PARTICLE PHYSICS

Probing Majorana neutrinos with double-β decay

M. Agostini[1], A. M. Bakalyarov[2], M. Balata[3], I. Barabanov[4], L. Baudis[5], C. Bauer[6], E. Bellotti[7,8], S. Belogurov[4,9], A. Bettini[10,11], L. Bezrukov[4], D. Borowicz[12], V. Brudanin[12], R. Brugnera[10,11], A. Caldwell[13], C. Cattadori[8], A. Chernogorov[9], T. Comellato[1], V. D'Andrea[14], E. V. Demidova[9], N. Di Marco[3], A. Domula[15], E. Doroshkevich[4], V. Egorov[12]*, R. Falkenstein[16], M. Fomina[12], A. Gangapshev[4], A. Garfagnini[10,11], M. Giordano[14], P. Grabmayr[16], V. Gurentsov[4], K. Gusev[1,2,12], J. Hakenmüller[6], A. Hegai[16], M. Heisel[6], S. Hemmer[11], R. Hiller[5], W. Hofmann[6], M. Hult[17], L. V. Inzhechik[4], J. Janicskó Csáthy[1], J. Jochum[16], M. Junker[3], V. Kazalov[4], Y. Kermaïdic[6], T. Kihm[6], I. V. Kirpichnikov[9], A. Kirsch[6], A. Kish[5], A. Klimenko[6,12], R. Kneißl[13], K. T. Knöpfle[6]†, O. Kochetov[12], V. N. Kornoukhov[4,9], P. Krause[1], V. V. Kuzminov[4], M. Laubenstein[3], A. Lazzaro[1], M. Lindner[6], I. Lippi[11], A. Lubashevskiy[12], B. Lubsandorzhiev[4], G. Lutter[17], C. Macolino[3], B. Majorovits[13], W. Maneschg[6], M. Miloradovic[5], R. Mingazheva[5], M. Misiaszek[18], P. Moseev[4], I. Nemchenok[12], K. Panas[18], L. Pandola[19], K. Pelczar[3], L. Pertoldi[10,11], P. Piseri[20], A. Pullia[20], C. Ransom[5], S. Riboldi[20], N. Rumyantseva[2,12], C. Sada[10,11], E. Sala[13], F. Salamida[14], C. Schmitt[16], B. Schneider[15], S. Schönert[1], A.-K. Schütz[16], O. Schulz[13], M. Schwarz[1], B. Schwingenheuer[6], O. Selivanenko[4], E. Shevchik[12], M. Shirchenko[12], H. Simgen[6], A. Smolnikov[6,12], L. Stanco[11], D. Stukov[2], L. Vanhoefer[13], A. A. Vasenko[9], A. Veresnikova[4], K. von Sturm[10,11], V. Wagner[6], A. Wegmann[6], T. Wester[15], C. Wiesinger[1], M. Wojcik[18], E. Yanovich[4], I. Zhitnikov[12], S. V. Zhukov[2], D. Zinatulina[12], A. Zschocke[16], A. J. Zsigmond[13], K. Zuber[15], G. Zuzel[18], GERDA Collaboration

A discovery that neutrinos are Majorana fermions would have profound implications for particle physics and cosmology. The Majorana character of neutrinos would make possible the neutrinoless double-β ($0\nu\beta\beta$) decay, a matter-creating process without the balancing emission of antimatter. The GERDA Collaboration searches for the $0\nu\beta\beta$ decay of ^{76}Ge by operating bare germanium detectors in an active liquid argon shield. With a total exposure of 82.4 kg·year, we observe no signal and derive a lower half-life limit of $T_{1/2} > 0.9 \times 10^{26}$ years (90% C.L.). Our $T_{1/2}$ sensitivity, assuming no signal, is 1.1×10^{26} years. Combining the latter with those from other $0\nu\beta\beta$ decay searches yields a sensitivity to the effective Majorana neutrino mass of 0.07 to 0.16 electron volts.

