

First Results on the Search for Lepton Number Violating Neutrinoless Double- β Decay with the LEGEND-200 Experiment

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The LEGEND Collaboration is searching for neutrinoless double-beta ($0\nu\beta\beta$) decay by operating high-purity germanium detectors enriched in ^{76}Ge in a low-background liquid argon environment. Building on key technological innovations from the GERmanium Detector Array (GERDA) experiment and the MAJORANA DEMONSTRATOR experiment, LEGEND-200 has performed a first $0\nu\beta\beta$ decay search based on 61.0 kg yr of data. Over half of this exposure comes from our highest performing detectors, including newly developed inverted-coaxial detectors, and is characterized by an estimated background level of $0.5_{-0.2}^{+0.3}$ cts/(keV ton yr) in the $0\nu\beta\beta$ decay signal region. A combined analysis of data from GERDA, the MAJORANA DEMONSTRATOR, and LEGEND-200, characterized by a 90% confidence level exclusion sensitivity of 2.8×10^{26} yr on the half-life of $0\nu\beta\beta$ decay, reveals no evidence for a signal and sets a new observed lower limit at $T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ yr (90% confidence level). Assuming the decay is mediated by Majorana neutrinos, this corresponds to an upper limit on the effective Majorana mass in the range $m_{\beta\beta} < 75\text{--}200$ meV, depending on the adopted nuclear matrix element.

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One of the most fundamental open questions in physics is the origin of the matter-antimatter asymmetry in the Universe, observed as an excess of baryons over antibaryons. This imbalance remains unexplained by the Standard Model of particle physics. A compelling explanation is provided by the framework of leptogenesis, which proposes that a lepton-antilepton asymmetry generated in the early Universe was partially transformed into the observed baryon asymmetry by electroweak sphaleron processes [1]. Neutrinos may play a key role in this scenario, particularly if they are Majorana fermions [2]—identical to their antiparticles—that inherently violate lepton number conservation [3]. Neutrinoless double-beta ($0\nu\beta\beta$) decay, in which two electrons are emitted by an atomic nucleus without accompanying antineutrinos, would directly confirm lepton number violation and the Majorana nature of neutrinos, marking a revolutionary step in our understanding of the cosmos [4–6]. Additionally, it would offer insights into a new theory of fermion masses and the absolute neutrino mass scale, bridging the gap between cosmology and particle physics [7].

A broad experimental program is focused on the search for $0\nu\beta\beta$ decay in ^{76}Ge [8,9], ^{100}Mo [10–12], ^{82}Se [13,14], ^{130}Te [15], ^{136}Xe [16,17], and other isotopes [4]. The experimental signature of $0\nu\beta\beta$ decay is a peak in the spectrum of the summed electron energies at the Q value ($Q_{\beta\beta}$) of the decay, as the two electrons carry all the available energy. The Large Enriched Germanium Experiment for Neutrinoless- $\beta\beta$ Decay (LEGEND) Collaboration is pursuing an experimental program [18] with discovery potential at a half-life beyond 10^{28} yr using the isotope ^{76}Ge [$Q_{\beta\beta} = 2039.061(7)$ keV [19]]. In this Letter, we report

results of the first search for $0\nu\beta\beta$ decay performed with LEGEND-200, the initial phase of the project.

In the first data-taking period, 142.5 kg of high-purity germanium (HPGe) detectors isotopically enriched in ^{76}Ge to 86%–92% were deployed in LEGEND-200. HPGe detectors are well-suited for double-beta decay searches since the energy is deposited locally, as ~ 1 MeV electrons are absorbed within 1–2 mm of germanium, leading to a detectable, high-resolution signal in a single detector. The detectors were deployed in the former GERDA [20] cryostat and water tank shield at the Laboratori Nazionali del Gran Sasso of the Italian Istituto Nazionale di Fisica Nucleare, located at a depth of 3500 m water-equivalent.

