First results of GERDA Phase II and consistency with background models

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Abstract. The GERDA (GERmanium Detector Array) is an experiment for the search of neutrinoless double beta decay ($0\nu\beta\beta$) in ^{76}Ge, located at Laboratori Nazionali del Gran Sasso of INFN (Italy). GERDA operates bare high purity germanium detectors submersed in liquid Argon (LAr). Phase II of data-taking started in Dec 2015 and is currently ongoing. In Phase II 35 kg of germanium detectors enriched in ^{76}Ge including thirty newly produced Broad Energy Germanium (BEGe) detectors is operating to reach an exposure of 100 kg·yr within about 3 years data taking. The design goal of Phase II is to reduce the background by one order of magnitude to get the sensitivity for $T_{1/2}^{0\nu} = O(10^{26})$ yr. To achieve the necessary background reduction, the setup was complemented with LAr veto. Analysis of the background spectrum of Phase II demonstrates consistency with the background models. Furthermore ^{226}Ra and ^{232}Th contamination levels consistent with screening results. In the first Phase II data release we found no hint for a *0νββ* decay signal and place a limit of this process $T_{1/2}^{0\nu} > 5.3 \cdot 10^{25}$ yr (90% C.L., sensitivity $4.0 \cdot 10^{25}$ yr). First results of GERDA Phase II will be presented.

1. Introduction

The GERmanium Detector Array (Gerda) is an experiment for the search of neutrinoless double beta decay (*0νββ*) in ^{76}Ge, located at the Laboratori Nazionali del Gran Sasso (LNGS) of the INFN in Italy. This process is considered a powerful probe to address still open issues in the neutrino sector of beyond Standard Model of Particle Physics. Germanium diodes enriched to ~ 86 % of ^{76}Ge isotope are exposed being both source and detector of *0νββ* decay. The germanium based double beta decay experiments Heidelberg-Moscow (HdM) and IGEX established world leading limits on the *0νββ* decay to ground state of $T_{1/2} > 1.9 \cdot 10^{25}$ (90% C.L.) in 2001 [1] and $T_{1/2} > 1.6 \cdot 10^{25}$ (90% C.L.) in 2002 [2], respectively. A subgroup of HdM claimed a 4.2σ evidence in 2004 [3] and later a more than 6σ observation in 2006 [4], though these results were met with criticism in the community. The latter result is not used for comparison by the Gerda collaboration, due to serious flaws in the analysis as shown by Schwingenheuer [5].

A new generation of double beta experiments is now aiming for half-life sensitivities in the order of 10^{26} yr, which is sufficient to reach the inverted hierarchy band.

2. The GERDA experiment

GERDA experiment [6] operates an array of bare germanium detectors in a stainless steel cryostat filled with 64 m^3 liquid argon (LAr) for cooling to their operating temperature (~90K) and for shielding against external radiation originating from the walls [7]. Internal wall of the cryostat is covered by plates of different profile made of pure copper. This additional shielding protects Ge array from radioactivity of stainless steel walls. The cryostat is further surrounded by a tank of 590 m3 water, which is instrumented with photomultiplier and used as a passive shield and an active Cherenkov light veto. The clean room with a glove box and lock on top of the structure houses to insert the detector strings and LAr veto system. Additionally, muons are vetoed with the help of scintillator panels that are installed above the clean room.

In Phase I of the experiment reprocessed p-type semi-coaxial germanium detectors from the HdM and IGEX experiments were used (10 detectors with 17.6 kg total mass). Phase I was completed reaching an exposure of 21.6 kg·yr with a background level of 0.01 cts/(keV·kg·yr). No signal of the *0νββ* decay of ^{76}Ge at $Q_{\beta\beta}$ was found and a lower limit was set at $T_{1/2} > 2.1 \cdot 10^{25}$ yr [4].