Neutrinos were discovered in 1956 (*1*), but only at the turn of the millennium was it experimentally proven that the three known neutrino types (flavors) ν_α ($\alpha = e, \mu, \tau$) can convert into one another (*2*–*4*). These flavor oscillations are possible only if neutrinos have nonzero mass, which is currently the only established contradiction to the standard model (SM) of particle physics. From tritium β decay experiments (*5*, *6*) and cosmological observations (*7*), we know that their masses are very small—less than 10^{-5} of the electron mass. Neutrinos are the only fundamental spin-½ particles (fermions) without electric charge. As a consequence, they might be Majorana fermions (*8*)—particles identical to their antiparticles. This is a key ingredient of some explanations for why matter is so much more abundant than antimatter in today's Universe and why neutrinos are so much lighter than the other elementary particles (*9*).

Majorana neutrinos would lead to nuclear decays that violate lepton number conservation and are therefore forbidden in the SM of particle physics. The so-called neutrinoless double-β ($0\nu\beta\beta$) decay simultaneously transforms two neutrons inside a nucleus into two protons with an emission of two electrons (Fig. 1). The SM-allowed double-β ($2\nu\beta\beta$) decay occurs with an emission of two electrons and two antineutrinos. In the $0\nu\beta\beta$ decay, the two electrons together carry the available decay energy ($Q_{\beta\beta}$) and the resulting monoenergetic signal is the chief experimental signature. A positive detection of this process would imply the first observation of a matter-creating process, without the balancing emission of antimatter, and would establish the Majorana nature of neutrinos (*10*, *11*).

We report here on the search for the $0\nu\beta\beta$ decay $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-$ [$Q_{\beta\beta} = 2039.061 \pm 0.007$ keV (*12*)] with the Germanium Detector Array (GERDA). Unlike previous experiments, GERDA surpasses the sensitivity for a $0\nu\beta\beta$ decay half-life of $T_{1/2} \sim 10^{26}$ years (90% C.L.) and operates in a background-free regime such that the expected number of background events is less than 1 in the energy region of interest at the final exposure (*13*); here the sensitivity is defined as the median limit expected from many repetitions of the experiment assuming no signal. This achievement, together with the excellent energy resolution of Ge detectors, is crucial in reaching a regime where it would be possible to detect a nonzero signal for the decay.

The GERDA experimental design was guided by the requirement to reduce interfering signals from naturally occurring radioactivity and from cosmic rays to negligible levels. The Ge detectors are made from high-purity (99.9999%) Ge material that is enriched in the ^{76}Ge isotope from the natural abundance of 7.8% to more than 85%. The Ge detectors act as both the source and detector for the $0\nu\beta\beta$ decay, as illustrated in Fig. 1. In total, GERDA deploys 37 enriched detectors with two different geometries [coaxial and broad-energy Ge (BEGe) detectors; see fig. S1] and with a total mass of 35.6 kg as bare crystals in 63 m^3 of liquid argon (LAr). The LAr serves as high-purity shielding against radiation from radioactive decays, and it also provides cooling for the Ge diodes. Moreover, the LAr—as a result of its scintillation property—acts as a veto system to discard events originating from background radiation, which simultaneously deposit energy inside the Ge detectors and the adjacent LAr. The scintillation light is detected by 16 photomultipliers and wavelength-shifting fibers connected to silicon photomultipliers. A water tank encloses the LAr cryostat to further attenuate γ radiation and neutrons from the experimental environment. It also serves as a water Cherenkov detector to identify cosmic-ray muons and their secondary shower particles that could mimic signal events. GERDA is operated deep underground, at the Gran Sasso National Laboratories (LNGS) of INFN in Italy, at a depth of 3500 m water equivalent to reduce the cosmic ray muon flux by six orders of magnitude with respect to Earth's surface. Detailed descriptions of phases I and II of the experiment can be found in (*14*, *15*).

