

Post-upgrade performance of GERDA Phase II

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Abstract. Excellent spectroscopic performance, event topology information and outstanding radiopurity are unique properties of HPGe detectors that facilitate the search for $0\nu\beta\beta$ decay of ^{76}Ge . A detection of this process would shed light onto physics beyond the standard model, as it would uncover the Majorana nature of neutrinos. The GERDA experiment employs an array of HPGe detectors, made from isotopically modified material, in an active liquid argon shield at the LNGS underground laboratory. The combination of an ultra-low background environment with active background rejection techniques allows the exploration of $0\nu\beta\beta$ decay half-lives beyond 10^{26} yr. No signal has been found in the first 58.9 kg·yr of Phase II data, from which the most stringent limit on $0\nu\beta\beta$ decay of ^{76}Ge has been derived. In the course of an upgrade new HPGe detectors of novel type have been added to the array, increasing the total mass of enriched germanium to 44.2 kg. More than one year of data has been collected in this configuration. The first 24.9 kg·yr reveal encouraging performance for the ongoing $0\nu\beta\beta$ decay search.

1. $0\nu\beta\beta$ decay search with HPGe detectors

Double beta ($\beta\beta$) decay is a second order isobaric ($A = \text{const.}$) transition of an isotope $^A_Z X$, that appears exothermal ($Q_{\beta\beta} > 0$) if the daughter nucleus $^A_{Z+2} Y$ is favored energetically. Nature offers a limited range of nuclei for which $\beta\beta$ decay remains the main decay mode - among them ^{76}Ge with $Q_{\beta\beta} = 2039$ keV [1]. As a Majorana mass term arises from particle-anti-particle oscillations, it is the search for lepton number violating neutrinoless double beta ($0\nu\beta\beta$) decay, that might reveal the Majorana nature of the neutrino [2]. Its signature is the emission of two electrons, not balanced by the emission of anti-neutrinos, and hence sharing all $Q_{\beta\beta}$.

High Purity Germanium (HPGe) detectors, made from material enriched in ^{76}Ge , offer a unique set of properties that facilitate the search for $0\nu\beta\beta$ decay. As they constitute simultaneously source and detector, from a material with large stopping power, high detection efficiency and peculiar $\beta\beta$ decay event topology are achieved. Electrons released within the germanium will deposit their energy within a very short range of $\mathcal{O}(1\text{ mm})$, wherefore single-crystal Single-Site Event (SSE) topology is a clear feature of bulk $\beta\beta$ decay. The excellent energy resolution of $\mathcal{O}(0.1\%)$ at MeV-energies, allows to separate the mono-energetic $0\nu\beta\beta$ decay signal from the standard-model two neutrino double beta ($2\nu\beta\beta$) decay continuum.

2. GERDA Phase II

As internal contaminations in HPGe detectors have been proven to be negligible [3], the GERDA experimental maxim follows a rigorous external background reduction. Bare HPGe detectors with an isotopic fraction of about 87% ^{76}Ge , are operated in a seven string array configuration. Nearby structural materials, e.g. detector holders and electronics, are selected for highest radiopurity and reduced to a minimum. A veto instrumentation, combining photomultipliers (PMTs)



