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The LEGEND experiment for the search for the Majorana neutrino(*)

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Summary. — The search for the neutrinoless double beta ($0\nu\beta\beta$) decay is considered the most promising way to prove the Majorana nature of neutrinos. The LEGEND (Large Enriched Germanium Detector for Neutrinoless $\beta\beta$ Decay) collaboration aims at building a 1 ton ^{76}Ge-based $0\nu\beta\beta$ experiment with 3σ half-life discovery sensitivity of 10^{28} years to fully span the inverted neutrino mass ordering region. Combining the efforts of previous Gerda and MAJORANA experiments, the LEGEND project will first proceed by deploying 200 kg of enriched HPGe detectors in the already existing Gerda facility at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. With an exposure of 1 t·yr and a background index of 0.5 counts/(FWHM·t·yr), LEGEND-200 will reach a 3σ half-life discovery sensitivity for the $0\nu\beta\beta$ decay of 10^{27} yr. An overview of the LEGEND project together with the current status and preliminary performance of LEGEND-200 are presented in this work.

1. – The Neutrinoless Double Beta Decay

Nowadays, the true nature of neutrinos is still unknown. These mysterious particles could either be Dirac or Majorana particles, leading to different scenarios. The golden channel to explore their nature is the neutrinoless double-beta decay ($0\nu\beta\beta$). This ultra-rare process, never observed to this date, would be possible only in the scenario of a Majorana neutrino where neutrinos coincide with their own antiparticles. A complete description of experimental, nuclear and particle theory aspects concerning the $0\nu\beta\beta$ decay can be found in ref. [1].

In the standard double-beta decay ($2\nu\beta\beta$) allowed by the Standard Model of particle physics, two neutrons are simultaneously transformed into two protons with the emission of two electrons and two electron antineutrinos, $(A, Z) \to (A, Z + 2) + 2e^- + 2\bar{\nu}_e$.

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The $2\nu\beta\beta$ decay has been already observed in several even-even isotopes for which the single-β decay is energetically forbidden, with half-lives of the order of 10^{18-21} yr. The experimental signature is a continuous distribution from 0 to $Q_{\beta\beta}$, where $Q_{\beta\beta}$ is well approximated with the total energy of the two outgoing electrons given that the nuclear recoil energy (< 0.1 keV) can be safely neglected. Assuming the exchange of a light Majorana neutrino in a $\beta\beta$ decay, the process $(A, Z) \rightarrow (A, Z + 2) + 2e^-$ would be allowed, manifesting as a sharp peak signal at $Q_{\beta\beta}$. However, the existence of this decay would imply the violation of the lepton number by two units, allowing the creation of matter without antimatter. The discovery of such a phenomenon would be of fundamental importance for understanding the observed cosmic baryon excess in the Universe as well as the origin of neutrino masses. The $0\nu\beta\beta$ half-life has the following form:

$$\frac{1}{T^{0\nu}_{1/2}} = \mathcal{G}^{0\nu} g_{\mathrm{A}}^4 \left(\mathcal{M}^{0\nu}_{\mathrm{light}}\right)^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2, \tag{1a}$$

where $\mathcal{G}^{0\nu}$ is the phase-space factor, g_A is the axial-vector coupling constant, $\mathcal{M}^{0\nu}_{\mathrm{light}}$ is the NME (nuclear matrix element) for the light neutrino exchange, m_e is the mass of the electron and $m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$ is the effective Majorana neutrino mass. Next-generation experiments will fully probe the parameter space allowed for the inverted neutrino mass ordering, for which the lowest allowed value is $m_{\beta\beta} = 18.4 \pm 1.3$ meV. Experimentally, the half-life sensitivity has the following behaviour [2]:

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot f \cdot \sqrt{\frac{\xi}{\Delta E \cdot BI}}, \tag{2a}$$

where ε is the detection efficiency of the two outgoing electrons, f is the abundance of the isotope undergoing the $\beta\beta$ decay, ξ is the exposure evaluated as the product between the isotope mass and the live time, ΔE is the energy resolution evaluated at $Q_{\beta\beta}$ and BI is the background index. It is important to underline that in case of a quasi-background-free regime([1]), the half-life sensitivity scales almost linearly with the exposure, *i.e.*, $T^{0\nu}_{1/2} \propto \varepsilon f \xi$.

