Improved limit on neutrinoless double beta decay of ^{76}Ge from GERDA Phase II

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(Dated: January 23, 2018)

The GERDA experiment searches for the lepton number violating neutrinoless double beta decay of ^{76}Ge (^{76}Ge $\rightarrow$ ^{76}Se $+ 2e^-$) operating bare Ge diodes with an enriched ^{76}Ge fraction in liquid argon. The exposure for BEGe-type detectors is increased threefold with respect to our previous data release. The BEGe detectors feature an excellent background suppression from the analysis of the time profile of the detector signals. In the analysis window a background level of $1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV·kg·yr) has been achieved; if normalized to the energy resolution this is the lowest ever achieved in any $0\nu\beta\beta$ experiment. No signal is observed and a new 90 % C.L. lower limit for the half-life of $8.0 \cdot 10^{25}$ yr is placed when combining with our previous data. The median expected sensitivity assuming no signal is $5.8 \cdot 10^{25}$ yr.

INTRODUCTION

Despite many decades of research several properties of neutrinos are still unknown. Among them is the fundamental question whether neutrinos are their own anti-particles (i.e. Majorana particles), as predicted by several extensions of the Standard Model of particle physics [1–3]. In this case neutrinoless double beta ($0\nu\beta\beta$) decay

could be observed, a process in which lepton number is not conserved.

Several experiments are taking data or are under preparation searching for this decay using a variety of suitable isotopes (see Refs. [4, 5] for overviews). The sum of the kinetic energies of the two electrons emitted in the $0\nu\beta\beta$ decay $(A, Z) \rightarrow (A, Z + 2) + 2\,e^-$ is equal to the mass difference $Q_{\beta\beta}$ of the two nuclei. A sharp peak in the energy spectrum is the prime signature for all $0\nu\beta\beta$ experiments.

Key parameters of these rare event searches are large mass M and long measuring time t on the one hand, and high energy resolution and low background on the other. Apart from the various isotopes the experiments differ in their setups and detection methods thereby exploiting the aforementioned parameters. The GERmanium Detector Array (GERDA) experiment searches for $0\nu\beta\beta$ decay of ^{76}Ge using germanium detectors made from material enriched in ^{76}Ge, i.e. source and detector are identical. This Letter shows that superior energy resolution and background suppression permit to achieve very sensitive results already at relative low exposure $\mathcal{E} = M \cdot t$.

EXPERIMENT

The GERDA experiment is located at the Gran Sasso underground laboratory (LNGS) of INFN in Italy. High-purity germanium detectors made from material with enriched ^{76}Ge fraction of $\sim 87\%$ are operated in a 64 m^3 liquid argon (LAr) bath. The argon cryostat is located inside a tank filled with 590 m^3 of high purity water. LAr and water shield against the external radioactivity. The water tank is instrumented with photomultipliers and operates as a Cherenkov detector to veto residual muon-induced events. Material for structural support of the detectors and for cabling is minimized in order to limit the background from close-by radioactive sources. More details of the experiment can be found in Refs. [6–8].

A first phase of data taking ended in 2013 with no indication of a signal [9]. The background index achieved at the ^{76}Ge $Q_{\beta\beta}$-value of 2039 keV was 10^{-2} cts/(keV·kg·yr). For the second phase a new component has been installed to detect argon scintillation light [8]. The enriched germanium mass was doubled in the form of small read-out electrode detectors (the Canberra BEGe detector model [10]) supplementing the previously used coaxial detectors. Both enhancements allow for a more efficient rejection of background events, which can be characterized by their energy deposition in the LAr, in several detectors or in several locations (including the surface) of a single detector. In contrast, $0\nu\beta\beta$ energy deposits are made by two electrons, which typically release all their energy in a small volume of a single detector. Localized and delocalized energy deposits are distinguished by pulse shape discrimination (PSD) based on the time profile of the detector signal. For BEGe detectors a simple variable A/E (the maximum A of the detector current signal normalized by the energy E) shows very good PSD performance which is superior to the one based on neural networks for coaxial detectors [11].