The experiment was subsequently upgraded to double the target mass and reduce the background level by a factor of 10. 30 additional Broad Energy Germanium (BEGe) detectors manufactured by Canberra with total mass ~20 kg (including five of which were already deployed during Phase I) have been deployed. An active suppression of background by detecting the LAr scintillation light, consisting of PMTs and wavelength shifting fibers coupled to SiPMs, has been introduced. Many components of the set-up were also upgraded, including the lock-system used for lowering the detectors in the LAr cryostat, the read-out electronics, the contacting solution and the detector holders.

3. Phase II background spectrum

The background spectra of Phase II (enriched coaxial in blue and BEGes in red) after quality cuts but before the application of the pulse shape discrimination and the LAr veto are shown in figure 1 [9]. The spectra are normalized by their current exposure.

The spectra show the expected clearly marked structures: the low energy region up to 500 keV is dominated by the long-lived ^{39}Ar isotope (*β*-emitter with $T_{1/2}$ = 269 yr and Q = 565 keV); from 600 to 1400 keV the *2νββ* spectrum shows up; the 1461 keV γ-line from ^{40}K – it is important to note that the count rate is higher with respect to Phase I (factor of ~4). This could be explained by the increased number of cables and detector holders and by the introduction of the LAr instrumentation; the 1525 keV γ-line from ^{42}K - the rate is about twice compared to Phase I where metallic shrouds shielded the detectors from the electric fields of HV contacts and cables. Phase II needs non-metallic shrouds to readout the LAr scintillation light, allowing electric field to be dispersed in LAr hence to move ^{42}K ions. This affects also the top detectors more than the others; from ^{238}U chains - the most intense ^{214}Bi γ-lines are observed with rates on the same level of Phase I and the ratios between lines of different energy indicate that the ^{214}Bi sources are located not only within the Ge array but also external ones; from ^{232}Th chains - ^{208}Tl γ-lines are also visible, the intensities are the same of Phase I and don't allow to indicate the source position; the high energy region (> 3500 keV) is dominated by the α structures from ^{210}Po (Q = 5.41 MeV) and ^{226}Ra (Q = 4.87 MeV) - the time dependence of the α rate in enriched coaxial shows an exponential decay with $T_{1/2}$= 177 ± 36 days (figure 2 right), a value compatible with ^{210}Po ($T_{1/2}$= 138 days) and a minor contribution from ^{226}Ra chain (constant); the 511 keV γ-line ("e^+ ann" in Table 1) is observed in the spectra.

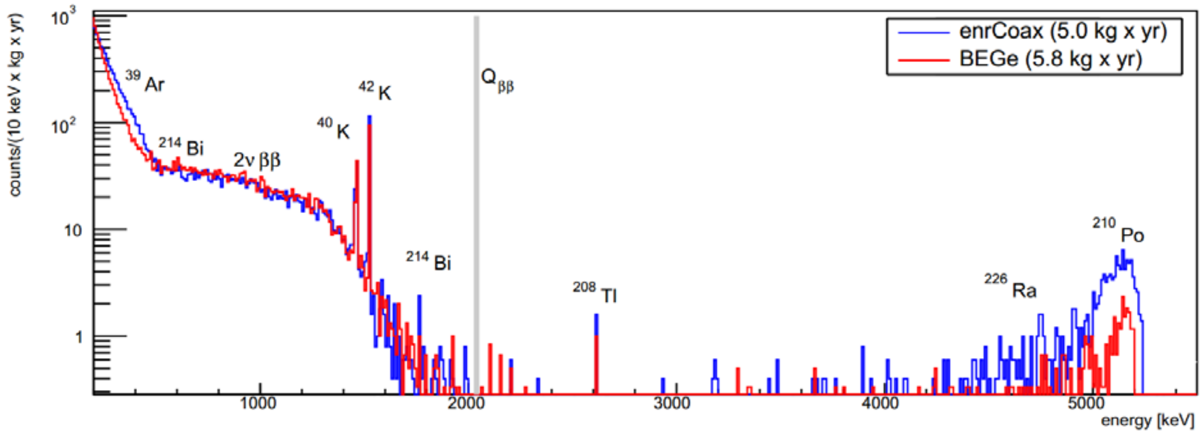

Figure 1. Gerda Phase II total spectra for enriched coaxial (blue) and BEGe (red) detectors (before PSD and LAr veto).

