Searching Neutrinoless Double Beta Decay with Gerda Phase II

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An observation of neutrinoless double beta ($0\nu\beta\beta$) decay would allow to shed light onto the nature of neutrinos. GERDA (GERmanium Detector Array) aims to discover this process in a background-free search using ^{76}Ge . The experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS) of the Istituto Nazionale di Fisica Nucleare (INFN) in Italy. Bare, isotopically enriched, high purity germanium detectors are operated in liquid argon. GERDA follows a staged approach. In Phase II 35.6 kg of enriched germanium detectors are operated since December 2015. The application of active background rejection methods, such as a liquid argon scintillation light read-out and pulse shape discrimination of germanium detector signals, allows to reduce the background index to the intended level of 10^{-3} cts/(keV·kg·yr). No evidence for the $0\nu\beta\beta$ decay has been found in 23.2 kg·yr of Phase II data, and together with data from Phase I the up-to-date most stringent half-life limit for this process in ^{76}Ge has been established, at a median sensitivity of $5.8\cdot 10^{25}$ yr the 90 % C.L. lower limit is $8.0\cdot 10^{25}$ yr.

Keywords: Neutrinoless double beta decay; ^{76}Ge .

1. Introduction

Double beta decay is a second order weak process occurring in isotopes in which single beta decay is forbidden by energy conservation or strongly suppressed because of a large change of spin between initial and final state. In case neutrinos are Majorana particles the lepton number violating mode of this process - neutrinoless double beta decay - exists.¹ Its signature is the emission of two electrons with summed energy at the full Q-value ($Q_{\beta\beta}$). So far this process has not been discovered. Existing half-life limits are in the range of 10^{21} to 10^{26} yr, depending on the double beta decaying isotope.^{2,3} GERDA is searching for $0\nu\beta\beta$ decay using ^{76}Ge .

2. Gerda approach

GERDA performs a staged, high resolution, background-free $0\nu\beta\beta$ decay search. The intrinsic properties of high-purity germanium (HPGe) detectors properly suit this approach. HPGe detectors have an excellent energy resolution of $\mathcal{O}(0.1)\%$ at $Q_{\beta\beta} = 2039$ keV. Isotopic enrichment in ^{76}Ge is well established. The detectors constitute simultaneously source and detector. Their intrinsic background is negligible.⁴

Extensive efforts in material selection of components in the detector surroundings and a graded passive shielding aim to minimize the external background. Due to the high density of germanium the topology of double beta events is a single-site interaction, i.e. a point-like energy deposition, in one HPGe detector. Background processes can be discriminated by event topology.⁵ The granularity of an array configuration allows to discard events with simultaneous energy deposition in several detectors by detector anti-coincidence. Similarly the operation of HPGe detectors in an active medium, such as liquid argon (LAr), allows to reject events with coincident energy deposition in the array surroundings (LAr veto). This active background rejection strategy is complemented by the ability to suppress events originating from multi-site energy depositions or detector surfaces in a single germanium detector by pulse shape discrimination (PSD). The internal field configuration leads to distinct features in the time profile of germanium detector pulses.⁶

Minimum initial background and the capability to actively suppress background events allow a background contribution of less than one count integrated over the full design exposure and the narrow energy region where the mono-energetic $0\nu\beta\beta$ peak is expected. These background-free conditions allow a maximum gain in discovery power per exposure.⁷

3. Gerda Phase II

GERDA is situated at the LNGS underground laboratory in Italy. A rock overburden of about 3500 m.w.e. reduces the cosmic ray background. The residual muon flux is about $1.2 \text{ m}^{-2}\text{h}^{-1}$. A 590 m^3 water tank provides additional shielding against gammas and neutrons. It is equipped with photomultipliers (PMTs). Together with plastic scintillator panels it acts as active muon veto. The water tank houses a 64 m^3 cryostat filled with LAr. The argon provides further shielding. At the same time it acts as coolant for the bare HPGe detectors. The instrumentation is lowered into the cryostat from a clean room on top of the experiment via an air-tight lock system.^{8,9}

In Phase II GERDA operates 35.6 kg of HPGe detectors enriched to about 87% of ^{76}Ge in a 7 string array configuration. This includes 7 (semi-)coaxial detectors formerly used in the Heidelberg-Moscow and IGEX experiments as well as 30 custom-made Broad Energy germanium (BEGe) detectors.^{10,11,12} BEGe detectors exhibit a better performance in energy resolution and PSD. The detectors are mounted in low mass holders made from copper and silicon. Signals from the germanium detectors are amplified with custom-made low radioactivity charge sensitive amplifiers situated about 35 cm above the array. The accumulation of ^{42}K ions originating from ^{42}Ar decays in the argon surroundings on detector surfaces is limited by nylon vessels reducing the collection volume.¹³ The LAr around the array is instrumented with PMTs and wavelength shifting fibers coupled to silicon photomultipliers (SiPMs) to detect scintillation light.^{14,15}

GERDA applies a blinding procedure during its data taking. All events in an energy interval $\pm 25 \text{ keV}$ around $Q_{\beta\beta}$ are stripped from the data stream. The analysis of the digitized germanium detector and scintillation light read-out signals is performed offline.¹⁶ Only after all analysis parameters are frozen all events are processed.

4. Performance and Results

Phase II data taking started in December 2015. With a duty cycle of 93%, $34.4 \text{ kg}\cdot\text{yr}$ of analysis data were collected until April 2017. This is divided into $18.2 \text{ kg}\cdot\text{yr}$ from enriched BEGe detectors and $16.2 \text{ kg}\cdot\text{yr}$ from enriched coaxial detectors.

