Conference Paper

New data release of GERDA Phase II: search for $0\nu\beta\beta$ decay of ^{76}Ge

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Abstract

The GERmanium Detector Array (GERDA) experiment is searching for the neutrinoless double beta decay ($0\nu\beta\beta$) of the isotope ^{76}Ge. High-purity germanium crystals enriched in ^{76}Ge, simultaneously used as source and detector, are directly deployed into ultra-pure, cryogenic liquid argon, which acts both as cooling medium and shield against the external radiation. The second phase of the experiment is taking data since end of 2015 with 20 additional kg of custom-made BEGe-type Germanium detectors and an active LAr veto. In this paper we will summarize the results of the last data release of June 2017. No evidence for a possible signal is found: the lower limit for the half-life of ^{76}Ge is $8.0 \cdot 10^{25}$ yr at 90% CL. The very low residual background found at the Q-value of the decay, about 10^{-3} cts/(keV·kg·yr), makes GERDA the first experiment in the field to be background-free for the complete design exposure of 100 kg·yr.

1. Introduction

The neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical lepton-number-violating nuclear transition predicted by several extensions of the Standard Model of particle physics. Its detection would prove that neutrinos have a Majorana mass component [1, 2] and that lepton number is not conserved, thus providing a possible answer to the matter-antimatter asymmetry in the Universe and the origin of neutrino masses [3–5].

Searches for $0\nu\beta\beta$ are ongoing in a number of experiment around the world using different nuclei as ^{76}Ge [6, 7], ^{136}Xe [8–10] and ^{130}Te [11, 12]. The experimental signature of $0\nu\beta\beta$ is a peak in the distribution of the energy sum of two electrons at the Q-value of the decay ($Q_{\beta\beta}$). Typically only a few signal counts per kg per year are expected: therefore a very strong suppression of all background sources and a high energy resolution are required.

2. The GERDA experiment

The GERDA experiment [13], located at the underground Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy, operates bare high-pure germanium detectors (HPGe) in liquid argon (LAr), which cools the detectors to their operating temperature of about 90 K and shields them from external radiation. The 64 m^3 LAr cryostat is contained in a 590 m^3 water tank, filled with ultra-pure water and equipped with photomultipliers, thus acting both as Cerenkov veto and additional shield. On the top of the water tank a clean room with a glove box and a lock is used for the assembly of HPGe detectors into

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strings. The HPGes are arranged in an array of 6 strings hosting detectors enriched in ^{76}Ge (^{enr}Ge): 7 coaxial detectors from the former Heidelberg-Moscow [14] and IGEX [15] experiments, and 30 newly developed Broad Energy germanium (BEGe) detectors [16] featuring superior pulse shape discrimination performance [17, 18]. The detector array is complemented with a central string instrumented with three coaxial detectors made from germanium of natural isotopic composition. In Phase II, the cylindrical volume around the detector strings is instrumented with a curtain of wavelength-shifting fibres read out at both ends with 90 silicon photomultipliers (SiPMs). Sixteen low-background photomultipliers (PMTs) are mounted below and above of the HPGe array.

All Ge detectors are connected to low radioactivity charge sensitive amplifiers. The charge signal traces are digitized with a 100 MHz sampling rate and a total window of 160 μs. Data are stored on disk and analyzed offline using the procedure described in [19, 20].

3. Data taking and event selection

GERDA is taking data since 2011. Data from the first phase of GERDA (Phase I) gave no positive indication of the $0\nu\beta\beta$ decay with an exposure of about 21.6 kg·yr and a background index at the $Q_{\beta\beta}$= (2039.061 ± 0.007) keV of 10^{-2} cts/(keV·kg·yr). A lower limit on the half-life of the process of $T^{0\nu}_{1/2}$> $2.1\cdot10^{25}$ yr (90% C.L.) was set [19]. The second phase (Phase II), is ongoing since December 2015 and initial results were released in June 2016 with 10.8 kg·yr of total exposure and a background index of 10^{-3} cts/(keV·kg·yr) [6]. In June 2017 new data collected up to April 15th 2017 have been fully validated and analyzed for a total exposure of 34.4 kg·yr of ^{enr}Ge (18.2 kg·yr from BEGe detectors and 16.2 kg·yr from coaxial detectors) [21].