The HPGe detectors are arranged in vertical strings mounted in a circular array 55 cm in diameter (a rendering is provided in [21]). Each detector rests on a scintillating polyethylene naphthalate (PEN) plate [22,23] suspended by rods made of underground electroformed copper [24], and is read out by low-radioactivity front-end electronics [25], cables, and connectors. The front ends are affixed to the PEN plates and connected to charge-sensitive amplifiers operated in liquid argon (LAr) 30 cm above the array [26]. Immersion of the strings into $>99.999\%$ pure LAr in GERDA's 64 m³ steel cryostat [27] simultaneously provides cooling, shielding, and background rejection, as the LAr volume is instrumented to efficiently detect vacuum-ultraviolet scintillation light produced in the LAr by background processes. Tetraphenyl butadiene (TPB)-coated wavelength-shifting (WLS) fibers, arranged as two cylindrical curtains, closely surround the HPGe detector array, and silicon photomultiplier (SiPM) modules read out the guided light at both ends of the fibers [28]. A cylindrical WLS reflector of 138 cm diameter is installed concentric to the array [29] to increase light collection. A dedicated apparatus installed at the bottom of the cryostat monitors the purity of LAr over time [30]. Each string is enclosed in a WLS TPB-coated nylon cylinder that provides a barrier to ^{42}K ions, produced by ^{42}Ar decays in LAr [31], reducing the LAr volume from which ^{42}K ions can be

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collected on the surface of the HPGe detectors. The cryostat is deployed in a tank filled with 590 m³ of purified water, instrumented with 66 photomultiplier tubes (PMTs) to tag cosmic ray-induced muon events with >99% efficiency [32].

During this first data-taking period, the HPGe array consisted of 86.7 kg of inverted-coaxial (IC) detectors [33,34], along with 22.1 kg of p-type point-contact (PPC) detectors from the MAJORANA DEMONSTRATOR [35], and 14.7 kg of semicoaxial (Coax) plus 19 kg of broad energy germanium (BEGe) detectors from GERDA [36]. Typical individual detector masses are 1 kg for PPC, 2.5 kg for Coax, 0.7 kg for BEGe, and 2–4 kg for IC. All are p-type detectors featuring a lithium-diffused n^+ electrode that wraps around most of the surface and creates a ~ 1 mm inactive layer. A thin boron-implanted p^+ electrode covers a small fraction of the surface, except for Coax detectors. A thin layer between the electrodes provides electrical insulation. The dimensions of the p^+ electrode and insulating layer typically vary depending on the manufacturer. An illustration of the general characteristics of the detector geometry and electric field configuration is provided in [21]. Detectors produced by Mirion [37] (all BEGe and 73.4 kg of IC) feature a smaller insulating surface than those produced by ORTEC [38] (all PPC and 13.3 kg of IC). The novel IC detectors, comprising the largest fraction of the array, feature the most advanced design in terms of sensitivity to $0\nu\beta\beta$ decay, combining effective pulse shape discrimination (PSD) performance, high energy resolution, and large individual masses to effectively reduce the background level. Ten of the deployed detectors, totaling about 10 kg of germanium, could not be operated due to connectivity issues and were switched off.

The data acquisition system synchronously reads out digitized signals from HPGe detectors and SiPM modules

(16-bit, 62.5 MHz, 8192 samples) [39,40]. If an HPGe signal above a threshold of 25 keV is detected, traces from all channels are stored on disk for offline analysis, implemented in the novel `pygama` framework [41]. Signals from the PMTs (12-bit, 250 MHz, 220 samples) are acquired independently, with the two data acquisition systems synchronized through a GPS clock.

Twelve ²²⁸Th sources of ~ 5 kBq each [42] are lowered near the HPGe detectors for about 4 h each week to calibrate their energy scale, resolution, and PSD performance. A test charge equivalent to a ~ 1 MeV signal is injected into the HPGe front-end electronics every 20 s to monitor the stability of the detector response (similar to [25,43]). Additionally, forced trigger events (i.e., acquired without a physical signal in the HPGe detectors) are recorded at the same rate to study electronic noise and random coincidences. After an initial commissioning period, a data blinding policy was enforced: events with energy in the HPGe detectors within ± 25 keV of $Q_{\beta\beta}$ were inaccessible until the analysis procedures and parameters were finalized. Data from time periods with instrumental instability, due to temperature fluctuations or hardware interventions, are discarded. The data reported here were collected from March 2023 to February 2024, corresponding to a total exposure of 85.5 kg yr.