Phase II data taking started in December 2015 with a target background index of 10^{-3} cts/(keV·kg·yr), a tenfold reduction of background with respect to Phase I. Thirty BEGe detectors (20.0 kg total mass) and seven coaxial detectors (15.6 kg) are deployed, whose energy resolution at $Q_{\beta\beta}$ is typically better than 3 keV and 4 keV full width at half maximum (FWHM), respectively.

As in Phase I, a ± 25 keV window around $Q_{\beta\beta}$ was blinded: events with an energy in one detector within this window were hidden until the entire data selection was finalized. The first unblinding of Phase II took place in June 2016 and no $0\nu\beta\beta$ signal was found. A lower limit of $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90 % C.L.) was extracted with a sensitivity, defined as the median expected lower limit assuming no signal, of $4.0 \cdot 10^{25}$ yr [7].

RESULTS

Here, the result from a second unblinding of data from the BEGe detectors taken between June 2016 and April 2017 is reported. The complete analysis of the new data set, including the detector energy reconstruction, LAr veto reconstruction, data selection, PSD and statistical treatment, is identical to the previous one published in Refs. [7, 9].

With the new exposure of 12.4 kg·yr, the total Phase II exposure doubles and the one for the lower background BEGe detectors triples. Fig. 1 shows the energy spectrum of the latter; the blinded region around $Q_{\beta\beta}$ is indicated by the grey vertical band. The spectrum below 500 keV is dominated by ^{39}Ar events, while the spectrum between 500 and 1800 keV is dominated by events from $2\nu\beta\beta$ decays of ^{76}Ge and Compton continua mainly from the ^{40}K and ^{42}K lines. α decays dominate the spectrum above 2620 keV. They are almost exclusively due to ^{210}Po decays at the p+ electrode or the isolating groove between p+ and n+ electrodes (degraded α particles). Since the ^{40}K γ line is from an electron capture, no energy is deposited in the LAr and only PSD is effective for rejecting events (see inset). The γ line of ^{42}K, the progeny of the long-lived ^{42}Ar, originates from a β decay which deposits up to 2 MeV in the argon. The LAr veto rejects more than 80 % of these events (see inset).

Near $Q_{\beta\beta}$ the spectrum is composed of degraded α's, β's of ^{42}K decays at the detector surface, and Compton scattered γ's from ^{214}Bi and ^{208}Tl decays. The background is evaluated in the range between 1930 and 2190 keV without the two intervals (2104 ± 5) keV and (2119 ± 5) keV from known γ lines and without
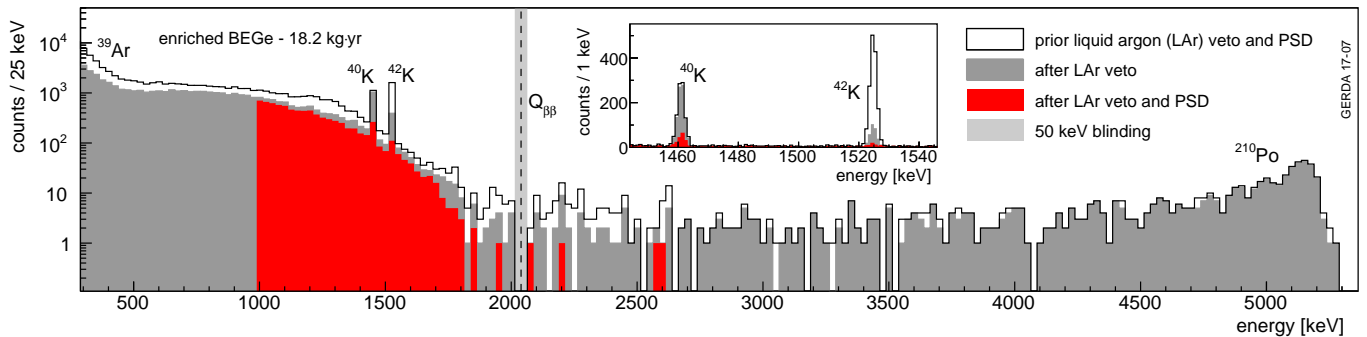
FIG. 1. Energy spectra of Phase II BEGe detectors prior to liquid argon (LAr) veto and PSD cuts (total histogram), after additional LAr veto (dark grey) and after after all cuts (red). The inset shows the spectrum in the energy region of the potassium lines (1460 keV from ^{40}K and 1525 keV from ^{42}K). The grey vertical band indicates the blinded region of ± 25 keV around the $Q_{\beta\beta}$-value.