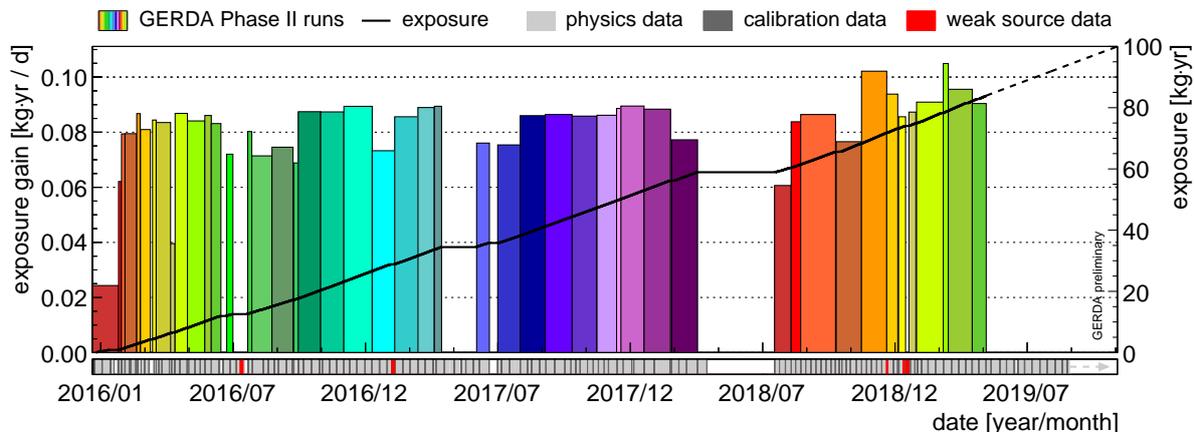


Figure 1. GERDA Phase II data taking started in December 2015. Until May 2018 physics data was taken at high duty cycle, only interrupted by the weekly calibrations, special data taking campaigns and a few short maintenance operations. After the upgrade, data taking resumed in July 2019. Thanks to a slight increase in HPGe detector mass, higher values in exposure gain are reached after the upgrade. The pre-upgrade analysis exposure amounts to 58.9 kg·yr, whereas by May 2019 a post-upgrade exposure of 24.9 kg·yr has been accumulated. By the end of 2019, a total analysis exposure above 100 kg·yr will be reached.

and wavelength-shifting fibers with silicon photomultiplier (SiPM) read-out, surrounds the HPGe array. Both, the HPGe array and the light detection system, are jointly submerged in a 64 m³ liquid argon (LAr) bath, bringing the HPGe detectors to operation temperature, providing large-scale radio-pure passive shielding and enabling the detection of LAr scintillation light from energy depositions within and close-by to the array. The LAr cryostat is housed in a water tank, holding 590 m³ of ultra-pure water, that acts as efficient neutron moderator. Cherenkov light produced by cosmic muons is detected with PMTs. Access to the cryostat volume is granted via an air-tight lock system in a clean-room on top of the experiment. The experiment is situated in the Laboratori Nazionali del Gran Sasso (LNGS) underground laboratory in Italy, which provides a rock shielding of 3500 m water equivalent [4].

Phase II was started using two different HPGe detector types (see Figure 2), 30 custom-made Broad-Energy Germanium (BEGe) detectors and 7(3) coaxial detectors, amounting to a total enriched(natural) detector mass of 35.6 kg (7.6 kg). Figure 1 shows the data collection progress. Weekly calibrations with ²²⁸Th sources guarantee a properly defined energy scale of each HPGe detector. Unstable periods are discarded on a detector-by-detector basis. Events with energy depositions in multiple HPGe detectors are rejected. The time structure of the acquired HPGe detector pulses gives access to the energy deposition topology within each germanium crystal [5]. Pulse shape discrimination (PSD) is tuned with calibration data, using the ²⁰⁸Tl double-escape peak as SSE proxy. For BEGe detectors a two-sided mono-parametric cut, based on the current pulse amplitude divided by the total collected charge (A/E) is used. It allows to reject both multi-site (MSE) and surface events. For the coaxial detectors MSE rejection is obtained by an artificial neural network analysis. Surface events are rejected by a consecutive cut based on the signal risetime. Events for which coincident scintillation light is detected by the LAr veto instrumentation, are discarded. All events recorded within ± 25 keV around $Q_{\beta\beta}$ are stripped from the public data stream and analyzed bias-free once the full analysis chain is frozen. A total analysis exposure of 58.9 kg·yr has been “unblinded” in 2018. In combination with data from Phase I, a median sensitivity of $1.1 \cdot 10^{26}$ yr (90% C.L.) for a limit on the $0\nu\beta\beta$ decay half-life