The offline data analysis flow foresees a blind approach: events with a reconstructed energy in the interval $Q_{\beta\beta}$±25 keV are not analysed but only stored on disk. After the entire analysis procedures and parameters have been frozen, these blinded events are processed.

Unphysical events, originating from electrical discharges or bursts of noise, are rejected by a set of multi-parametric cuts based on the flatness of the baseline, polarity and time structure of the pulse. Physical events at $Q_{\beta\beta}$ are accepted with an efficiency greater than 99.9% while no unphysical event survives the cuts above 1.6 MeV.

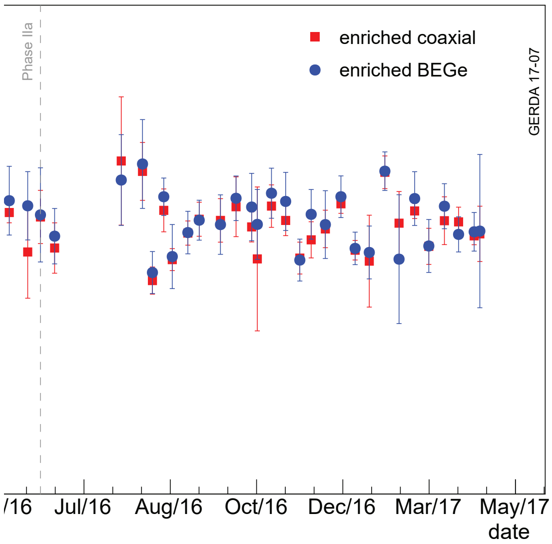
In 92% of $0\nu\beta\beta$ decays occurring in the active detector volume, the total $0\nu\beta\beta$ energy is detected in that detector. Therefore multiple detector coincidences are discarded as background events. In order to discriminate time-correlated decays from primordial radioisotopes, such as the radon progenies ^{214}Bi and ^{214}Po, two consecutive candidate events within 1 ms are rejected. Candidate events are also rejected if a muon trigger occurred within 10 μs before a germanium detector trigger or if any of the LAr light detectors record a signal of amplitude above 50% of the expectation for a single photo-electron within 5 μs from the germanium trigger.

The deposited energy is reconstructed with an improved digital filter [22] optimized for each detector and each calibration. The energy scale and resolution is set by taking weekly calibration with ^{228}Th sources. The stability of the scale is continuously monitored by injecting charge pulses (test pulses) with a rate of 0.05 Hz and, weekly, by checking the shift of the position of the 2615 keV γ line between two consecutive calibration (Fig. 1a). The average resolution at $Q_{\beta\beta}$, evaluated by using the calibration data, is shown in Fig. 1b; for coaxial detectors the width of the strongest γ lines in the physics data (1460 keV from ^{40}K and 1525 keV from ^{42}K) is found to be 0.5 keV larger than expected, probably due to gain instabilities in the corresponding readout channels between calibrations. The effect is accounted for by including a correction term; the average resolution at $Q_{\beta\beta}$ is 3.90(7) keV and 2.93(6) keV FWHM for the ^{enr}Ge coaxial and BEGe detectors, respectively.

