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Final results from GERDA: a neutrinoless double beta decay search

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The GERmanium Detector Array (GERDA) experiment searched for the lepton-number-violating neutrinoless double-β decay of ^{76}Ge. Observing such a decay would allow to shed light onto the nature of neutrinos and its discovery would have far-reaching implications in cosmology and particle physics. By operating an array of high purity bare germanium detectors, enriched in ^{76}Ge, in an active liquid argon shield aided by pulse shape discrimination of germanium detector signals, GERDA achieved an unprecedentedly low background index of 5.2×10^{-4} counts/(keV $\cdot$ kg $\cdot$ yr) in the signal region and was able to surpass the design goal of collecting an exposure of 100 kg $\cdot$ yr in a background-free regime. With a total exposure of 127.2 kg $\cdot$ yr combining Phase I and Phase II, no signal was observed and a lower limit on the half-life of the neutrinoless double-β decay in ^{76}Ge is set at $T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L., which coincides with the sensitivity assuming no signal.

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1. Introduction

The matter-antimatter asymmetry of the Universe remains an important unsolved puzzle of cosmology and particle physics. Many theories predict that the asymmetry is produced by a violation of lepton number via leptogenesis [1]. These theories naturally lead to neutrinos being their own antiparticles and developing a Majorana mass component.

Neutrino Majorana masses and lepton-number violation can be verified at the same time by observing a hypothetical nuclear transition $(A; Z) \to (A; Z + 2) + 2e$, called neutrinoless double-β ($0\nu\beta\beta$) decay [2].

The GERmanium Detector Array (GERDA) collaboration searched for the $0\nu\beta\beta$ decay of the isotope ^{76}Ge with a Q-value of $Q_{\beta\beta} = 2039.061(7)$ keV [3] by operating high-purity germanium (HPGe) detectors isotopically enriched to more than 86% in ^{76}Ge, making them also the potential source of $0\nu\beta\beta$ decay: this approach maximizes the detection efficiency as source and detector coincide.

2. Setup

The GERDA experiment was located in Italy, at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, where a rock overburden of 3500 m water equivalent reduced the flux from cosmic muons by 6 orders of magnitude. The arrays of germanium detectors were lowered in a cryostat containing 64 m^3 of LAr through a lock system inside a clean room. The cryostat was surrounded by a water tank (590 m^3 purified water) equipped with photomultipliers (PMTs) to detect the residual cosmic muons reaching the experiment. Water and LAr also shielded the detector array from external natural radioactivity and neutrons. Furthermore, the muon veto system [4] was complemented by scintillator panels installed on the top of the clean room. There were in total 41 germanium detectors, assembled into seven strings and each string was placed inside a nylon cylinder to limit the LAr volume from which radioactive ions could be collected by electric fields. A cylindrical volume around the array was instrumented with photosensors, which detected the scintillation light in the LAr. The LAr veto system consisted of a curtain of wavelength-shifting fibers connected to silicon photomultipliers and 16 cryogenic PMTs [5, 6].

3. Detectors

Three types of enriched germanium detectors were used: 30 broad energy germanium (BEGe) detectors, 7 semi-coaxial detectors, and 5 newer inverted coaxial (IC) detectors. The BEGe detectors are smaller (average 0.7 kg) but offer superior energy resolution and pulse shape discrimination (PSD) properties compared to the semi-coaxial detectors [7], while the IC detectors provide energy resolution and PSD properties similar to the BEGe detectors [8] but with a larger mass (average 1.9 kg) comparable to that of the coaxial detectors (average 2.3 kg), allowing for the easier design of larger germanium arrays. The energy resolution is stable within 0.1 keV for most of the detectors over the full data taking period.

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4. Background suppression

The unique feature in Phase II of GERDA is the LAr veto system that allows to reject events in which energy is deposited in the LAr volume surrounding the germanium detectors. If any of the photosensors detect a signal of at least one photoelectron within about 6μs of the germanium detector trigger, the event is classified as background. Additionally, the pulse shape of the germanium detector signals is used to discriminate background events. In addition to γ-induced multiple-site events (MSEs), events due to α or β decays on the detector surface can also be identified. An additional cut is applied to all detectors to remove events with slow or incomplete charge collection [9]. The combined signal efficiency of pulse shape discrimination are reported in Table I of [10] for each detector type, before and after the upgrade.