the signal interval ($Q_{\beta\beta}\pm 5$) keV. The analysis window for the $0\nu\beta\beta$ search is identical but includes the signal interval. The low background index of BEGe detectors, previously based on one single event, is now confirmed with a more than threefold exposure to be $BI = 1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV·kg·yr). If normalized according to the energy resolution and total signal efficiency ϵ, i.e. $BI\cdot$FWHM$/\epsilon$, this value corresponds to $4.9^{+2.9}_{-1.9}$ cts/(ton·yr). Hence, GERDA will remain "background-free", i.e. the average background in the energy interval 1·FWHM at $Q_{\beta\beta}$ is expected to be less than 1 for the entire design exposure of 100 kg·yr. The efficiency ϵ (see Tab. I) accounts globally for the abundance of ^{76}Ge in the detectors, the active volume fraction, the probability that the entire decay energy $Q_{\beta\beta}$ is released in the active volume fraction of one Ge detector and the efficiency of all selection and analysis cuts [7]. The normalized GERDA background $BI\cdot$FWHM$/\epsilon$ is at least a factor five lower than that in any other competing non-^{76}Ge experiment.

The MAJORANA Demonstrator experiment also searches for $0\nu\beta\beta$ decay of ^{76}Ge employing passive shielding made of ultra-pure copper. With the same normalization [12], their background is $5.7^{+4.3}_{-3.6}$ cts/(ton·yr). This result is reported in the same issue of this journal [13]. Both experiments have consequently extremely low background.

The total exposure analyzed here is calculated from the total mass and amounts to 23.5 kg·yr and 23.2 kg·yr for Phase I and Phase II, respectively. This corresponds to (471.1 ± 8.5) mol·yr of ^{76}Ge in the active volume of the detectors. Data from both phases are grouped in six data sets depending on detector type and background level as summarized in Tab. I.

The spectrum in the analysis window is displayed in Fig. 2. Since there is no event close to $Q_{\beta\beta}$ we place a 90 % C.L. lower limit of $T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr on the decay half-life derived from a frequentist (profile likeli-

TABLE I. Summary of the Phase I (PI) and Phase II (PII) analysis datasets (exposure $\mathcal{E}$, energy resolution at $Q_{\beta\beta}$ (FWHM), total efficiency ϵ and background index BI).

data set	$\mathcal{E}$ [kg·yr]	FWHM [keV]	ϵ	BI [10^{-3}cts/(keV·kg·yr)]
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
total PI	23.5			
PII coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PII BEGe	18.2	2.93(6)	0.60(2)	$1.0^{+0.6}_{-0.4}$
total PII	23.2			
total	46.7			

hood) analysis with a median sensitivity of $5.8 \cdot 10^{25}$ yr. The chance to have a stronger limit is 30 % as evaluated by an ensemble of toy Monte Carlo realizations of the experiment (for details of the statistical analysis see the 'Methods' section in Ref. [7]). A Bayesian analysis with a flat prior in $1/T^{0\nu}_{1/2}$ yields a lower limit of $5.1 \cdot 10^{25}$ yr at 90 % credibility and a sensitivity of $4.5 \cdot 10^{25}$ yr.