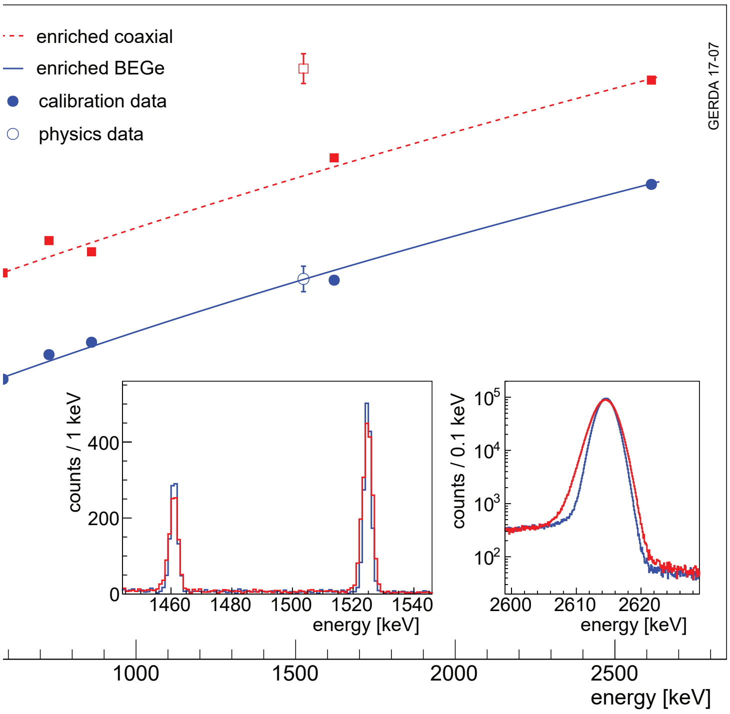
Due to the short range of electrons in germanium (~1 mm), $0\nu\beta\beta$ decays produce a localized energy deposit. The time profile of the Ge current signal can be used to disentangle $0\nu\beta\beta$ decays (single-site events, SSE) from background events such as γ-rays, which mainly interact via Compton scattering with an average free path of ~1 cm (multi-site events, MSE), or external α/β-rays, which deposit their energy on the detector surface. The geometry of the BEGe detectors allows the application of a simple mono-parametric Pulse Shape Discrimination (PSD) technique based on the maximum of the detector current pulse A normalized to the total energy E [17, 18, 23]. The cut on A/E allows to reject $> 90\%$ of (γ-like) MSEs and basically all α-like surface events, with a $0\nu\beta\beta$ selection efficiency of (87 ± 2)%. For coaxial detectors two neural network algorithms (ANN) are applied to discriminate SSEs from MSEs and from α surface events [18] with a combined selection efficiency for $0\nu\beta\beta$ decays of (79 ± 5)%.

4. Statistical analysis and results

In June 2017, data from the BEGe detectors taken between June 1, 2016 and April 15, 2017 has been unblinded, providing an additional exposure of 12.4 kg·yr with respect to [6]. Two extra events passing all selection cuts are found in the blinded energy region; both of them being more than 15 keV away from $Q_{\beta\beta}$ (namely $> 10\sigma$) they cannot be attributed to $0\nu\beta\beta$ decay. Due to a recently identified background population



(a)



(b)

Figure 1: (a) Average shift of the 2615 keV γ-ray line between consecutive calibrations. The error bars represent the standard deviation of the shifts of the individual detectors. (b) Average energy resolution for γ lines observed in calibration data and in physics data, for the BEGe and coaxial detectors. The inset displays a zoom of the γ lines at 1460 keV (^{40}K) and 1525 keV (^{42}K) in physics data, and a zoom of the 2615 keV line from calibration data.

not efficiently rejected by ANN PSD, data from coaxial detectors (11.2 kg·yr) were not unblinded. It will be unblinded in a future data release, when a new cut is developed to suppress this background. The background in the signal region is 10^{-3} cts/(keV·kg·yr) for BEGe detectors and 2.7$\times 10^{-3}$ cts/(keV·kg·yr) for coaxials. The energy spectra around $Q_{\beta\beta}$ for Phase I, Phase II coaxial detectors and Phase II BEGe detectors (after all cuts) are shown in Fig. 2.

The total exposure available for analysis is (471.1 ± 8.5) mol·yr of ^{76}Ge. Both a frequentist and a Bayesian analysis, based on an unbinned extended likelihood function described in the Methods Section of Ref. [6], is performed. The fit function is a flat distribution for the background and a Gaussian centered at $Q_{\beta\beta}$ with a width according to the resolution for a possible $0\nu\beta\beta$ signal. The signal strength S = 1/$T^{0\nu}_{1/2}$ is calculated for each data set (both for Phase I and Phase II, for coaxial and BEGe detector respectively) according to its exposure and efficiency while the inverse half-life 1/T is a common free parameter. The analysis accounts for the systematic uncertainties due to efficiencies and energy resolutions, and to a possible offset in the energy scale. The limit on the half-life of ^{76}Ge is $T^{0\nu}_{1/2}> 8.0 \cdot 10^{25}$ yr (90% CL) (frequentist) and $T^{0\nu}_{1/2}> 5.1 \cdot 10^{25}$ yr (Bayesian), while the median sensitivity for the 90% CL lower limit of $T^{0\nu}_{1/2}$ is $5.8 \cdot 10^{25}$ yr (frequentist) and $T^{0\nu}_{1/2}> 4.5 \cdot 10^{25}$ yr (Bayesian).

