Results on neutrinoless double beta decay of $^{76}\text{Ge}$ from GERDA Phase I

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Abstract. The Germanium Detector Array (GERDA) experiment is searching for the neutrinoless double beta ($0\nu\beta\beta$) decay of $^{76}\text{Ge}$ by operating bare germanium diodes in liquid argon. GERDA is located at the Gran Sasso National Laboratory (LNGS) in Italy. During Phase I, a total exposure of $21.6 \text{ kg yr}$ and a background index of $0.01 \text{ cts/(keV kg yr)}$ were reached. No signal was observed and a lower limit of $T_{1/2}^{0\nu} > 2.1 \times 10^{25} \text{ yr (90\% C.L.)}$ is derived for the half life of the $0\nu\beta\beta$ decay of $^{76}\text{Ge}$.

1. Introduction
Neutrino accompanied double beta ($2\nu\beta\beta$) decay is a second order weak process predicted by the Standard Model of particle physics. This decay has been observed for several isotopes and the experimentally determined half-lives lie in the range of $10^{19}$ to $10^{24}$ years [1, 2].

Neutrinoless double beta ($0\nu\beta\beta$) decay is a process that violates lepton number conservation by two units, and its observation would indicate physics beyond the Standard Model [3, 4, 5]. Furthermore, it would prove that neutrinos have a Majorana mass component. This process has not been observed so far and the half-life limits set on $0\nu\beta\beta$ decay for $^{76}\text{Ge}$ lie in the range of $(1.6 - 1.9) \times 10^{25}$ years [6, 7, 8]. In 2004, part of the HdM collaboration claimed an observation of $0\nu\beta\beta$ decay [9], reporting a half-life of $T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23}) \times 10^{25}$ years. The experimental signature of $0\nu\beta\beta$ decay is a monoenergetic peak of the sum electron kinetic energy at the $Q$-value of the decay, $Q_{\beta\beta} = 2039$ keV, above the continuous energy spectrum of the $2\nu\beta\beta$ decay.

The GERDA experiment is introduced in section 2. The results from GERDA Phase I are summarised in the following sections. The measurement of the half-life of $2\nu\beta\beta$ decay, the modelling of the background energy spectrum and the background discrimination methods are discussed in sections 3, 4 and 5, respectively. The result on the search of $0\nu\beta\beta$ decay is presented in section 6. The status of the ongoing transition to Phase II is presented in section 7.

2. The GERDA experiment
The GERDA experiment searches for the $0\nu\beta\beta$ decay of $^{76}\text{Ge}$ [10]. The experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. GERDA operates bare germanium diodes inside liquid argon (LAr) which serves as a coolant and as shielding. The array of germanium detectors is suspended inside a stainless steel cryostat filled with $64 \text{ m}^3$ of LAr. The cryostat is located inside a water tank that contains $590 \text{ m}^3$ of high purity water, moderating
ambient neutrons and gamma radiation. The water tank is instrumented with 66 photomultiplier tubes (PMTs) and operates as a Čerenkov muon veto reducing the cosmic induced background index to less than $10^{-5}$ cts/(keV kg yr) [11]. The rate of events coincident between the germanium detectors and the GERDA muon veto system is $(9.3 \pm 0.4) \times 10^{-5}$/s [12]. The detector strings are lowered into the cryostat from the clean room, located above the GERDA tank. An artist’s view of the experimental setup is shown in figure 1.

Two types of detectors were used during GERDA Phase I. Eight p-type high purity germanium (HPGe) semi-coaxial detectors from the HdM [6] and IGEX [7] experiments were refurbished and used as the main GERDA Phase I detectors. They have an n+ conductive lithium layer and a boron implanted p+ contact, separated by a groove. They are enriched to $\sim 86\%$ in $^{76}$Ge and have a total mass of 17 kg. Additionally, 30 enriched p-type broad energy germanium (BEGe) detectors were produced and will be used in Phase II of the experiment [13, 14]. Five of them were already deployed in GERDA during Phase I. Their total mass is 3.6 kg.

The data collected during Phase I, from November 2011 until May 2013, correspond to 492 days and a total exposure of 21.6 kg yr. The average duty cycle is 88%. The data were divided into three datasets. The golden coaxial dataset with an exposure of 17.9 kg yr contains all data taken with the enriched semi-coaxial detectors with the exception of a short period of approximately 30 days. This was due to increased activity after the insertion of the five BEGe detectors. This dataset, referred to as silver coaxial dataset, corresponds to 1.3 kg yr. The BEGe dataset consists of data taken with the BEGe detectors and has an exposure of 2.4 kg yr.