DISCUSSION

The lower half-life limit can be converted to an upper limit on the effective Majorana neutrino mass $m_{\beta\beta}$ assuming the light neutrino exchange as dominant mechanism. Using the standard value of $g_A = 1.27$, phase space factors of Ref. [14], and the set of nuclear matrix elements [15–22] discussed in a recent review [23], the range for the upper limit on $m_{\beta\beta}$ is 0.12–0.26 eV for ^{76}Ge. The $m_{\beta\beta}$ limits for several $0\nu\beta\beta$ experiments obtained from

TABLE II. Comparison of lower half-life limits $T_{1/2}^{0\nu}$ (90 % C.L.) and corresponding upper Majorana neutrino mass $m_{\beta\beta}$ limits of different $0\nu\beta\beta$ experiments. The experiments, the isotopes and the isotopic masses M_i deployed are shown in cols. 1–3. The ranges of nuclear matrix elements (NME) [15–22] are given in col. 4. The lower half-life sensitivities and limits are shown in cols. 5 and 7, respectively. The corresponding upper limits for $m_{\beta\beta}$ derived with the NMEs are shown in cols. 6 and 8.

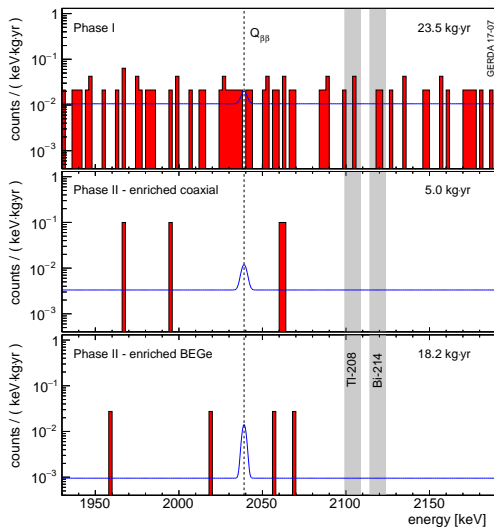| experiment		isotope	M_i	NME	sensitivity		limit	
					$T_{1/2}^{0\nu}$	$m_{\beta\beta}$	$T_{1/2}^{0\nu}$	$m_{\beta\beta}$
			[kg]		$[10^{25}$ yr]	[eV]	$[10^{25}$ yr]	[eV]
GERDA		^{76}Ge	31	2.8-6.1	5.8	0.14–0.30	8.0	0.12–0.26
MAJORANA	[13]	^{76}Ge	26	2.8-6.1	2.1	0.23–0.51	1.9	0.24–0.53
KamLAND-Zen	[24]	^{136}Xe	343	1.6-4.8	5.6	0.07–0.22	10.7	0.05–0.16
EXO	[25, 26]	^{136}Xe	161	1.6-4.8	1.9	0.13–0.37	1.1	0.17–0.49
CUORE	[27, 28]	^{130}Te	206	1.4-6.4	0.7	0.16–0.73	1.5	0.11–0.50

FIG. 2. Energy spectra in the analysis window for Phase I and Phase II coaxial detectors and Phase II BEGe detectors, resp., after all cuts. The binning is 2 keV. The grey vertical bands indicate the intervals excluding known γ lines. The blue lines show the hypothetical $0\nu\beta\beta$ signal for $T_{1/2}^{0\nu}= 8.0\cdot10^{25}$ yr, on top of their respective constant backgrounds.

profile likelihood analyses are listed in Tab. II. Despite the small deployed isotope mass M_i the $m_{\beta\beta}$ sensitivity and actual limit of ^{76}Ge are currently merely a factor of $\approx$1.5 larger relative to the most sensitive one in the field – if the worst case NMEs are considered.

GERDA continues to collect data and is projected to reach a sensitivity on the half-life well beyond $1 \cdot 10^{26}$ yr with the design exposure of 100 kg·yr. The excellent energy resolution and extremely low background make GERDA very well suited for a possible discovery, having a 50 % chance of a 3σ evidence for a half-life up to $\sim$8 · 10^{25} yr at the design exposure.

GERDA and MAJORANA Demonstrator both work in a "background free" regime. Therefore, the combined sensitivity on the ^{76}Ge $0\nu\beta\beta$ decay will increase almost linearly with the sum of the two exposures (see Fig. 2 of Ref. [8]). Having two experiments of similar background obtained by different methods paves the way for the future LEGEND experiment [29].

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