2. – Germanium-based Experiments

One candidate isotope for searching for the $0\nu\beta\beta$ decay is $^{76}_{32}$Ge decaying to $^{76}_{34}$Se with $Q_{\beta\beta} = 2039.061(7)$ keV [3]. The germanium crystals, with 1-3 kg masses, are used as fully depleted semiconductors that act both as the source and as the detecting medium of the $0\nu\beta\beta$ decay, leading to high detection efficiencies ($\varepsilon \sim 80 - 90\%$). Low intrinsic background levels and excellent resolutions, *i.e.*, FWHM($Q_{\beta\beta}$) $\sim 0.1\%$, are achievable with HPGe detectors. However, the natural abundance of ^{76}Ge is rather low ($f \sim 8\%$) and enrichment is necessary, up to fractions $f \sim 80 - 90\%$ [1]. The most remarkable ^{76}Ge-based experiments are Gerda (GERmanium Detector Array) and the Majorana Demonstrator (MJD). In particular, Gerda was able to provide the best sensitivity and the most stringent constraint on the half-life of any $0\nu\beta\beta$ decay, showing the feasibility of operating bare germanium detectors in liquid argon (LAr)

([1]) "Quasi-background-free" refers to background expectation values where there is high probability to observe less than one background count in the ROI (region of interest) around $Q_{\beta\beta}$.

TABLE I. – *Comparison of germanium-based experiments.* GERDA *and* MJD *values refer to final results present in refs.* [4] *and* [5]*, respectively. The design goals for LEGEND-200 ("L-200") and LEGEND-1000 ("L-1000") are taken from ref.* [6]*. Detector masses reported for* GERDA *and* MJD *refer to the maximum mass amount reached by the experiments during their operations. The energy resolution refers to the best value achieved across different detector types, i.e., to BEGe (Broad Energy Ge) detectors for* GERDA *and to PPC (P-type Point Contact) detectors for* MJD*. The lower limit on* $T^{0\nu}_{1/2}$ *and* $m_{\beta\beta}$ *shown for* GERDA *and* MJD *are set at 90% CL. For LEGEND, instead, we report the 3σ (99.7% CL) discovery sensitivities. Effective Majorana mass values are quoted as a range of values obtained taking the largest and smallest* ^{76}*Ge NMEs available among different calculation methods.*

	GERDA	MJD	L-200	L-1000
Mass (kg)	44.2	40.4	200	1000
Exposure (kg·yr)	127.2	63.3	1000	10000
FWHM at $Q_{\beta\beta}$ (keV)	2.6 ± 0.2	2.53 ± 0.08	2.5	2.5
BI (counts/(keV·kg·yr))	$5.2^{+1.6}_{-1.3} \times 10^{-4}$	$6.2^{+0.6}_{-0.5} \times 10^{-3}$	2×10^{-4}	10^{-5}
$T^{0\nu}_{1/2}$ (yr)	$> 1.8 \cdot 10^{26}$	$> 8.3 \cdot 10^{25}$	10^{27}	1.3×10^{28}
$m_{\beta\beta}$ (meV)	$< 79 - 180$	$< 113 - 269$	$< 34 - 78$	$< 9.4 - 21.4$

to significantly reduce the background level. The final results, accounting for a total exposure of 127.3 kg·yr, leads to $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr (90% CL) with $BI = 5.2^{+1.6}_{-1.3} \times 10^{-4}$ (counts/(keV·kg·yr)) [4]. It is worth noting that GERDA, during the Phase II, was the first Ge experiment to reach the background-free regime. A comparison with MJD results that operated high-purity Ge detectors in vacuum cryostats is shown in table I.