The signals of the Ge detectors are read out by low radioactive charge–sensitive amplifiers,

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[1]Physik Department, Technische Universität München, D-85748 Munich, Germany. [2]National Research Centre "Kurchatov Institute," Moscow 123182, Russia. [3]INFN Laboratori Nazionali del Gran Sasso and Gran Sasso Science Institute, I-67010 Assergi, Italy. [4]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia. [5]Physik Institut der Universität Zürich, CH-8057 Zurich, Switzerland. [6]Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany. [7]Dipartimento di Fisica, Università Milano Bicocca, I-20126 Milan, Italy. [8]INFN Milano Bicocca, I-20126 Milan, Italy. [9]Institute for Theoretical and Experimental Physics, Moscow 117259, Russia. [10]Dipartimento di Fisica e Astronomia dell'Università di Padova, I-35121 Padua, Italy. [11]INFN Padova, I-35131 Padua, Italy. [12]Joint Institute for Nuclear Research, Dubna 141980, Russia. [13]Max-Planck-Institut für Physik, D-80805 Munich, Germany. [14]INFN Laboratori Nazionali del Gran Sasso and Università degli Studi dell'Aquila, I-67100 L'Aquila, Italy. [15]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01069 Dresden, Germany. [16]Physikalisches Institut, Eberhard Karls Universität Tübingen, D-72076 Tübingen, Germany. [17]European Commission, JRC-Geel, B-2440 Geel, Belgium. [18]Institute of Physics, Jagiellonian University, Cracow 40-348, Poland. [19]INFN Laboratori Nazionali del Sud, I-95123 Catania, Italy. [20]Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, I-20133 Milan, Italy.
*Deceased.
†Corresponding author. Email: gerda-eb@mpi-hd.mpg.de

digitized at a sampling rate of 100 MHz and stored for off-line analysis. Weekly calibrations with ^{228}Th sources are performed to monitor the energy scale and resolution, as well as to define and monitor the analysis cuts. The derived energy resolution, full width at half maximum (FWHM), at $Q_{\beta\beta}$ is 3.6 ± 0.1 keV for the coaxial detectors and 3.0 ± 0.1 keV for the BEGe detectors, both corresponding to $\sigma/Q_{\beta\beta} < 10^{-3}$ (σ = FWHM/2.35).

During physics data taking, all Ge and LAr scintillation channels are read out if one or more Ge diodes detect a signal above a preset trigger threshold. Multiple detector hits are discarded as background events. Similarly, events are classified as background (Fig. 1) if at least one photoelectron is detected in the LAr within ~6 μs around the Ge detector signal—that is, ~5 times the lifetime of the argon excimer observed in GERDA. Random coincidences lead to a loss of potential 0νββ signals of 2.3 ± 0.1%. All events with a muon trigger preceding a Ge trigger by less than 10 μs are rejected with a signal loss of <0.1%. Background events from γ radiation often lead to multiple interactions separated in space but within the same detector. The time structure of the recorded signal allows us to reject this background as well as events occurring at the surface of a detector from α or β decays (Fig. 1, pulse shape discrimination, PSD). More than 95% of the background is rejected by the LAr veto and PSD (Fig. 2), whereas 69% of the 0νββ decay events would be kept for the coaxial detectors and 86% for the BEGe detectors. Relative to (*16*), the Phase II exposure has been more than doubled while improving both energy resolution (by 10%) and background rate (by ~80%) in the coaxial detectors and maintaining the excellent energy resolution of the BEGe detectors throughout the run; the result is a doubling of the sensitivity to more than 10^{26} years.