A set of quality cuts is applied to identify events incompatible with ordinary energy depositions in the HPGe array. These cuts are based on the flatness of the baseline preceding the HPGe signal rising edge and the structure of the signal itself, targeting phenomena such as electrical crosstalk or small electric discharges along the high-voltage line or in the detectors. The estimated acceptance of physical events at $Q_{\beta\beta}$, reported in Table I, varies across detectors and in time.

TABLE I. Summary of the parameters characterizing the LEGEND-200 dataset presented in this Letter. Energy reconstruction parameters and all $0\nu\beta\beta$ decay detection efficiencies are reported as exposure-weighted averages for each detector type with uncertainties propagated as fully correlated. The total mass excludes detectors that could not be operated reliably. The $0\nu\beta\beta$ decay detection efficiency of the muon anticoincidence cut is >99.9% and is omitted. Data for individual detectors and running periods are provided in [21].

	BEGe	PPC	Coax	IC
Number of detectors	25	12	6	29
Total mass	17.1 kg	10.7 kg	14.6 kg	65.1 kg
Exposure	10.9 kg yr	4.2 kg yr	7.8 kg yr	38.1 kg yr
Energy resolution (FWHM at $Q_{\beta\beta}$)	(2.1 \pm 0.1) keV	(2.5 \pm 0.1) keV	(4.4 \pm 0.1) keV	(2.6 \pm 0.1) keV
Energy bias at $Q_{\beta\beta}$	(0.3 \pm 0.3) keV	(0.3 \pm 0.3) keV	(0.0 \pm 0.3) keV	(0.3 \pm 0.3) keV
Signal efficiency	(49.5 \pm 3.2)%	(56.1 \pm 3.4)%	(47.6 \pm 4.5)%	(59.9 \pm 2.3)%
Quality cuts		(97.5 \pm 0.1)%		
$0\nu\beta\beta$ decay containment in active volume	(77.0 \pm 3.2)%	(83.3 \pm 2.3)%	(80.4 \pm 4.2)%	(85.9 \pm 0.8)%
⁷⁶ Ge isotopic enrichment	(87.4 \pm 0.3)%	(87.4 \pm 0.5)%	(86.2 \pm 1.7)%	(91.3 \pm 0.5)%
Pulse shape discrimination	(81.1 \pm 3.9)%	(85.0 \pm 4.5)%	(76.0 \pm 5.7)%	(84.3 \pm 3.0)%
Liquid argon cut		(93.3 \pm 0.5)%		

The energy of HPGe events is reconstructed using a truncated cusp filter [44], with parameters optimized for each detector and data-taking run based on weekly ^{228}Th calibration data. A charge-trapping correction is also applied to the energy values [45]. The observed energy resolution (see Table I) is improved by 20%–30% compared to that achieved in GERDA Phase II. The energy calibration procedure follows prior work [43,46]. The stability of the energy scale and resolution is monitored over time using calibration data. Data from detectors and periods with unstable energy scales (e.g., when instabilities at $Q_{\beta\beta}$ are comparable to the energy resolution), amounting to 11.3 kg yr, are only used to determine event multiplicity, i.e., the number of detectors in which a signal was recorded. The bias of the energy estimator at $Q_{\beta\beta}$ due to analog-to-digital converter nonlinearity is estimated following [43] as the difference between 2039.06 keV and the estimated energy (see Table I) and is accounted for in the $0\nu\beta\beta$ decay analysis.

Events with energy depositions in multiple HPGe detectors are rejected. The evaluation of event multiplicity accounts for electrical crosstalk between channels (following [47]), which is estimated from calibration data to be below 1% for most cases, with only a few channel pairs exceeding this threshold. Data from PMTs in the water tank are analyzed offline to identify muon signals. HPGe events accompanied by a muon signal in a window of 3.5 μs around an HPGe trigger are also discarded with a negligible dead time.