Table 1. The intensities of the visible or expected γ-lines estimated with a Bayesian fit for Phase I and Phase II data releases for the BEGe and enriched coaxial detectors.

		Phase II		Phase I	
		BEGe	^{enr}**Coax**	**BEGe**	^{enr}**Coax**
	energy [keV]	rate [cts/(kg·yr)]	rate [cts/(kg·yr)]	rate [cts/(kg·yr)]	rate [cts/(kg·yr)]
^{40}**K**	1460.8	$50.3^{+2.5}_{-3.4}$	$55.4^{+3.3}_{-3.9}$	$12.7^{+3.2}_{-3.1}$	$14.1^{+1.1}_{-1.2}$
^{42}**K**	1524.7	$88.0^{+4.8}_{-3.0}$	$113.0^{+4.3}_{-5.6}$	$46.6^{+4.6}_{-4.9}$	$60.6^{+2.0}_{-1.8}$
^{214}**Bi**	609.3	$8.9^{+2.8}_{-2.3}$	$8.0^{+3.5}_{-2.8}$	$12.0^{+6.2}_{-5.3}$	$8.1^{+2.2}_{-2.5}$
	1120.3	$2.6^{+1.2}_{-1.8}$	$3.6^{+2.3}_{-2.0}$	$6.7^{+4.0}_{-4.2}$	< 2.9
	1764.5	$0.8^{+0.5}_{-0.4}$	$2.0^{+0.8}_{-0.6}$	< 2.5	3.2 ± 0.5
^{208}**Tl**	583.2	$7.6^{+3.5}_{-2.8}$	< 5.3	< 11.0	$4.0^{+2.2}_{-2.1}$
	2614.5	$1.0^{+0.5}_{-0.4}$	$1.7^{+0.7}_{-0.6}$	$0.6^{+0.7}_{-0.5}$	1.5 ± 0.4
e^+**ann**	511	$12.6^{+3.4}_{-3.4}$	$11.9^{+3.7}_{-3.1}$	$16.5^{+6.4}_{-6.1}$	$10.4^{+2.4}_{-2.6}$

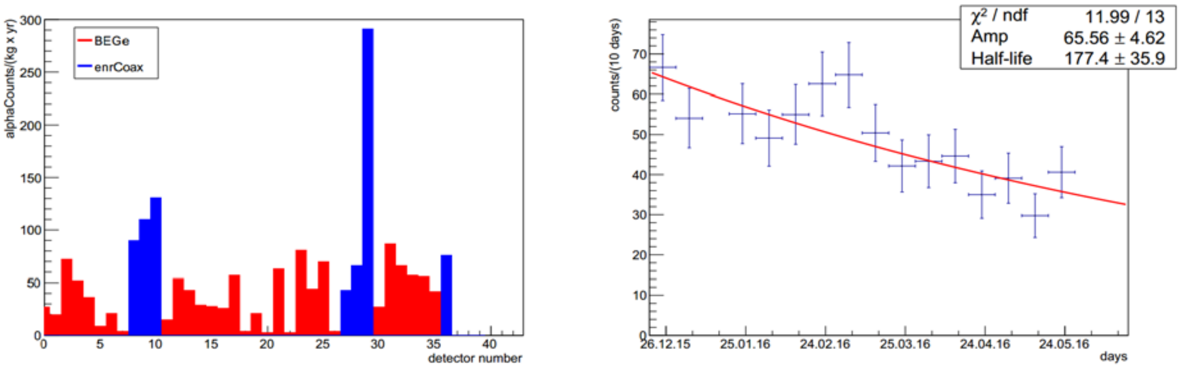

Figure 2. Left: The count rate of alpha events per detector: enriched coaxial (blue), BEGe (red). Right: The time dependence of the count rate of alpha events for enriched coaxial detectors.