GERDA Phase II data were collected between December 2015 and November 2019. The total exposure is 103.7 kg yr (58.9 kg yr already published in [9] and 44.8 kg yr of data from Phase II). Fig. 1 shows the energy distribution of all events before and after applying the analysis cuts. At low energy, the counting rate is mostly accounted for by the $2\nu\beta\beta$ decay of ^{76}Ge with a half-life of $T_{1/2}^{2\nu\beta\beta} = (1.926 \pm 0.094) \cdot 10^{21}$ yr [11].

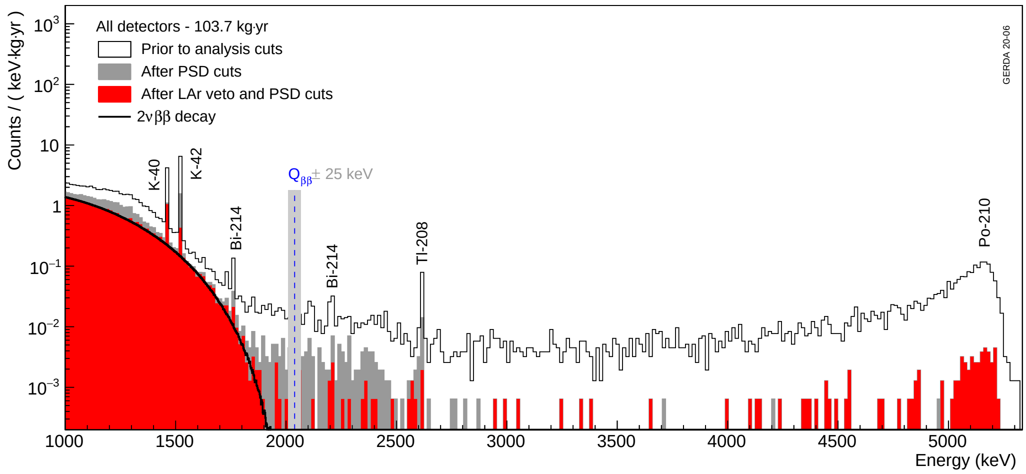

Figure 1: Energy distribution of GERDA Phase II events between 1.0 and 5.3 MeV before and after analysis cuts; the exposure is 103.7 kg yr. The expected distribution of $2\nu\beta\beta$ decay events is shown assuming the half-life measured by GERDA [11]. The prominent γ-lines and the α population around 5.2 MeV are also labeled.

5. Analysis

The energy range considered for the $0\nu\beta\beta$ decay analysis goes from 1930 to 2190 keV, with the exclusion of the intervals (2104 ± 5) and (2119 ± 5) keV that contain two known background peaks (Fig. 2). No other γ-line or structure is expected in this analysis window according to the background model [12]. After unblinding, 13 events are found in this analysis window after all cuts.

The energy distribution of the events in the analysis window is fitted to search for a signal due to $0\nu\beta\beta$ decay. The fit model includes a Gaussian distribution for the signal, centered at $Q_{\beta\beta}$ with a width corresponding to the energy resolution, and a flat distribution for the background. The free parameters of the fit are the signal strength $S = T_{1/2}$ and the background index B.

The statistical analysis is based on an unbinned extended likelihood function and it is performed in both frequentist and Bayesian frameworks, following the procedure described in [13]. A detailed description of the likelihood and analysis parameters is available at [10].

