The readout of the Ge detectors will be performed with front-end application-specific integrated circuit (ASIC) boards installed in close proximity to the detectors, instead to have, as in LEGEND-200, the very front end circuits installed on the detectors and the charge-sensitive amplifiers positioned at a distance of 80 cm or more from the detectors. The Germanium detectors together with their LAr instrumentation system will be immersed in a reentrant tube containing underground-sourced liquid argon to

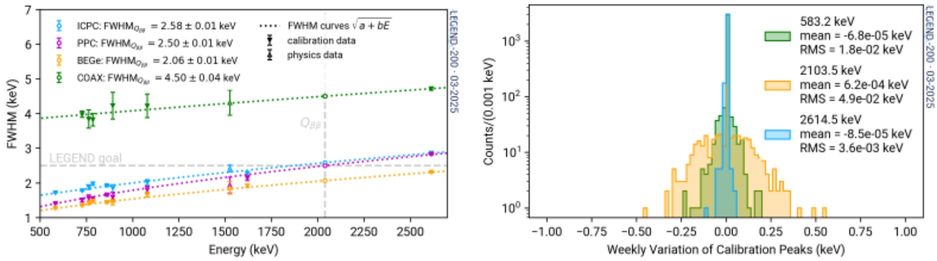

Figure 3. The figure on the left shows the energy resolution of the Ge detectors used in LEGEND-200. The filled triangular markers come from the calibration runs using ^{208}Th sources, the open triangular markers come from ^{42}K data collected during the physics runs. The dotted curves give, for each type of detector, how the energy resolution changes with energy. The vertical gray line shows the energy resolution at the Q . The LEGEND goal in terms of energy resolution (2.5 keV FWHM) is shown by the horizontal gray line. The figure on the right shows the energy scale stability as measured from the weekly variation of three particular calibration peaks: 583.2 keV, 2103.5 keV and 2614.5 keV.

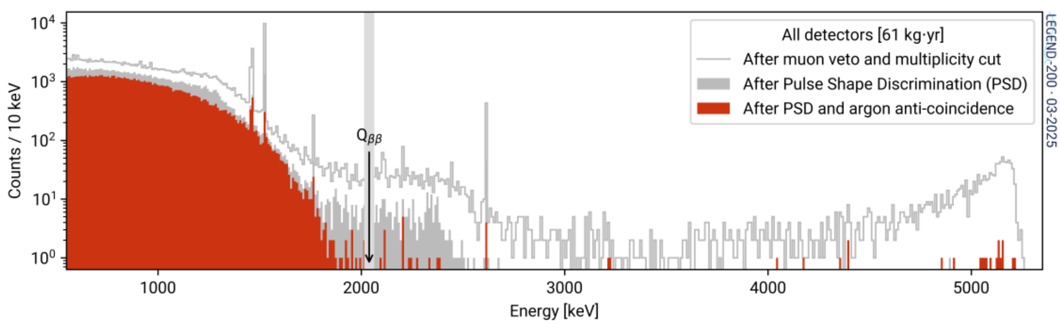

Figure 4. Energy distribution of events between 565 and 5300 keV prior to liquid argon veto and PSD cuts (total histogram), after PSD cut (light gray) and after all cuts (red). The gray vertical band indicates the blinded region of ± 25 keV around the Q value. The exposure is 61 kg·yr.

minimize the background from ^{42}K, progeny of ^{42}Ar. The cryostat volume outside the reentrant tube will be filled with normal liquid argon. Here, a new detector made of acrylic slabs and of scintillating light guides will be constructed around the reentrant tube. The purpose of this detector is to suppress the background due to the γ and -decays of ^{77}Ge and ^{77m}Ge produced by the neutron capture on ^{76}Ge. The neutrons are produced during showering of the cosmic rays.

The LEGEND collaboration is actively working to seek funding for the experiment in both United State and Europe. A milestone, in this context, will be Critical Design-1 review this year organized by the DOE.