From the pulse shape of the observed α events, it can be determined that they are mostly located at the p+ contact surface: the α count rate per detector (figure 2 left) shows that coaxial detectors are typically higher than BEGes, this is due to their larger p+ contact surface.

According the screening results, the main contributions to the background are from materials located close to the detector array.

The intensities of the visible or expected γ-lines has been estimated with a Bayesian fit, the results are showed in Table 1 together with the Phase I values [9].

4. First Phase II results

GERDA Phase II started in December 2015 with 37 detectors (35.6 kg) from enriched material (30 BEGe, 7 enriched coaxial detectors. After this date the data were blinded in a window of $Q_{\beta\beta}$±25 keV. Here we present data collected during the first 6 months.

To guarantee the energy scale stability weakly calibration runs were performed with ^{228}Th sources. The resolution of the detectors at 2.6 MeV was 3.2 keV FWHM for the BEGe detectors and 3.8 keV FWHM for the coaxial detectors.

After applying the LAr veto to the physics data an almost pure sample of *2νββ* decays is left with a count rate that corresponds to the half life measured in Phase I (see figure 3 left). The effect of the PSD cut on physics data is shown on figure 3 right. The ratio of the peak amplitude of the current signal and the total energy is used as a single parameter cut for PSD in BEGe detectors (A/E cut). A low value of the A/E parameter is typical for multi-site events and a high value for surface events. Only a narrow band of signal like events passes the cut. The exact value of the cut parameter was optimized in place for each detector using calibration data.

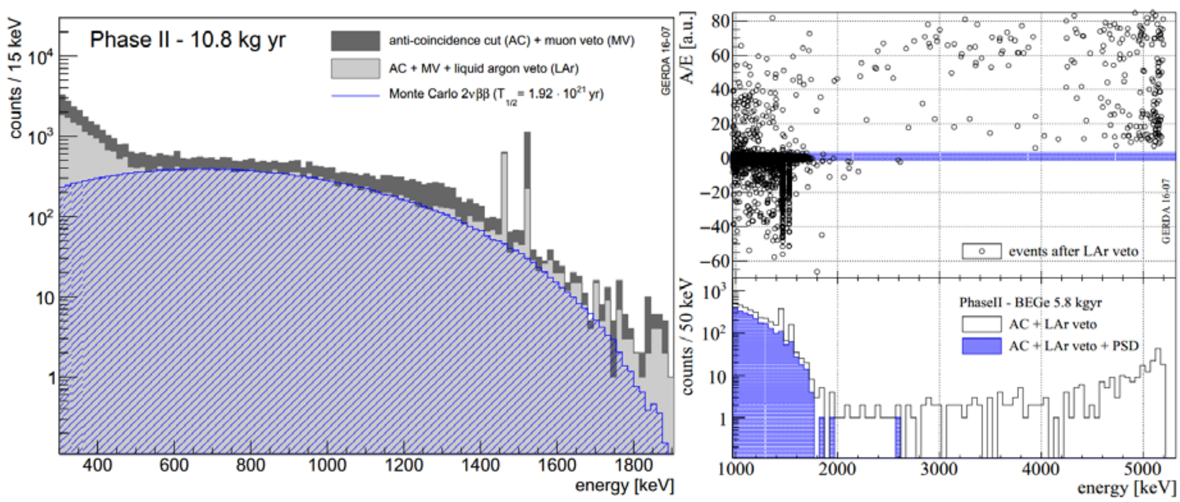

Figure 3. Left: almost pure *2νββ* remains in the low energy part of the spectrum after applying the LAr veto. The blue shaded area is the simulated *2νββ* spectrum scaled to the half life measured in Phase I. Right: The PSD cut applied to the BEGe physics data after the LAr veto. In the signal band of the A/E parameter only one event survives all cuts in $Q_{\beta\beta}\pm100$ keV.