Regular calibration runs were taken on a weekly basis, using a $^{228}$Th source, in order to determine the energy scale of the individual detectors. The energy shift between successive calibrations is less than 1 keV at $Q_{\beta\beta}$. This is due to gain drifts of the readout chain [10]. The mean exposure-weighted energy resolutions for the GERDA detectors are $4.8 \pm 0.2$ keV for the semi-coaxial detectors and $3.2 \pm 0.2$ keV for the BEGe detectors.

3. Measurement of the $2\nu\beta\beta$ decay half-life
The measurement of the half-life of the neutrino accompanied double beta decay of $^{76}$Ge by GERDA corresponds to an exposure of 5.04 kg yr [15]. The observed energy spectrum between 600 and 1800 keV is dominated by the neutrino accompanied double beta decay of $^{76}$Ge. The signal-to-background ratio in this energy range is on average 4:1. A global model was fitted to the observed energy spectra above the cosmogenic $^{39}$Ar background, which dominates the energy spectrum below 565 keV. The model contains the $2\nu\beta\beta$ decay of $^{76}$Ge and three independent background contributions from $^{42}$K, uniformly distributed in liquid argon, as well as $^{214}$Bi and

Figure 1. An artist’s view of the GERDA detector. The array of germanium detectors (1), the LAr cryostat (2), the internal copper shield (3), the water tank (4), the clean room (5) and the lock system (6) are indicated. Taken from [10].
40K from close sources. The presence of these sources is established by the observation of their characteristic gamma lines. Possible contributions from other background components were included in the systematic uncertainties. The spectral fit has 32 free parameters, the $2\nu\beta\beta$ half-life, the detector masses and enrichment fractions and the background contributions. The experimental energy spectrum together with the best fit model and the individual spectral contributions are shown in figure 2. The ratio between experimental data and the prediction of the best fit model is shown in the lower panel. The green, yellow and red regions are the smallest intervals containing 68%, 95% and 99.9% probability for the ratio, respectively, assuming the best fit parameters. After marginalising over all nuisance parameters, the best half-life estimate is $T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \times 10^{21}$ yr. This result is shown in figure 3, together with previous publications and two weighted averages. The value reported by GERDA is longer than the previous measurements. There is a tendency towards higher values for more recent measurements. This is probably related to the improved signal-to-background ratio, which reduces the relevance of background
modelling and subtraction.

4. Background modelling for GERDA Phase I

A good understanding of the background is important in order to extract a possible $0\nu\beta\beta$ signal or to obtain a limit on the half-life of the process in case no signal events are observed. A background model was developed, prior to the $0\nu\beta\beta$ analysis, to describe the observed energy spectrum using data corresponding to an exposure of 18.5 kg yr [12]. The model contains several contributions that are either expected after material screening or established through the observation of characteristic structures in the energy spectrum. The energy spectra for the enriched semi-coaxial detectors, the BEGe detectors and one non-enriched detector are shown in figure 4. The low energy part, up to 565 keV, is dominated by the beta decay of cosmogenic $^{39}$Ar. Between 600 and 1500 keV the spectra of the enriched detectors are dominated by the $2\nu\beta\beta$ decay of $^{76}$Ge. Gamma lines from the decays of $^{40}$K and $^{42}$K can be identified in all spectra. Gamma lines from $^{60}$Co, $^{208}$Tl, $^{214}$Bi, $^{214}$Pb and $^{228}$Ac are visible in the spectra of the enriched semi-coaxial detectors. A peak-like structure around 5.3 MeV in the spectrum of the enriched semi-coaxial detectors can be attributed to the decay of $^{210}$Po on the detector p+ surface. Further peak-like structures at energies of 4.7, 5.4 and 5.9 MeV can be attributed to the alpha decays of $^{226}$Ra, $^{222}$Rn and $^{218}$Po on the detector p+ surface, respectively. A 40 keV window around $Q_{\beta\beta}$ was kept blinded during the analysis.