3. – The LEGEND Project

The LEGEND (Large Enriched Germanium Detector for Neutrinoless $\beta\beta$ Decay) project aims at combining the previous efforts and significant innovations developed and demonstrated by GERDA and MJD. The ultimate goal is the construction of LEGEND-1000, a ton-scale experiment designed to probe the $0\nu\beta\beta$ decay with a 99.7% CL discovery sensitivity of 10^{28} yr by employing 1 ton of Ge detectors. Performing a quasi-background-free search over 10 years of operations, LEGEND-1000 can make an ambiguous discovery of the $0\nu\beta\beta$ decay with a handful of counts in the ROI chosen as $Q_{\beta\beta} \pm 2\sigma$. Until LEGEND-1000 comes online, 200 kg of bare germanium detectors will be deployed in the upgraded infrastructure of the GERDA experiment at LNGS in Italy. The LEGEND-200 design already integrates most of the features that will be used in LEGEND-1000, starting from the ICPC (Inverted Coaxial Point Contact) Ge detectors and the LAr instrumentation. LEGEND-200 will be a leading experiment in the $0\nu\beta\beta$ field, aiming to reach a half-life discovery sensitivity of 10^{27} yr after 5 years of operations. The 2.5 background reduction factor with respect to GERDA can be attributed to the usage of larger average detector mass (resulting in fewer materials per kilogram of detector), to the adoption of low-noise electronics, to low-mass and radiopure detector components, and to an improved LAr system for the scintillation light readout. The design goals for the two stages of the LEGEND project are summarised in table I.

3˙1. *LEGEND-200: Experimental Setup.* – The core of LEGEND-200 consists of bare germanium detectors arranged in 12 vertical strings that form the central array. The

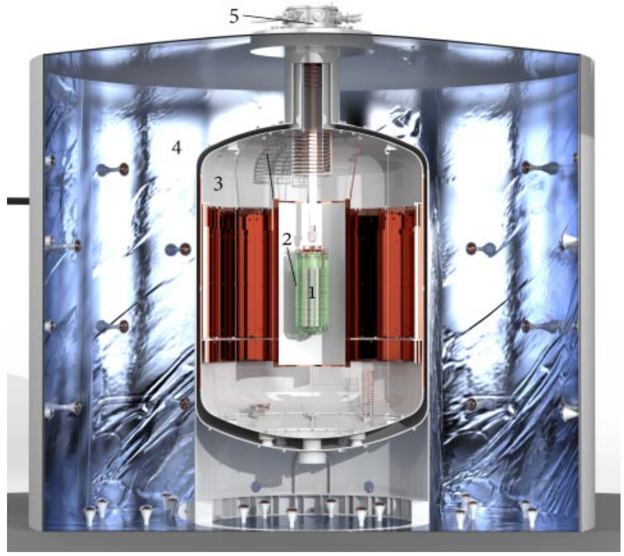

Fig. 1. – Schematic view of the LEGEND-200 experiment: 1) the array of Ge detectors; 2) the LAr veto; 3) the LAr cryostat; 4) the ultra-pure water tank and Cherenkov detectors; 5) the lock system for the lift and deployment of the array in the cryostat.

surrounding volume is instrumented with wavelength-shifting (WLS) fibers arranged into two barrels, both coupled to silicon photomultipliers (SiPMs) to detect coincident light. Everything is deployed in a cryostat filled with 64 m^3 of LAr at $\sim$ 88 K that acts as a coolant, as an active veto and as a shield [7]. The cryostat is immersed in a ultra-pure water tank instrumented with photomultipliers (PMTs). The tank acts both as a shield from external radiation (n, γ) and as a Cherenkov detector for muons [8]. The muon flux is naturally reduced by almost six orders of magnitudes by operating the experiment under the Gran Sasso mountains that provide a shield of almost 3500 m water equivalent [9]. The schematic view of the experiment is shown in fig. 1.