After all analysis cuts were tuned on the blinded data the first unblinding of Phase II data (June 2016) when 10.8 kg·yr exposure was reached (5.0 kg·yr from enriched coaxial and 5.8 kg·yr from BEGes detectors). In addition a remaining of 1.9 kg·yr Phase I data recorded after May 2013 was also unblinded and analyzed. figure 4 shows the Phase II spectra of the enriched coaxial and BEGe detectors.

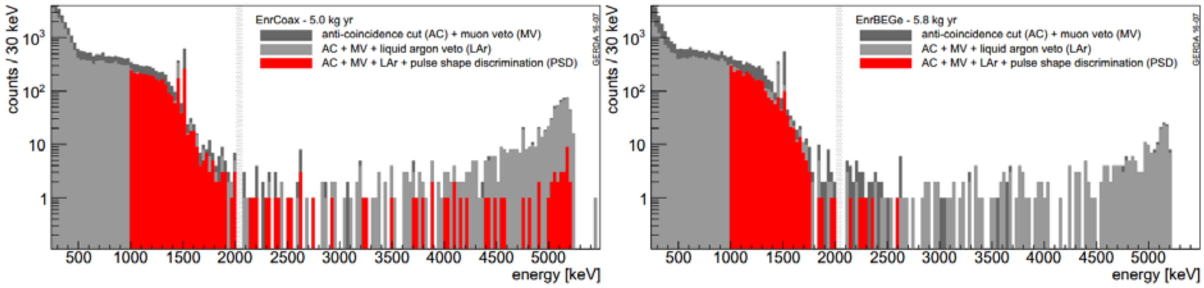

Figure 4. Gerda Phase II total spectra for enriched coaxial (left) and BEGe (right) detectors.

The planned background level in Phase II is achieved and the number of counts in the coaxial data set corresponds to $3.5^{+2.5}_{-1.5}\cdot10^{-3}$ cts/(keV·kg·yr) and in the BEGe data set corresponds to $0.7^{+1.1}_{-0.5}\cdot10^{-3}$ cts/(keV·kg·yr). Using the published Phase I data [10] and the 12.7 kg·yr unblinded data (see Table 2) a combined fit was performed and a new limit was set: $T^{0\nu}_{1/2} > 5.3\cdot10^{25}$ yr (90% C.L., median sensitivity $4.0\cdot10^{25}$ yr).

Table 2. List of data sets, exposures (for total mass), energy resolutions in FWHM, efficiencies with all cuts applied and background indices in the analysis window.

data set	exposure [kg·yr]	FWHM [keV]	efficiency	background [10^{-3} cts/(keV·kg·yr)]
PI golden	17.9	4.27±0.13	0.57±0.03	11±2
PI silver	1.3	4.27±0.13	0.57±0.03	30±10
PI BEGe	2.4	2.74±0.20	0.66±0.02	5^{+4}_{-3}
PI extra	1.9	4.17±0.19	0.58±0.04	5^{+4}_{-2}
PII coax	5.0	4.0±0.2	0.51±0.07	3.5^{+2}_{-1}
PII BEGe	5.8	3.0±0.2	0.60±0.02	$0.7^{+1.1}_{-0.5}$

5. Conclusion

Data analysis from the first Phase II data release showed Gerda has achieved its challenging background goal and it is the first background free experiment of the field.

The study of background spectrum in Phase II showed the presence of well known α and γ structures, also visible in the Phase I spectrum. For the background model creating and understanding of expected contamination level in the region around the $Q_{\beta\beta}$ value the information of the contributions to the observed background and the sources localization are needed.

In the first Phase II data release no hint for a *0νββ* decay signal at $Q_{\beta\beta}$ was found and place a limit of this process $T^{0\nu}_{1/2} > 5.3\cdot10^{25}$ yr (90% C.L., sensitivity $4.0\cdot10^{25}$ yr). Data taking of Phase II is continued and in a few years Gerda will be able to detect a signal with $T_{1/2}$ up to 10^{26} yr.

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