The background model was obtained by fitting the simulated spectra of different contributions to the measured energy spectrum using a Bayesian approach. The high energy part of the spectrum between 3.5 and 7.5 MeV, above the Q-value of $^{42}$K, was analysed first, providing a best fit for the alpha induced spectrum. This result was used along with other contributions to establish a model covering the energy range from 570 to 7500 keV. The main contributions at $Q_{\beta\beta}$ come from $^{42}$K (uniform in LAr), $^{60}$Co (in germanium and on the detector assembly), $^{214}$Bi (on the detector assembly and p+ surface), $^{208}$Tl (on the detector assembly), as well as alpha events from surface contamination and $^{222}$Rn in LAr. Figure 5 shows the best fit model in black, together with the observed counts and the individual background contributions considered in the high energy alpha fit, for the golden coaxial dataset. Figure 6 shows the best fit model in black, together with the observed counts and the individual background contributions considered in the global fit, for the golden coaxial dataset. In the lower panels, the ratios of data and model are shown together with the smallest intervals of 68%, 95% and 99.9% probability for the model expectation.
5. Pulse shape discrimination analysis

The experimental sensitivity can be improved by analysing the pulse shapes of the detector signals with the aim of rejecting background events. Pulse shape discrimination (PSD) is therefore used to separate single-site (SSE) from multi-site (MSE) events. The signature of
Figure 7. Experimental spectrum with the minimum (left) and maximum (right) background model around $Q_{\beta\beta}$ for the golden coaxial dataset. The upper panels show the experimental data (grey histograms) with the individual background contributions considered in the fit (coloured histograms). The light grey histogram corresponds to the partially unblinded data, not used for the modelling of the background. The lower panels show the best fit models fitted with a constant. In the legend, the following abbreviations are used for the location of the background contributions: H: detector holders, p+: p+ contact, LAr: uniform in liquid argon, Ge: inside the germanium crystal, n+: n+ surface, S: radon shroud, HE: heat exchanger. Taken from [12].

Figure 8. Cross section of a semi-coaxial (top) and a BEGe (bottom) detector. The n+ electrode is drawn in black and the p+ electrode in grey. The weighting potential inside the detector crystals is indicated through a colour map. Taken from [16].

A double beta decay is a SSE, i.e. the energy is deposited in a single location in the detector. On the other hand, MSEs, e.g. from multiple Compton scattering, deposit energy in well separated locations in the detector.

Different PSD techniques were used for the semi-coaxial and the BEGe detectors [16]. This is due to the different geometries and, hence, different electric field distributions of the detectors. The cross sections of a semi-coaxial and a BEGe detector, along with the corresponding weighting potentials, are shown in figure 8. For the semi-coaxial detectors a neural network approach was utilised, where the rising part of the charge pulse was used for the network analysis. For the BEGe detectors a mono-parametric A/E method was implemented, where A corresponds to the maximum of the current pulse and E is the reconstructed energy. For MSEs, the current pulses of the charges from different locations will have different drift times and, hence, more time-separated current pulses. Therefore, for the same total energy, E, the maximum amplitude,
A, will be smaller for MSEs. As a proxy of SSEs, events from the double-escape peak (DEP) at 1593 keV from the 2614 keV line of $^{208}$Tl are used. Events in the full energy line of $^{212}$Bi at 1621 keV are mostly MSEs and are used as the background sample. More information on pulse shapes from semi-coaxial and BEGe detectors and about the details of the analysis can be found in [16].

Figure 9 shows the result of the PSD methods applied to data for the semi-coaxial and the BEGe detectors. The events surviving the PSD selection are shown in grey. The neural network method has a $0\nu\beta\beta$ acceptance of 90% while it rejects approximately half of the background around $Q_{3\beta}$. The A/E method has an efficiency of 92% and rejects 80% of the background events around $Q_{3\beta}$. On $2\nu\beta\beta$ events, the methods have an efficiency of 85% and 91% for the semi-coaxial and BEGe detectors, respectively.

6. Results on neutrinoless double beta decay of $^{76}$Ge

The combined energy spectrum from all enriched germanium detectors around the region of interest after unblinding is shown in figure 10, before (open histogram) and after (filled histogram) PSD selection. The energy region used for the background interpolation is shown in the lower panel.

After opening the blinded window, no excess of events was found above the expected background. Two analyses were performed to derive the lower limit for the half-life of $0\nu\beta\beta$ of $^{76}$Ge. The baseline analysis was a frequentist analysis, where a profile likelihood fit was performed to the datasets using a common half-life. The fit function was the sum of a constant term for the background and a gaussian term for the signal. The best fit corresponded to
zero counts and an upper limit of 3.5 counts. The derived lower limit for the half-life of $0\nu\beta\beta$ is $T_{1/2} > 2.1 \times 10^{25} \text{yr}$ at 90% confidence level, including the systematic uncertainty. The corresponding median sensitivity for the 90% C.L. limit is $T_{1/2} > 2.4 \times 10^{25} \text{yr}$. A second, Bayesian analysis was performed, using a flat prior on the inverse half-life in the $0 - 10^{-24} \text{yr}^{-1}$ range. The best fit was again zero counts corresponding to a lower limit of $T_{1/2} > 1.9 \times 10^{25} \text{yr}$ at 90% credible interval. The median sensitivity is $T_{1/2} > 1.9 \times 10^{25} \text{yr}$. The profile likelihood fit was also extended to include the energy spectra from IGEX and HdM experiments, giving a lower limit of $T_{1/2} > 3.0 \times 10^{25} \text{yr}$ at 90% confidence level. Constant background for all five datasets and gaussian peaks with a common half-life were assumed.