Since the outset, GERDA has adopted a rigorous blind analysis strategy to ensure an unbiased search for 0νββ decays. Events with a reconstructed energy of $Q_{\beta\beta} \pm 25$ keV are blinded (i.e., removed from the data stream) until the data selection is fixed. Figure 2 displays the energy spectra corresponding to 53.9 kg·year Phase II exposure before and after analysis cuts, including a PSD method for coaxial detectors that was not used in prior work (*15*). At low energies, the spectrum after analysis cuts is dominated by 2νββ decays. The insets in Fig. 2 display separately the event distribution of the coaxial detector and BEGe detector datasets in the analysis window 1930 to 2190 keV. After unblinding, only three events in the coaxial dataset and four events in the BEGe dataset remain in the analysis window (*17*). GERDA thus reaches an unprecedented low background rate of $5.7^{+4.1}_{-2.6} \times 10^{-4}$ counts/(keV·kg·year) for the coaxial detectors and $5.6^{+3.4}_{-2.4} \times 10^{-4}$ counts/(keV·kg·year) for the BEGe detectors.

An unbinned maximum likelihood fit is carried out simultaneously in the different datasets (see table S3), including those from GERDA Phase I (*18*). In total, 82.4 kg·year have been scrutinized for a 0νββ signal so far. The fit function (*13*) comprises flat distributions for the background, independent for each dataset, and Gaussian distributions for a possible 0νββ signal: The mean is $Q_{\beta\beta}$, the resolutions are taken from calibration data individually for each set, and the normalizations are calculated from the target half-life $T_{1/2}$. A null signal maximizes the likelihood. Confidence intervals are evaluated in both the frequentist and Bayesian frameworks (*15*). The frequentist analysis is based on the profile likelihood method, and systematic uncertainties are included as nuisance parameters with Gaussian pull terms. The derived limit of $T_{1/2} > 0.9 \times$

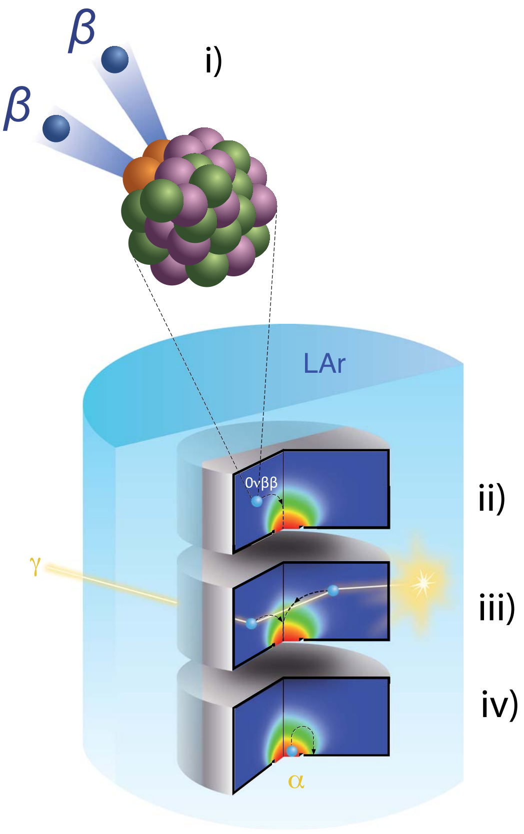

Fig. 1. The concept of active background suppression. GERDA searches for the 0νββ decay $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$, $Q_{\beta\beta}$ = 2039 keV, with high-purity Ge detectors enriched in ^{76}Ge that are operated in liquid argon (LAr). (i) Artist's view of the 0νββ decay of a nucleus by an emission of two electrons (β particles). (ii to iv) Three BEGe detectors, out of the 40 Ge detectors of the GERDA detector array (table S1 and fig. S2), immersed in LAr (bluish cylinder). Events from 0νββ decays would deposit energy $Q_{\beta\beta}$ within a few cubic millimeters in a single detector (ii). Events with coincident LAr scintillation light or with multiple interactions in the Ge detector [e.g., from Compton scattering (iii)] are classified as background events. The special detector design with a small readout electrode (fig. S1) enhances drift time differences between different trajectories (black dashed lines) of the charges (holes) generated by the energy depositions. The color code (see fig. S1 for color bar) indicates the electrical signal strength at the respective location. Hence, single- and multi-site events can be identified efficiently by the time profile of their electronic signal. Similarly, α decays at the readout electrode show unique signal characteristics (iv).