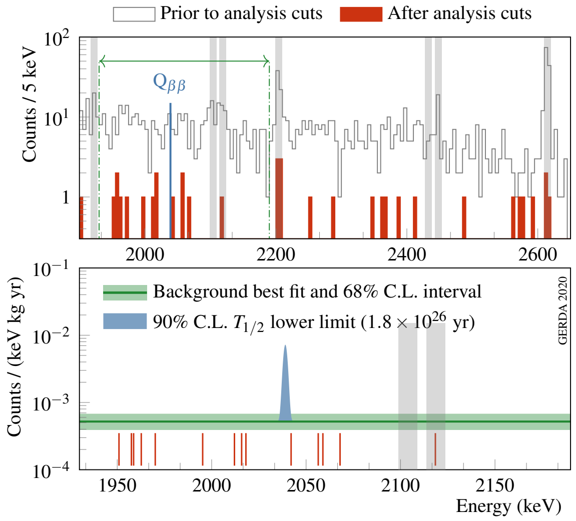

Figure 2: Top: Enlarged view of the energy distribution of GERDA Phase II events between 1900 and 2650 keV before and after analysis cuts. This energy interval includes the analysis window (edges marked by dashed lines) and the regions of expected γ-lines (marked by gray areas), among those the prominent γ-line at 2615 keV. Bottom: Result of the unbinned extended likelihood fit: The blue peak displays the expected $0\nu\beta\beta$ decay signal for $T_{1/2}$ equal to the lower limit, $1.8 \cdot 10^{26}$yr. Its width is the resolution of the partition which contains the event closest to $Q_{\beta\beta}$. The data partitioning scheme is described in [10]. Vertical lines indicate the energies of the events in the analysis window after analysis cuts.

6. Results

The analysis of the $N = 13$ events of Phase II yields no indication for a signal. Phase I and Phase II data together give a total exposure of 127.2 kg yr, which corresponds to (1.288 ± 0.018) kmol yr of ^{76}Ge in the active volume. The combined analysis has also a best fit for null signal strength, and provides a halflife limit of $T_{1/2} > 1.8 \cdot 10^{26}$yr at 90% C.L. in the frequentist framework. Using a Bayesian approach (implemented using the Bayesian analysis toolkit BAT [14]), a halflife limit of $T_{1/2} > 1.4 \cdot 10^{26}$yr at 90% C.I. is obtained assuming a priori equiprobable signal strengths S between 0 and 10^{-24} yr^{-1}, while a stronger limit, $T_{1/2} > 2.3 \cdot 10^{26}$yr at 90% C.I. can be set when assuming a priori equiprobable Majorana neutrino masses $m_{\beta\beta}$ (as $S \propto m^2_{\beta\beta}$). The limits coincide with the sensitivities, defined as the median expectation under the no signal hypothesis.

GERDA achieved an unprecedentedly low background in Phase II, as derived from the fit, of $B = 5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ counts/(keV kg yr), and met the design goal of background free performance: the mean background expected in the signal region ($Q_{\beta\beta} \pm 2\sigma$) is 0.3 counts.

Fig. 3 shows the improvement achieved by GERDA with increasing exposure for the measured lower limit on the $0\nu\beta\beta$ decay half-life of ^{76}Ge and for the sensitivity. The background-free regime results in a nearly linear improvement of sensitivity vs exposure.

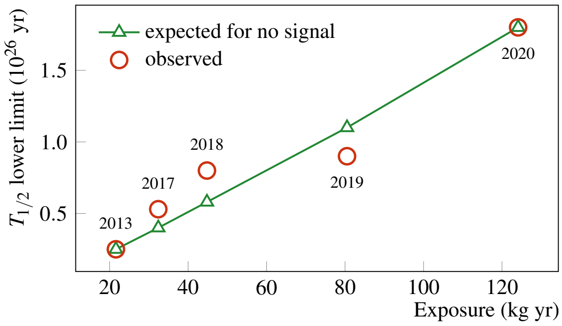

Figure 3: Circles: lower limit (90% C.L.) on the $0\nu\beta\beta$ decay halflife of ^{76}Ge set by GERDA as a function of the exposure [9, 13, 15, 16]. Triangles: median expectation in the assumption of no signal.

The $T_{1/2}$ limit can be converted into an upper limit on the effective Majorana neutrino mass under the assumption that the decay is dominated by the exchange of light Majorana neutrinos. Assuming a standard value of $g_A = 1.27$, the phase space factor and the set of nuclear matrix elements from Refs. [36–46] of [10], a limit of $m_{\beta\beta} < 79 - 180$ meV at 90% C.L. is obtained. GERDA has been a pioneering experiment in the search for $0\nu\beta\beta$ decay. GERDA improved the sensitivity by one order of magnitude with respect to previous ^{76}Ge experiments [17, 18] and proved that a background-free experiment based on ^{76}Ge is feasible.

Building on the success of GERDA, the LEGEND Collaboration [19] is preparing a next generation experiment aiming at a sensitivity to the half-life of $0\nu\beta\beta$ decay of 10^{28} yr and beyond.

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