3˙2. *LEGEND-200: Preliminary Results.* – In Summer 2022, LEGEND-200 deployed the first 60 kg of Ge mass. During this first campaign, the hardware and readout electronics, the operation of HPGe detectors, and the full LAr instrumentation were tested. Preliminary results for the performance of PSD (Pulse Shape Discrimination) cuts are shown in fig. 2. The PSD cuts have been tuned over calibration data collected on a weekly basis between physics runs using 13 ^{228}Th sources with $\mathcal{O}\,(1\,\mathrm{kBq})$ activity each. The power of PSD cuts for single-site event, SSEs (multi-site event, MSEs) is well visible for the ^{208}Tl (^{214}Bi) double-escape (full energy) peak at 1593 keV (1621 keV). For a survival fraction of $\sim$ 90% of SSEs, the PSD cuts lead to a survival fraction of $\sim$ 10% for MSEs. In October 2022, a total of 101 detectors (6 coaxial, 26 PPC, 28 BEGe, 41 ICPC) arranged over 10 strings have been deployed for a total mass of 142.4 kg, of which $\sim$ 122 kg are currently usable for analysis studies. LEGEND-200 started physics data taking in Spring 2023. A total exposure of $\sim$ 6 kg·yr was collected between March and April 2023. From this first dataset, fig. 3 shows that most of the detectors fulfilled the LEGEND-1000 requirements for the energy resolution, *i.e.*, the FWHM is below 2.5 keV at $Q_{\beta\beta}$. Among all, coaxial detectors perform relatively poorly in terms of resolution

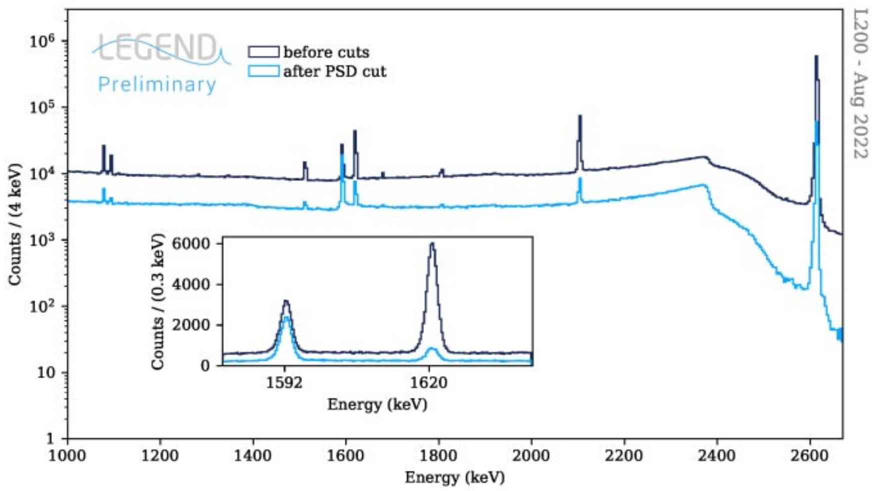

Fig. 2. – Events before (dark blue line) and after (light blue line) PSD cuts for calibration data collected with ^{228}Th sources during the 60 kg campaign. The effectiveness of PSD cuts is visible for MSEs at 1621 keV (^{214}Bi full energy peak) where only $\sim 10\%$ of events survive the cuts.

with respect to other detector types. However, their average resolution equal to 4.5 keV is still compatible with GERDA Phase II values listed in ref. [4]. Figure 4 shows the residual distribution for two of the ^{228}Th high statistics peaks, *i.e.*, for γ lines at 583.2 keV and 2614.5 keV. The narrow distribution reveals strong energy stability across the entire array over a one-month time frame.