The physics data collected by LEGEND-200 surviving quality, HPGe multiplicity, and muon cuts are shown in Fig. 1. The types of background events observed are the same as those in GERDA [48]. We characterize the dominant background contributions and validate the

interpretation of spectral features by comparing data and Monte Carlo simulations, following the same techniques used in GERDA [48] and by the MAJORANA DEMONSTRATOR [49,50]. At energies below $Q_{\beta\beta}$, the spectrum is dominated by the continuous distribution of $2\nu\beta\beta$ decay events. The γ lines and continuum below ~ 3 MeV originate from γ rays emitted by the ^{40}K , ^{238}U , and ^{232}Th decay chains in the structural materials, and also the decay of ^{42}K in LAr. These γ rays can be fully absorbed within a single HPGe detector or may deposit some energy in germanium and the surrounding optically active materials, primarily LAr and PEN. In the first case, multiple Compton scatters can occur within an HPGe detector [multiple-site event (MSE)], which differs from the single-site event (SSE) topology of $\beta\beta$ decay. Even if only a single-site Compton scatter takes place in an HPGe detector, coincident scintillation light due to γ or accompanying β radiation is likely to be detected. At higher energy the spectrum is dominated by energy-degraded α particles from the ^{238}U decay chain, primarily from ^{210}Po decays on the p^+ electrode or insulating surfaces. The vast majority of these α events originate from the Coax detectors, featuring the largest p^+ surfaces. Additionally, β particles from ^{42}K decay ($Q_\beta = 3.53$ MeV) on the detector surface can penetrate into the active volume.

To evaluate the presence of scintillation light coincident with the HPGe signal, SiPM traces are analyzed to reconstruct the time and amplitude of each pulse. Low-amplitude pulses from transient noise in the SiPMs are discarded, with a rejection threshold varying between channels, typically around 0.5 photoelectrons. The coincidence window is defined as $[-1, 5]$ μs relative to the onset