Table 1. Comparison of present and prior experiments. Lower half-life limits $L(T_{1/2})$ and sensitivities $S(T_{1/2})$, both at 90% C.L., reported by recent 0νββ decay searches with indicated deployed isotope masses M_i and FWHM energy resolutions. Sensitivities $S(T_{1/2})$ have been converted into upper limits of effective Majorana masses $m_{\beta\beta}$ using the nuclear matrix elements quoted in (*20*).

Experiment	Isotope	M_i (kmol)	FWHM (keV)	$L(T_{1/2})$ (10^{25} years)	$S(T_{1/2})$ (10^{25} years)	$m_{\beta\beta}$ (meV)
GERDA (this work)	^{76}Ge	0.41	3.3	9	11	104 to 228
MAJORANA (*27*)	^{76}Ge	0.34	2.5	2.7	4.8	157 to 346
CUPID-0 (*28*)	^{82}Se	0.063	23	0.24	0.23	394 to 810
CUORE (*29*)	^{130}Te	1.59	7.4	1.5	0.7	162 to 757
EXO-200 (*30*)	^{136}Xe	1.04	71	1.8	3.7	93 to 287
KamLAND-Zen (*21*)	^{136}Xe	2.52	270	10.7	5.6	76 to 234
Combined						66 to 155