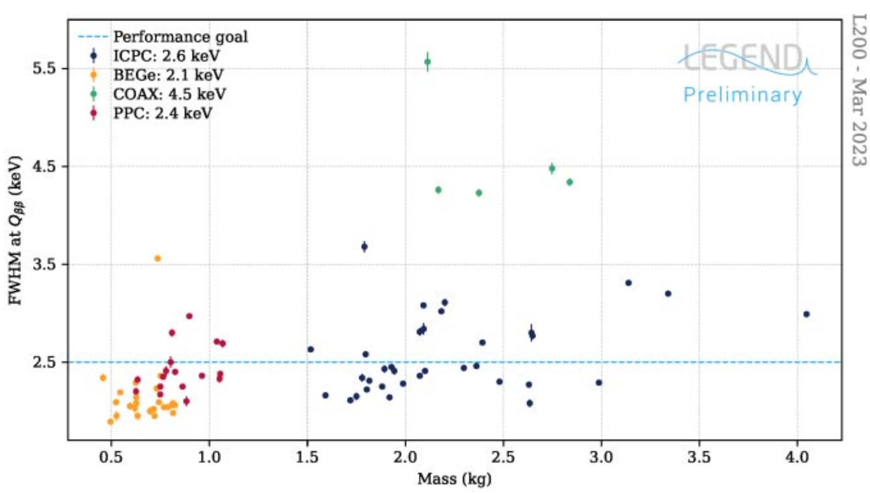

Fig. 3. – Energy resolution at $Q_{\beta\beta}$ as a function of the LEGEND-200 detector masses for an exposure of ~ 6 kg·yr. The legend displays the weighted average energy resolution in terms of FWHM at $Q_{\beta\beta}$ for each detector type. The blue horizontal line marks the 2.5 keV performance goal of LEGEND.

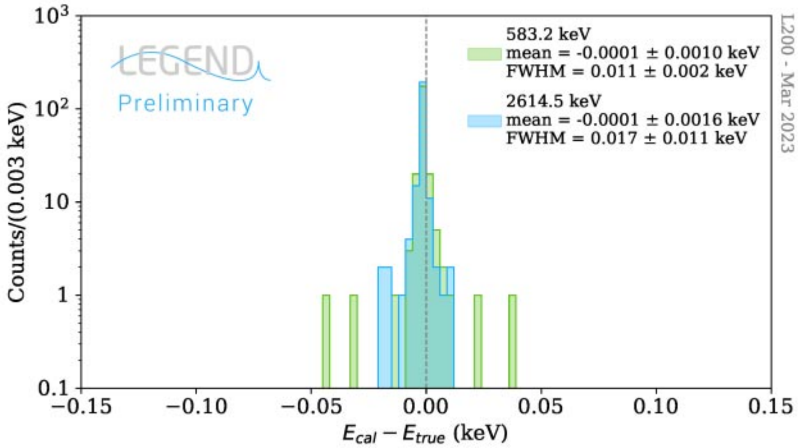

Fig. 4. – Distribution of calibration peak residuals evaluated at γ energies of 583.2 keV (green) and 2614.5 keV (blue): E_{true} is the expected γ energy; E_{cal} is the ADC energy extracted from the fit result of the corresponding peak and then converted in keV using the calibration curve. For each detector, corresponding to a single entry in the distribution, the global residual was determined by averaging over the residuals extracted for each calibration run.

4. – Conclusions

Neutrinos and their properties have been at the centre of many studies for decades. The fundamental question of whether the neutrino is a Majorana particle remains unanswered, but the potential discovery of the $0\nu\beta\beta$ decay could offer valuable insights. Using the experience gathered with GERDA and MJD, the LEGEND project aims at a $0\nu\beta\beta$ discovery that covers the inverted-ordering neutrino mass scale by employing 1 ton of Ge mass. The first stage, LEGEND-200, is online at LNGS and taking physics data since March 2023 with 142.2 kg of germanium detectors. The presented results show the effectiveness of the PSD background suppression technique over calibration data. A large fraction of detectors has shown to already fulfil the LEGEND-1000 resolution requirements, with energy shifts of 0.03 ± 0.31 keV at $Q_{\beta\beta}$ over an exposure of ~ 6 kg·yr. The current plan is to add the remaining Ge detectors mass in early 2024 and to continue data taking up to the design exposure of 1 t·yr.

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