5. Conclusions

The GERDA experiment is currently taking data. The ambitious design goal for the background level of 10^{-3} cts/(keV·kg·yr) was fulfilled, thus, making GERDA the first "background-free" experiment for the whole design exposure; the sensitivity is therefore expected to grow linearly with the exposure and the median sensitivity is expected to reach 10^{26} yr within 2018. At present, thanks to the powerful pulse shape discrimination of BEGe detectors and to the detection of the argon scintillation light, GERDA has reached the world-best background index (BI) at $Q_{\beta\beta}$ if weighted with the energy resolution of the detectors.

The excellent performances in terms of background index and energy resolution motivates a future extension of the program in a medium term time scale. The LEGEND collaboration aims to build a 200 kg enriched germanium experiment using the GERDA cryostat. Such an experiment would remain background-free up to an exposure of 1000 kg·yr provided the background can be further reduced by a factor 5-10;; thus LEGEND-200 [24] would allow to reach a half-life of 10^{27} yr. The 200 kg project is conceived as a first step towards a more ambitious 1-ton experiment that would allow to reach a sensitivity of 10^{28} yr, thus, fully covering the inverted hierarchy region in ten years of data taking.

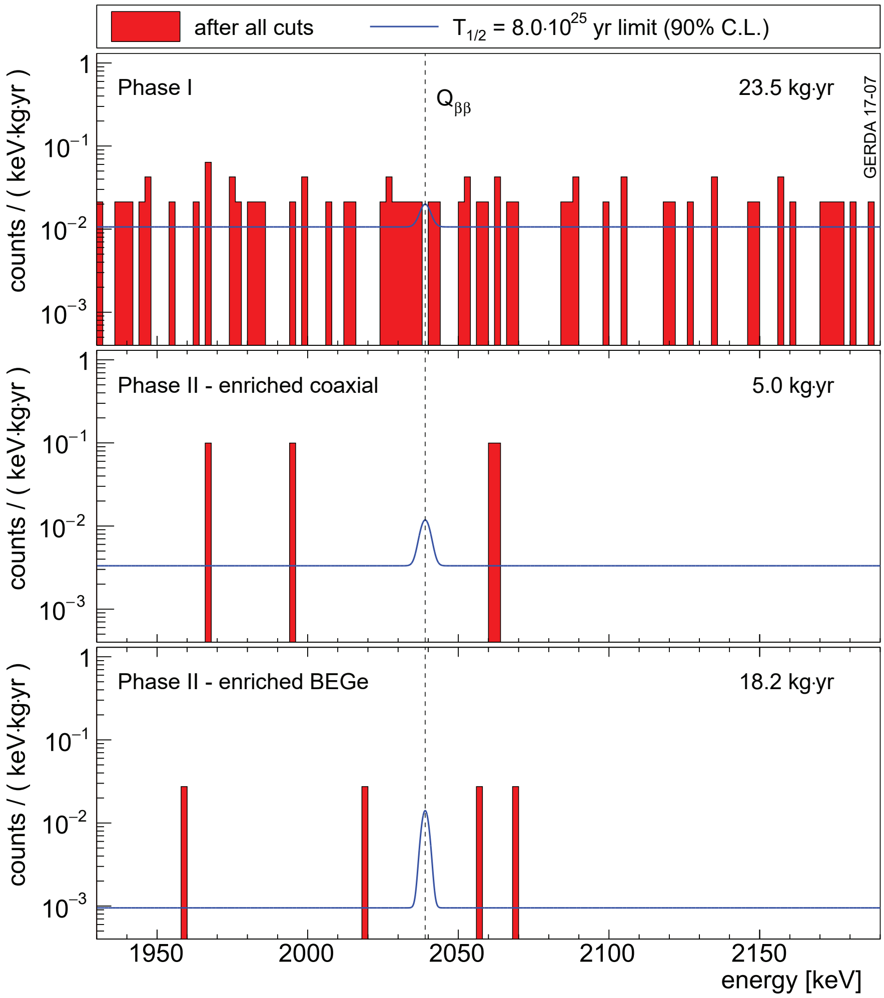


Figure 2: Energy spectra around $Q_{\beta\beta}$ for Phase I, Phase II coaxial detectors and Phase II BEGe detectors after all cuts. The binning is 2 keV. The blue lines show the hypothetical $0\nu\beta\beta$ signal for $T^{0\nu}_{1/2}$= $8.0 \cdot 10^{25}$ yr, sitting on the constant background.

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