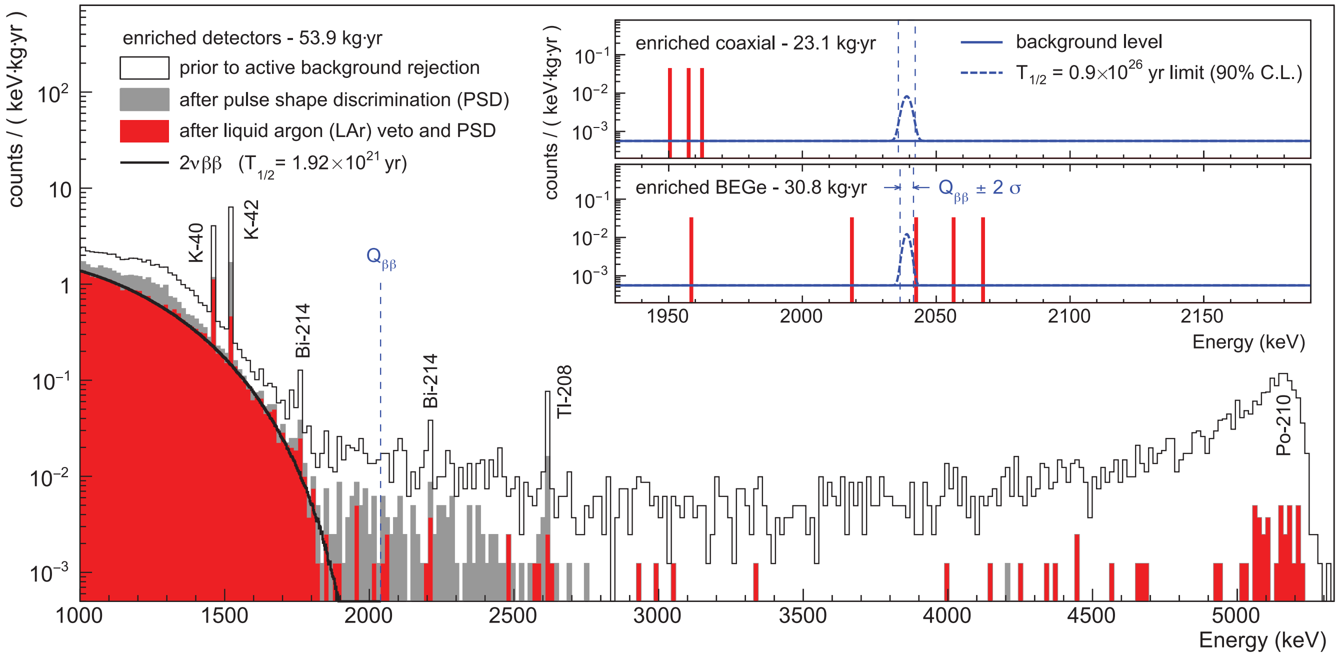

Fig. 2. GERDA Phase II energy spectra (53.9 kg·year). Enriched coaxial and BEGe data are displayed in a combined spectrum after indicated cuts. Main contributions to the spectra are labeled. The insets display the analysis window for coaxial and BEGe detectors separately, including the background rates (solid blue lines). No event reconstructs within $Q_{\beta\beta}$ ± 2σ. The dashed blue curves depict the 90% C.L. limit for a 0νββ signal of $T^{0\nu}_{1/2} = 0.9 \times 10^{26}$yearsderived from the likelihood analysis of all GERDA datasets.

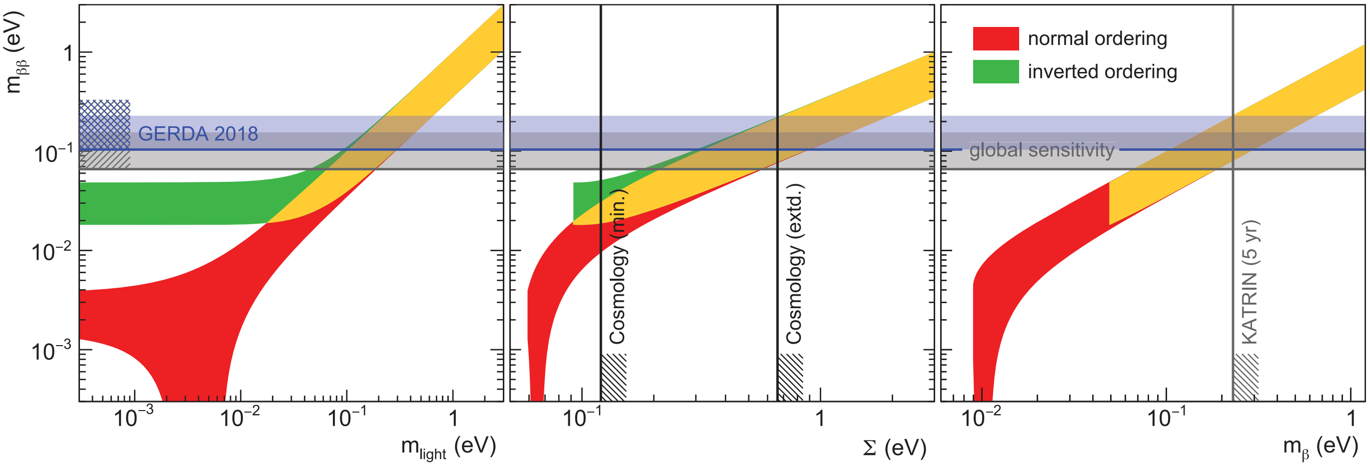

Fig. 3. Constraints of the parameter space for $m_{\beta\beta}$ in the scenario of three light Majorana neutrinos. Constraints are shown, left to right, as function of the lightest neutrino mass m_{light}, the sum of neutrino masses Σ, and the effective neutrino mass m_β. Contours follow from a scan of the Majorana phases with the central oscillation parameters from NuFIT 4.0 (*22*). The blue horizontal band shows the upper limits on $m_{\beta\beta}$ obtained by GERDA; the gray band shows those from combining sensitivities of all leading experiments in the field (see Table 1). Vertical lines denote Σ = 0.12 eV and Σ = 0.66 eV, a stringent limit from cosmology (*24*) and an extended model bound (*7*), as well as m_β = 0.23 eV, the 5-year sensitivity of the KATRIN experiment (*23*). Hatching denotes the excluded parameter space.