In order to compare the GERDA result with the signal claim, a hypothesis test was performed. The expected number of counts for the background only hypothesis, $H_0$, is $2 \pm 0.3$ in the $\pm \sigma$ window around $Q_{\beta\beta}$. As an alternative hypothesis, $H_1$, the claimed signal corresponding to a half-life of $T_{1/2} = 1.19 \times 10^{25} \text{yr}$ plus a background was considered, corresponding to $5.9 \pm 1.4$ expected counts. In figure 10, the exposure corrected expectation according to the signal claim is shown in dotted red line together with the lower limit derived from the GERDA analysis in blue. The number of observed counts is 3. Assuming the model $H_1$, the probability to obtain zero counts as the best fit from the profile likelihood analysis is 0.01. Also the Bayes factor, i.e. the ratio of the probabilities of the two models $P(H_1)/P(H_0)$, computed with the GERDA result alone as well as with the combined result is 0.024 and $2 \times 10^{-4}$, respectively, therefore the claim is strongly disfavoured. This comparison is restricted to the result of [9] and not [18], due to inconsistencies in the latter, pointed out in [19].

A comparison to the recent limits on the half-life of $^{136}\text{Xe}$ from KamLAND-Zen [20] and EXO-200 [21] is possible, assuming that the leading mechanism is the exchange of a light Majorana neutrino. The experimental results, the claimed signal and the different NME calculations are shown in figure 11.

7. GERDA Phase II

GERDA Phase II aims to improve the half-life sensitivity by another order of magnitude. The sensitivity as a function of the exposure for different background levels is shown in figure 12. An
order of magnitude improvement on the $0\nu\beta\beta$ half-life sensitivity is expected in approximately 5 years.

The size of the detector array is increased to 7 strings. The detectors are assembled in a dry nitrogen atmosphere. The new cable chain is made of selected stainless steel of low radioactivity. The Phase II cables exhibit more than a factor of 10 lower $^{228}$Th and $^{226}$Ra activities compared to Phase I cables.

The liquid argon will be instrumented with a scintillation background veto system. PMT arrays are installed above and below the detector array. Silicon photomultipliers coupled to wavelength shifting fibres surround the detector array. They will provide increased background reduction capability by detecting scintillation light in liquid argon. Pulse shape analysis in combination with the liquid argon veto provide a suppression factor of $5.2 \times 10^3$ at $Q_{\beta\beta}$ for a close $^{228}$Th source.

For Phase II, 30 new BEGe detectors were produced. A significant amount of copper and PTFE, for the detector modules, has been replaced by intrinsically radio pure silicon. The energy resolution (FWHM) of the detectors was determined with a $^{60}$Co source to be less than 1.9 keV at 1.3 MeV in vacuum. In addition, the A/E pulse shape discrimination, described in section 5, is a robust, simple and well-understood method of background rejection that was successfully implemented during Phase I. Finally, careful handling of the detectors during manufacturing and transportation insures a very low background contribution from $^{60}$Co and $^{68}$Ge due to cosmogenic activation.

8. Conclusions
Phase I of the GERDA experiment was completed successfully and the design goals were reached. A total exposure of 21.6 kg yr was accumulated. The background index at $Q_{\beta\beta}$ after pulse shape analysis was 0.01 cts/keV kg yr. A blinded analysis looking for the $0\nu\beta\beta$ decay of $^{76}$Ge was performed. No signal was observed and the most competitive limit on the half-life of this process for $^{76}$Ge was derived, strongly disfavouring the long standing claim of $0\nu\beta\beta$ signal observation.

The transition to GERDA Phase II is ongoing. An additional 20 kg of detector mass will be deployed. The new custom-made BEGe detectors have an excellent pulse shape discrimination capability and a subset of them was tested successfully during Phase I. A liquid argon instrumentation surrounding the detector array will be utilised for further background reduction. The background target of GERDA Phase II is $10^{-3}$ cts/keV kg yr, which will allow
the exploration of $^{76}\text{Ge} \, 0\nu\beta\beta$ half-life values in the $10^{26}$ yr range.

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