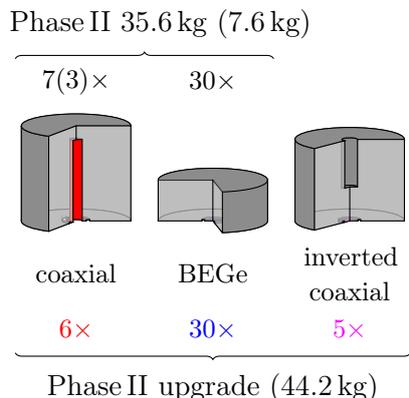


Figure 2. GERDA employs three different HPGe detector types. Since the upgrade five inverted coaxial detectors are deployed in addition to six (formerly seven) coaxial and 30 BEGe detectors.

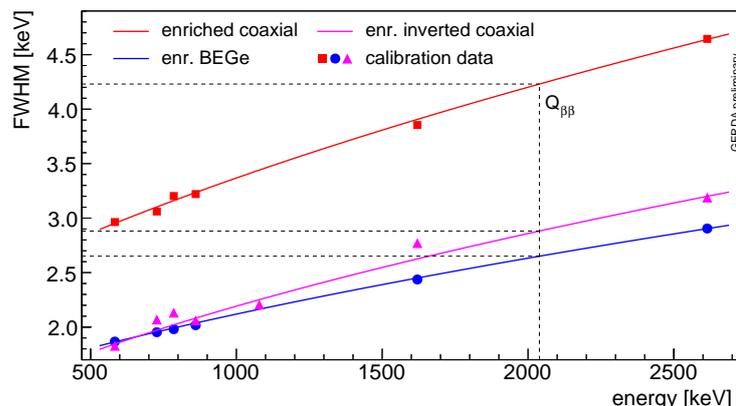


Figure 3. With a resolution of 2.9(1) keV (FWHM) at $Q_{\beta\beta}$ the inverted coaxial detectors achieve similar performance as the BEGe detectors. Improved noise conditions due to a new cable routing results in an improved BEGe detector resolution of 2.6(1) keV. The energy estimator is based on the Zero Area Cusp (ZAC) digital shaping [8].

was reached. No signal was found, placing the most stringent limit on $0\nu\beta\beta$ decay in ${}^{76}\text{Ge}$ at $0.9 \cdot 10^{26}$ yr (90% C.L.) [6].

3. Upgrade of GERDA Phase II

Thanks to their small read-out electrode and internal field configuration, BEGe detectors feature outstanding spectroscopic and PSD performance. Unfortunately their design implies a limited detector mass, whereas larger detectors would be beneficial in terms of reduced auxiliary material (e.g. cables) per detector mass, better surface-to-volume as well as peak-to-Compton ratio. A new detector type, the so-called inverted coaxial point contact detector, has been developed to overcome this limitation [7]. In May 2018 the GERDA data taking has been stopped to deploy the first 5 enriched HPGe detectors of this design. They replace the former coaxial detectors of natural isotopic composition and one enriched detector (see Figure 2). As part of this upgrade an improved LAr veto instrumentation with higher fiber density and novel central read-out was mounted. Data taking was resumed in July 2018 (see Figure 1).

4. Post-upgrade performance

Figure 3 shows the spectroscopic performance of the GERDA detectors after the upgrade. The inverted-coaxial detectors show similar performance as the BEGe type detectors. The analysis methods applied after the upgrade are coherent with the pre-upgrade analysis. PSD for the inverted coaxial detectors is performed analogue to BEGe detectors, using the A/E method [9]. Figure 4 shows the spectrum corresponding

to the first 24.9 kg·yr of post-upgrade data. The background level at $Q_{\beta\beta}$ is estimated from the single events remaining within 1930 to 2190 keV, excluding known γ lines and the 50 keV blinding window. A comparison of the obtained numbers with the pre-upgrade background indices

Table 1. Phase II background indices.