10^{26} years (90% C.L.) is compatible with the sensitivity (assuming no signal) of 1.1×10^{26} years; this is an improvement over previous experiments, which had sensitivities of less than 10^{26} years. The weaker limit is a consequence of an event in the signal region at 2042.1 keV, 2.4 standard deviations (σ) away from $Q_{\beta\beta}$. The statistical analysis attributes it to background. Statistical analysis including Bayesian inference is detailed in (*15*).

Table 1 compares our results with those of other 0νββ decay searches. The $T_{1/2}$ sensitivities of other experiments are at most half of ours despite sometimes higher exposures; this is caused by GERDA's lower background and superior energy resolution (*15*). Several physical processes beyond the SM can produce 0νββ decay. Here, we focus on the paradigm of the mixing of three light Majorana neutrinos. In this context, the half-life can be converted into a 0νββ decay strength that has the dimension of mass, denoted the effective Majorana mass (*19*),

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| \qquad (1)$$

Nuclear structure details enter the decay rate, and uncertainties in the nuclear structure calculations result in a spread of $m_{\beta\beta}$ values for a given $T_{1/2}$ by typically a factor of 2 to 3 (*20*). Some reported half-life limits L deviate by almost a factor of 2 from the associated sensitivity S, indicating significant underfluctuation (CUORE, KamLAND-Zen) or upward fluctuation (EXO-200). To overcome this possible behavior of frequentist limits, we used the sensitivity to extract the constraints on $m_{\beta\beta}$ shown in Table 1. For GERDA, the median limit is $m_{\beta\beta} < 0.1$ to 0.23 eV. Combining it with the sensitivities of the other searches (*15*), the bound tightens to $m_{\beta\beta} < 0.07$ to 0.16 eV (90% C.L.), very similar to the bound deduced by KamLAND-Zen from their $T_{1/2}$ limit (*21*).

Figure 3 shows the dependence of the effective Majorana mass $m_{\beta\beta}$ as a function of the lightest neutrino mass $m_{\text{light}} = \min(m_i)$, the cosmological observable of the sum of neutrino masses, $\Sigma = \sum_i m_i$, and the effective neutrino mass,

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2} \qquad (2)$$

—that is, the mass observable in single beta decays. The allowed parameter space is classified according to the ordering of the neutrino mass eigenstates as normal ($\Delta m_{31}^2 > 0$) or inverted ($\Delta m_{31}^2 < 0$). The overlap region is called quasi-degenerate; here, the mass splittings are small relative to the absolute mass scale. The latest oscillation data prefer normal ordering at the 3σ level (*22*). Figure 3 shows that our extracted limits of $m_{\beta\beta}$ disfavor a large fraction of the parameter space of quasi-degenerate Majorana neutrino masses. The combined limit of $m_{\beta\beta}$ = 0.16 eV corresponds to constraints on $m_{\text{light}} <$ 0.15 to 0.44 eV, $\Sigma < 0.46$ to 1.3 eV, and $m_\beta < 0.16$ to 0.44 eV. Direct measurements of m_β yield a limit of ~2.3 eV (*5*, *6*). In the coming years, the KATRIN tritium decay experiment will increase the sensitivity to ~0.2 eV (*23*). The sum of the neutrino masses influences the evolution and structure of the Universe. In the framework of the 6 + 1–parameter cosmological SM, the latest Planck data on the anisotropy of the cosmic microwave radiation along with baryonic acoustic oscillation data provide limits as low as $\Sigma < 0.12$ eV (95% C.L.) (*24*). Extended models relax these limits to <0.37 eV for one additional parameter, and to <0.66 eV for five additional parameters (*7*).