To ensure a properly defined energy scale over the full data taking, weekly calibrations with ^{228}Th sources are performed. Data periods where no stable energy scale could be guaranteed are not used for analysis. An optimized digital shaping

Fig. 1. Energy spectra prior unbinding and with consecutively applied background rejection cuts for enriched coaxial (top) and BEGe detectors (bottom). The $Q_{\beta\beta} \pm 25$ keV blinded energy region is marked. PSD is only applied above 1 MeV. The inset shows the energy region around the γ lines from ^{40}K and ^{42}K .

filter for low-frequency noise rejection is used for energy reconstruction.¹⁷ The resolution is corrected for deviations seen in background data. At $Q_{\beta\beta}$ the full-width at half-maximum is (2.93 ± 0.06) keV for BEGe detectors and (3.90 ± 0.07) keV for coaxial detectors.

Fig. 1 shows the energy spectra obtained by the two different enriched detector types deployed in GERDA Phase II. The impact of consecutively applied active background rejection by LAr veto and PSD is highlighted. At energies below 500 keV the beta spectrum from ^{39}Ar is well visible. It is naturally present in the surrounding LAr. Except for two full energy peaks from ^{40}K and ^{42}K , the intermediate energy region up to the Q-value is dominated by the continuous energy distribution from neutrino accompanied double beta decay ($2\nu\beta\beta$). At higher energies alpha decays on the p+ and groove surface of the HPGe detectors with a degraded observed energy are visible.

The LAr veto anti-coincidence cut removes events with coincident signals registered in the scintillation light read-out channels. Accordingly, events populating the ^{42}K line at 1525 keV face strong reduction by the coincident energy release of the beta decay in the argon itself. On the other hand, the ^{40}K line at 1461 keV is barely suppressed because it originates from electron capture without further coincident energy release in the argon. Accidental coincidences lead to a signal acceptance of $(97.7 \pm 0.1)\%$ for $0\nu\beta\beta$ events. PSD removes events with pulse shape differing from the ones expected for single-site bulk energy depositions. For coaxial detectors this is done by application of two neural network algorithms to reject multi-site and alpha surface events. The special internal field configuration of BEGe detectors allows to apply a more efficient mono-parametric PSD method on them. It is based on the maximum of the current pulse and the total energy. The acceptance

for the $0\nu\beta\beta$ events determined from calibration data, pulse shape simulations and the $2\nu\beta\beta$ events is $(87\pm3)\%$ for BEGe detectors and $(79\pm5)\%$ for coaxial detectors.

Fig. 2. Different components of a preliminary background model based on data prior LAr veto and PSD cut. The inset shows the region around $Q_{\beta\beta}$. The background window is defined from 1930 keV to 2190 keV excluding known γ lines.

Fig. 3. Unblinded energy spectra around $Q_{\beta\beta}$ after application of all cuts. A hypothetical signal with half-life corresponding to the lower-limit is shown.

Fig. 2 shows the contributions from different background components obtained by a preliminary background model fit. Constraints by screening measurements of components in the detector vicinity are used. It is based on the higher statistics spectra prior LAr veto and PSD cut. Around $Q_{\beta\beta}$ a flat background is expected. The background contribution for the $0\nu\beta\beta$ decay search is determined from an energy window from 1930 to 2190 keV excluding ± 5 keV around $Q_{\beta\beta}$, the 2103 keV single escape peak from ^{208}Tl and the 2119 keV full energy peak from ^{214}Bi .

Fig. 3 shows the unblinded region of interest used in the $0\nu\beta\beta$ analysis. The result is based on a combined unbinned likelihood fit of a gaussian signal on a flat background. Data from Phase I and Phase II are combined. The full enriched BEGe detector data with 18.2 kg·yr is used. This corresponds to 12.4 kg·yr increase compared to previous GERDA results.¹⁸ The total exposure amounts to 46.7 kg·yr. No signal at $Q_{\beta\beta}$ was found. The frequentist analysis results in a lower limit of $8.0\cdot 10^{25}$ yr at 90 % C.L. for the half-life of $0\nu\beta\beta$ decay of ^{76}Ge . The median sensitivity is $5.8\cdot 10^{25}$ yr. All efficiencies like e.g. active volume and containment fraction as well as the above mentioned signal acceptances are included into the result.¹⁹ The background index of $1.0^{+0.6}_{-0.4}\cdot 10^{-3}$ cts/(keV·kg·yr) of enriched BEGe detectors fulfills the Phase II goal.

5. Conclusions and Outlook

The extremely low background achieved by combining extensive passive and novel active background reduction techniques allows GERDA to perform a background-free $0\nu\beta\beta$ decay search. Taking into account the narrow energy region defined by the HPGe detector resolution a background level better than any competing non- ^{76}Ge experiment is achieved. The presented result is based on part of the data taken in the first 1.5 yr of GERDA Phase II combined with Phase I. Already available data and currently ongoing data taking will allow to go beyond 10^{26} yr median sensitivity in $0\nu\beta\beta$ half-life of ^{76}Ge early 2018. After 2019 the LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay) collaboration aims to operate up to 200 kg of enriched germanium in the existing GERDA infrastructure at LNGS. Exploiting the active background rejection approach and the expertise gained by the GERDA and MAJORANA collaborations an even lower background is envisioned. In a second 1-ton phase LEGEND will reach discovery sensitivities beyond 10^{28} yr and ultimately cover the parameter space of inverted mass hierarchy.²⁰

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