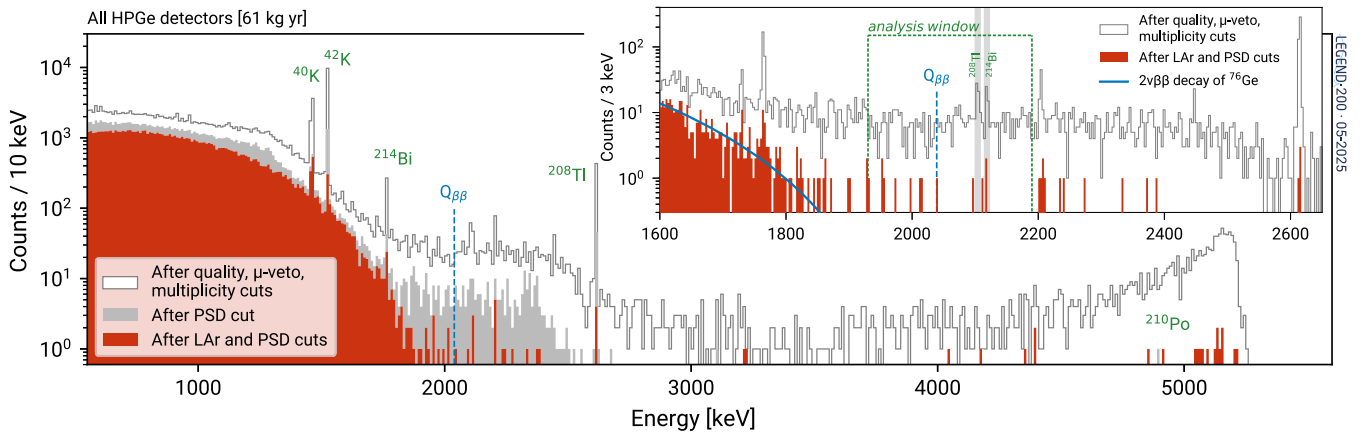


FIG. 1. The energy spectrum of the first LEGEND-200 dataset, corresponding to 61.0 kg yr of germanium exposure, above the ^{39}Ar $Q_\beta = 565$ keV. The white histogram shows events passing quality and muon anticoincidence cuts and with energy deposited in one single HPGe detector. The main radioactive background contributors are indicated in green. The gray and red histograms show the subsets of events passing the PSD cut and additionally the LAr anticoincidence cut, respectively. The inset shows a close-up around the region of interest for $0\nu\beta\beta$ decay with finer binning. The expected contribution from the $2\nu\beta\beta$ decay of ^{76}Ge ($T_{1/2}^{2\nu} = 2.022 \times 10^{21}$ yr [51]) corresponds to the solid blue line. The events used to set a constraint on the $0\nu\beta\beta$ decay rate are contained by the analysis window, marked in green. Only two significant γ peaks (shaded areas) are expected within this window, and the corresponding 10 keV wide energy regions are excluded from the statistical analysis.

of the HPGe rising edge. Events are excluded from the analysis if the sum of the amplitudes across all SiPM channels exceeds 4 photoelectrons, or if the multiplicity (i.e., the number of channels with a signal above threshold) exceeds 4, considering only pulses within the coincidence window. This cut results in a survival fraction of signal events of $(93.3 \pm 0.5)\%$, as determined using forced trigger events and ^{40}K full energy peak events, where no coincident light is expected.

The shape of the rising edge of HPGe signals is analyzed to further identify background events. We use two PSD techniques to identify signal-like event topologies in detectors featuring a small p^+ electrode: first, A/E measures the maximum current amplitude (A) over the charge amplitude (E) [52,53]. Second, late-charge (LQ) PSD measures the area above the last 20% of the charge signal normalized by the charge amplitude [8]. For signal-like events, these parameters are normally distributed, with mean and standard deviation measured using the 1593 keV double escape peak (DEP) induced by the 2614 keV ^{208}Tl γ ray from the calibration sources, an SSE-enriched event sample. Both PSD estimators are corrected for correlations with drift time [54] and energy.

A/E is used to reject MSEs, which exhibit lower A/E values than SSEs. The cut threshold is tuned to achieve 90% survival fraction of ^{208}Tl DEP events. α and β particles incident on surfaces can also be rejected by PSD. Events near the p^+ electrode result in high values of A/E and LQ. Events near the n^+ and passivated surfaces produce low values of A/E and high values of LQ. For Mirion IC and BEGe detectors with a narrow passivated groove between the p^+ and n^+ electrode, a value of A/E 3 standard deviations above the mean is used to reject these events. For ORTEC detectors with a wide passivated surface (PPCs and one IC), a value of LQ 3 standard deviations above the mean is used. Five IC detectors with abnormally wide p^+ pads (indicated as IC₂) had a significant population of MSEs that passed the A/E cut. For these detectors LQ values 3 standard deviations above the mean are also used to reject MSEs. The Coax detectors exhibit different pulse-shape characteristics than detectors featuring a small p^+ electrode, severely reducing the effectiveness of A/E and LQ cuts. For these detectors, following the procedure in [52], an artificial neural network is employed to reject MSEs, in combination with a cut on the rise time of the signal to eliminate fast events originating from the p^+ electrode.

The $0\nu\beta\beta$ decay PSD survival fraction is corrected for several systematic effects. We correct for dependence on energy, measured using a ^{56}Co source with multiple DEPs ranging from 1013 to 2429 keV [8]. We also correct for the differences in spatial distribution between DEP events (concentrated near surfaces) and $\beta\beta$ events (uniformly distributed in the bulk) by measuring the detection efficiency for $2\nu\beta\beta$ events in an energy range of 1.0–1.3 MeV. These corrections reduce the $0\nu\beta\beta$ decay detection efficiency

(reported in Table I) by a few percent. Finally, we add uncertainties related to weekly shifts in the DEP efficiency and energy dependence. Data from periods characterized by significantly unstable PSD performance, amounting to 13.2 kg yr, are only used to determine event multiplicity.