4 Conclusions

Using the experience gathered with Gerd and M jor n Demonstr tor, the LEGEND project aims at a 0ν half-life discovery sensitivity of beyond 10^{28} yr that permits to cover the inverted-ordering neutrino mass scale. The first stage, LEGEND-200, is online at LNGS and analyzed a total of 61 kg·yr of exposure in its first year of data taking, demonstrating a

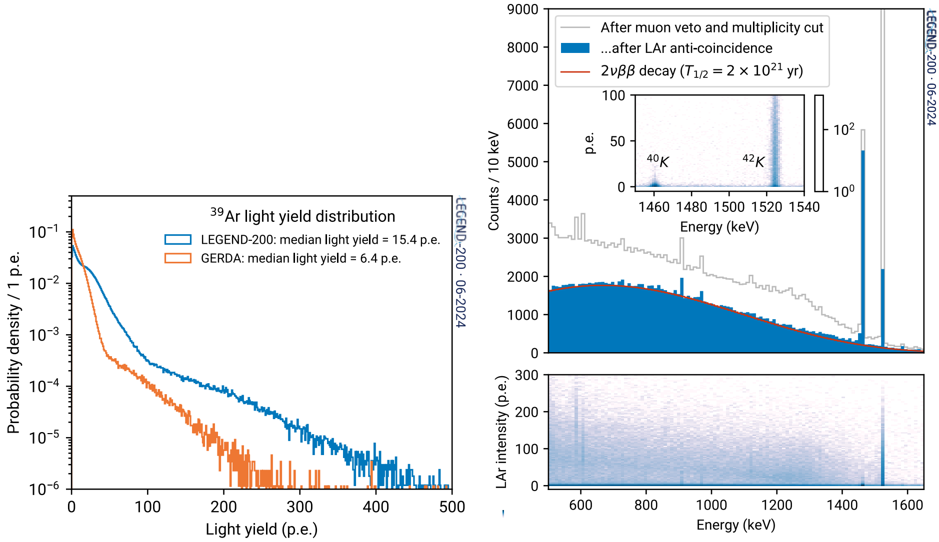

Figure 5. Left plot: comparison of the light yield distributions between LEGEND-200 and Gerd using the signal from the decay of ^{39}Ar. A clear improvement is visible. Right upper plot: energy distribution of events between 565 keV and 1620 keV prior to LAr anti-coincidence and PSD cuts (total histogram) and after LAr anti-coincidence cut (full blue). The red curve represents the 2ν contribution normalized using the half-life measured by Gerd [7]. The inset shows the photo-electrons detected by the LAr instrumentation in the energy region around the two potassium γ lines. Right lower plot: The photo-electrons distribution as a function of the energy (from 565 keV to 1620 keV) registered in the Ge detectors.

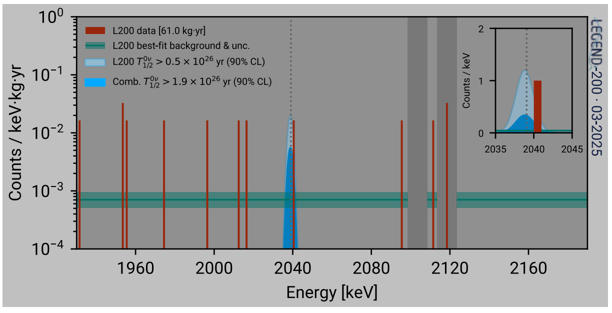

Figure 6. Enlarged view of the energy distribution of events between 1930 and 2190 keV after all cuts. Events in the gray regions, corresponding to ±5 keV around known γ lines, are excluded from the analysis. Confidence intervals from the frequentist analysis are shown for the background index (68% C.L., in green) and for the signal strength (90% C.L., in light blue). The dark blue peak displays the expected 0ν decay signal for $T_{1/2}$ equal to the lower limit including data from other ^{76}Ge experiments, 1.9×10^{26} yr [6].