Currently, there are no tensions among the three mass observables. A discovery of 0νββ decay close to the current experimental half-life sensitivity should have counterpart signals in tritium β decay and in cosmology, provided that the paradigm of three light Majorana neutrinos holds. In case of discrepancies with the other mass observables, a 0νββ signal would point to other lepton number–violating processes. Within the framework of three light Majorana neutrinos and the cosmological SM, and in the absence of a 0νββ decay at or close to the current sensitivity, the KATRIN experiment would not observe a signal. Conversely, a positive measurement of $m_\beta > 0.44$ eV in KATRIN would point to Dirac neutrinos or to an incomplete understanding of the nuclear physics (*20*) of 0νββ decay. It also would require extensions to the current minimal cosmological model. Instead, if the cosmological limit on Σ holds, 0νββ decay experiments would have to probe a mass range $m_{\beta\beta} < 0.05$ eV, which requires a half-life sensitivity of 10^{27} years and above for a ^{76}Ge-based experiment.

The leading performance of GERDA in terms of background suppression, energy resolution, and sensitivity opens the way to LEGEND, a next-generation Ge experiment with sensitivity to half-lives of 10^{27} years and beyond. A first-phase 200-kg ^{76}Ge experiment, LEGEND-200 (*25*), is in preparation at LNGS.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S12
Tables S1 to S7
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Probing Majorana neutrinos with double-β decay

M. Agostini, A. M. Bakalyarov, M. Balata, I. Barabanov, L. Baudis, C. Bauer, E. Bellotti, S. Belogurov, A. Bettini, L. Bezrukov, D. Borowicz, V. Brudanin, R. Brugnera, A. Caldwell, C. Cattadori, A. Chernogorov, T. Comellato, V. D'Andrea, E. V. Demidova, N. Di Marco, A. Domula, E. Doroshkevich, V. Egorov, R. Falkenstein, M. Fomina, A. Gangapshev, A. Garfagnini, M. Giordano, P. Grabmayr, V. Gurentsov, K. Gusev, J. Hakenmüller, A. Hegai, M. Heisel, S. Hemmer, R. Hiller, W. Hofmann, M. Hult, L. V. Inzhechik, J. Janicskó Csáthy, J. Jochum, M. Junker, V. Kazalov, Y. Kermaïdic, T. Kihm, I. V. Kirpichnikov, A. Kirsch, A. Kish, A. Klimenko, R. Kneißl, K. T. Knöpfle, O. Kochetov, V. N. Kornoukhov, P. Krause, V. V. Kuzminov, M. Laubenstein, A. Lazzaro, M. Lindner, I. Lippi, A. Lubashevskiy, B. Lubsandorzhiev, G. Lutter, C. Macolino, B. Majorovits, W. Maneschg, M. Miloradovic, R. Mingazheva, M. Misiaszek, P. Moseev, I. Nemchenok, K. Panas, L. Pandola, K. Pelczar, L. Pertoldi, P. Piseri, A. Pullia, C. Ransom, S. Riboldi, N. Rumyantseva, C. Sada, E. Sala, F. Salamida, C. Schmitt, B. Schneider, S. Schönert, A.-K. Schütz, O. Schulz, M. Schwarz, B. Schwingenheuer, O. Selivanenko, E. Shevchik, M. Shirchenko, H. Simgen, A. Smolnikov, L. Stanco, D. Stukov, L. Vanhoefer, A. A. Vasenko, A. Veresnikova, K. von Sturm, V. Wagner, A. Wegmann, T. Wester, C. Wiesinger, M. Wojcik, E. Yanovich, I. Zhitnikov, S. V. Zhukov, D. Zinatulina, A. Zschocke, A. J. Zsigmond, K. Zuber, G. Zuzel and GERDA Collaboration

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Looking for an exotic decay

Neutrinos––elementary fermionic particles with no electrical charge––defy the standard model of particle physics by having a tiny, but nonzero mass. One explanation for their properties is that they are Majorana fermions, which are particles equal to their antiparticles. If neutrinos were Majorana fermions, a process called neutrinoless double-β decay would become possible: an unstable nucleus could decay by turning two of its neutrons into protons with the emission of two electrons but no antineutrinos. The GERDA Collaboration searched for this decay in a particular isotope of germanium. Housed deep underground to reduce the background signal, the experiment did not detect the elusive process but did place improved boundaries on its half-life.

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