After data selection, the total exposure used for analysis amounts to 61.0 kg yr. The energy spectrum, after applying the LAr anticoincidence and PSD cuts, is shown in red in Fig. 1. A remarkably low background level is observed across the entire energy range, above the $2\nu\beta\beta$ decay events. At $Q_{\beta\beta}$, the LAr cut provides the primary rejection of Compton scatters from the 2615 keV γ ray of ^{208}Tl , which dominate the spectrum prior to cuts. The PSD cut independently removes about 60% of these events, as measured in calibration data. The next largest contributors, β decays of ^{42}K on the HPGe surface and γ rays from ^{214}Bi , are also strongly suppressed by the cuts. The enhanced rejection achieved through the combination of LAr and PSD cuts reflects the complementarity of these techniques, which target different interaction topologies (see Fig. 1). The contribution of cosmogenic backgrounds is estimated to be less than 2×10^{-5} cts/(keV kg yr) [55].

Statistical inference on the $0\nu\beta\beta$ decay rate is performed using both frequentist and Bayesian frameworks. Following [9], the analysis window is defined as the energy range from 1930 to 2190 keV, excluding ± 5 keV regions around the 2104 keV (^{208}Tl) and 2119 keV (^{214}Bi) γ ray full energy peak events. There are 11 events that survive all cuts within this window (see Fig. 2). The low event count and the expected background flatness in the region of interest allow the use of an analytical model comprising a uniform component and a normal distribution at the expected $0\nu\beta\beta$ decay signal location. The likelihood function is defined as the product of extended unbinned likelihood terms for each HPGe detector and for each time period (“partitions,” see detailed

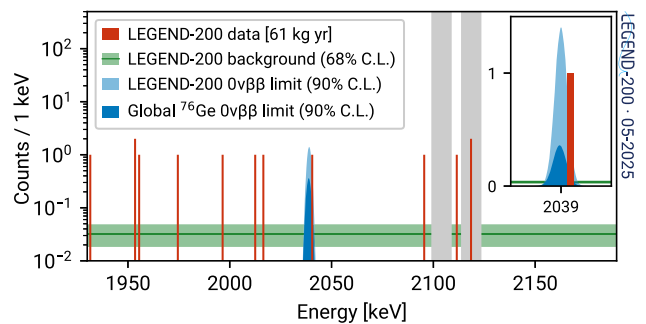


FIG. 2. The energy spectrum of the first LEGEND-200 dataset (61.0 kg yr) after all analysis cuts in the [1930, 2190] keV window. Events in the gray regions, corresponding to ± 5 keV around known γ lines, are excluded from the analysis. Confidence intervals from the frequentist analysis are visualized for the exposure-weighted combined background index (68% C.L., in green) and for the signal strength (90% C.L., in blue). The $0\nu\beta\beta$ decay rate upper limit derived by including data from other ^{76}Ge experiments is shown in dark blue.

description in Ref. [56]) with stable energy reconstruction and $0\nu\beta\beta$ decay detection efficiency parameters.

The location, scale, and normalization parameters of the normal distribution modeling $0\nu\beta\beta$ decay in each likelihood term are constrained to their expected values using normal distributions as pull terms (or priors in the Bayesian approach). The uncertainty on the $0\nu\beta\beta$ decay detection efficiency is conservatively assumed to be maximally correlated between partitions, simplifying the model by reducing the number of free parameters. If a statistical test does not indicate significant variation of background rate within a dataset, a single background index parameter is used to model the background across all its partitions. Following this approach, data from Coax and IC₂ detectors (the *silver* dataset, 12.7 kg yr) are assigned a separate background index, as their background level is expected to be higher than that of the rest of the data (the *golden* dataset, 48.3 kg yr). All information required to implement the likelihood function used here is provided in [57].