	pre-upgrade	post-upgrade
	[10^{-3} cts/(keV·kg·yr)]	
coaxial	$0.6^{+0.4}_{-0.3}$	$0.7^{+1.0}_{-0.5}$
BEGe	$0.6^{+0.3}_{-0.2}$	$0.4^{+0.6}_{-0.3}$
inverted-coaxial	-	< 2.6 (90%)

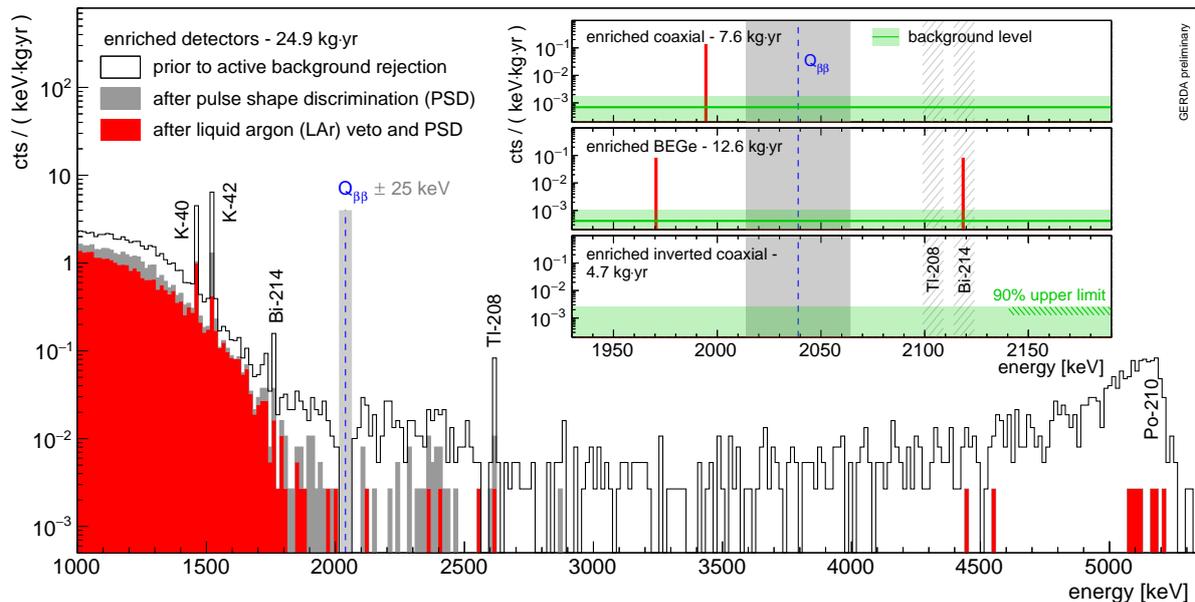


Figure 4. The “blinded” spectra acquired since the upgrade show the GERDA-typical features: ^{210}Po surface alphas, leaking to lower energies through degradation; γ lines from the ^{238}U and ^{232}Th chain, as well as ^{40}K ; ^{42}K γ and ^{39}Ar β (at <500 keV) contributions from decays in the LAr. These components are strongly suppressed by the combination of PSD and LAr veto, leaving only the $2\nu\beta\beta$ continuum and a few single isolated counts.

is shown in Table 1. With no counts appearing in the full 4.7 kg-yr of inverted coaxial detector exposure, only an upper limit on their background level can be placed.

5. Conclusions

Thanks to the ultra-low background of 10^{-3} cts/(keV.kg.yr) at $Q_{\beta\beta}$ and an excellent energy resolution, GERDA is the first experiment to reach a $0\nu\beta\beta$ half-life sensitivity beyond 10^{26} yr. After a successful upgrade Phase II is approaching its 100 kg-yr exposure goal. The new enriched inverted coaxial detectors show promising performance, both in energy resolution and background level, that encourages the future ^{76}Ge $0\nu\beta\beta$ decay exploration with the Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay (LEGEND) [10].

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