The frequentist analysis [58] uses a two-sided profile likelihood ratio test statistic with parameters constrained to physical values [59]; its distribution is computed via Monte Carlo methods. No evidence of a signal is found, resulting in a lower limit on the half-life of $0\nu\beta\beta$ decay of 0.5×10^{26} yr at 90% confidence level (C.L.). The background index at 68% C.L. is $0.5_{-0.2}^{+0.3}$ cts/(keV ton yr) for the *golden* dataset and $1.3_{-0.5}^{+0.8}$ cts/(keV ton yr) for the *silver* dataset; both are consistent within uncertainty with the GERDA background index [9]. A visualization of these confidence intervals is shown in Fig. 2. The Bayesian analysis is performed using the BAT.jl software library [60,61], adopting uniform priors for the signal and background rates. The resulting 90% credibility interval (C.I.) on the signal strength is identical to that obtained in the frequentist analysis.

The expected statistical distribution of 90% C.L. intervals was estimated via toy Monte Carlo experiments under the assumption of no signal. The observed limit lies within the central 95% interval of the expected distribution and is less stringent than its median of 1.0×10^{26} yr (see Ref. [21]). This is partly due to an event at an energy 1.3 standard deviations from the expected signal location within its partition. The event was recorded in a PPC detector and exhibits a pulse shape with a high value of A/E , compatible with an interaction near the p^+ electrode.

The full MAJORANA DEMONSTRATOR [8] and GERDA [9] datasets (amounting to 64.5 and 127.2 kg yr of exposure, respectively) are incorporated into the analysis as additional extended terms in the likelihood to extract a combined $0\nu\beta\beta$ decay constraint. These terms are unchanged from the original analyses. With a p value of 0.29 for the background-only hypothesis in the combined dataset, no evidence of a signal is found. Therefore, we extract a combined lower limit on the half-life of $0\nu\beta\beta$ decay of 1.9×10^{26} yr (90% C.L.). The corresponding 90% C.L. interval for the signal strength in the LEGEND-200 dataset is

visualized in Fig. 2. The observed limit lies within the central 68% interval of the expected limit distribution, characterized by a median of 2.8×10^{26} yr (see Ref. [21]), the best achieved among $0\nu\beta\beta$ decay searches to date. The Bayesian analysis yields an identical 90% C.I. lower limit under uniform signal and background priors. Adopting a uniform prior on the Majorana neutrino mass yields a stronger limit of 2.8×10^{26} yr.

The overall effect of uncertainties in the $0\nu\beta\beta$ decay signal model on the limit is at the percent level. Systematic uncertainties in the fit model have a marginal impact; for example, assuming a linear background shifts the limit by a few percent.

We calculate constraints on the effective Majorana mass $m_{\beta\beta}$ using a range of nuclear matrix elements (NMEs) calculations [62–73], i.e., 2.35–6.34, yielding a range of upper limits of $m_{\beta\beta} < 75$ –200 meV in the frequentist framework. In addition, we provide a second estimate based on a recent *ab initio* calculation that includes “quenching” physics [74], the leading short-range neutrino-exchange mechanism [75,76], and, for the first time, a comprehensive Bayesian treatment of theoretical uncertainties [77]. Using this approach, we derive an upper limit of $m_{\beta\beta} < 320$ meV in the Bayesian framework, with its strength significantly limited by the large uncertainty in the NME value. The posterior distributions are available in [21].

We have presented first results from the initial data-taking phase of LEGEND-200. With the deployment of additional large mass IC detectors and background reduction through refined surface treatment of nearby components, data acquisition will resume with an improved detector array. This Letter marks the beginning of the phased LEGEND program, which ultimately aims to operate up to one ton of HPGe detectors enriched in ⁷⁶Ge in the future LEGEND-1000 infrastructure [18]. The program is designed to achieve discovery sensitivities for $0\nu\beta\beta$ decay half-lives beyond 10^{28} yr that explore the inverted and a significant fraction of the normal neutrino mass ordering regime, as predicted by neutrino oscillation experiments [4,78].

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Data availability—The data that support the findings of this article are openly available [57].

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