

The GERDA experiment: results and perspectives

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Abstract. The Germanium Detector Array, GERDA, at Laboratori Nazionali del Gran Sasso (Italy), is designed to search for Majorana neutrinos via neutrinoless double beta ($0\nu\beta\beta$) decay of ^{76}Ge . GERDA completed the Phase I in 2013, after an exposure of 21.6 kg-yr and with a background of about 0.01 cts/(keVkgyr): no signal was found and a limit on the half-life of $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.) was established. The previous claim of $0\nu\beta\beta$ observation for ^{76}Ge is strongly disfavoured in a model independent way. The commission for GERDA Phase II is currently ongoing and about 20 kg of additional enriched Ge diodes will be deployed. Pulse-shape analysis, together with the liquid argon instrumentation will allow to reach a background level one order of magnitude lower than in Phase I. In this paper the measurement of the half-life of $0\nu\beta\beta$ decay from GERDA Phase I and the expected sensitivity for Phase II are discussed.

1. Introduction

The observation of neutrinoless double beta decay ($0\nu\beta\beta$) probes fundamental questions about lepton number violation and neutrino properties, indeed it would give direct information on the possible “Majorana” nature of the neutrino and could determine the absolute neutrino mass complementary to other techniques. $0\nu\beta\beta$ decay could be observed experimentally as a narrow peak at the end-point of the $2\nu\beta\beta$ decay energy spectrum, corresponding to the Q-value ($Q_{\beta\beta}$) of the decay, given by the sum energy of the two emitted electrons. The GERDA experiment [1, 2, 3] searches for neutrinoless double beta decay of ^{76}Ge , in which ^{76}Ge ($Z=32$) would decay into ^{76}Se ($Z=34$) and two electrons. GERDA detectors are germanium semiconductors with an enrichment fraction in ^{76}Ge of about 86%. The crystals act as both the decay source and a 4π detector and their very good energy resolution translate in a narrow $0\nu\beta\beta$ peak at $Q_{\beta\beta}=2039$ keV.

2. The GERDA experiment

The GERDA experimental setup consists in an array of bare ^{enr}Ge (Ge detectors enriched in ^{76}Ge) semiconductors, placed in strings into a cryostat filled with liquid argon (LAr) and surrounded by an additional shield of ultra-pure water. Liquid argon is the cooling medium for the ^{enr}Ge detectors and also acts as shield against external gamma radiation from the cryostat walls. The water buffer provides the Cherenkov medium for the muon veto, attenuates the flux of the external γ radiation and absorbs neutrons. Further details about the GERDA experimental setup are reported in ref. [3]. Data acquisition of GERDA Phase I started on November, 2011 with nine p-type ^{enr}Ge semi-coaxial (HPGe) detectors (from the previous HdM

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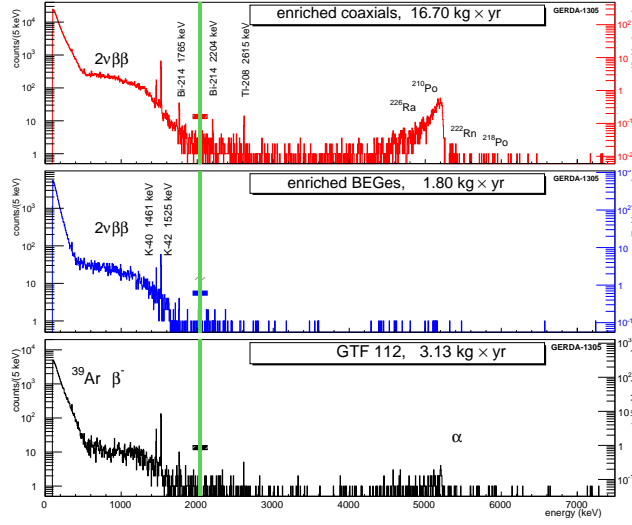


Figure 1. Spectra from enriched semi-coaxial (top), enriched BEGe (middle) and non-enriched (bottom) detectors of GERDA Phase I. The y-axis scale on the right-hand side indicates the number of counts divided per (keV·kg·yr). Plots from ref. [6].

and IGEX experiments) with a total mass of about 20.7 kg (17.7 kg enriched and 3 kg not enriched). Five Broad Energy Germanium diodes² (BEGes), were deployed on July 2012, with total mass of about 3.6 kg. The energy scale is determined by calibrating the detectors with ^{228}Th sources on a weekly basis. The exposure-weighted average energy resolution (FWHM), extrapolated at $Q_{\beta\beta}$, is (4.8 ± 0.2) keV for semi-coaxial detectors and (3.2 ± 0.2) keV for BEGes. Events in the region of interest (in the interval $Q_{\beta\beta} \pm 20$ keV) were kept “blinded”, *i.e.* not processed, until the calibration was finalized and all the selection cuts and analyses were fixed. The experimental energy spectra for the enriched and natural detectors are shown in fig. 1. The green boxes indicate the blinded window at $Q_{\beta\beta} \pm 20$ keV. Visible gamma peaks are from ^{40}K and ^{42}K decays and from the decay chains of ^{226}Ra and ^{232}Th . The low energy part of the spectrum is dominated by the β -decay of ^{39}Ar and events from $2\nu\beta\beta$ decay populate the range from 600 to 1800 keV; the half-life of $2\nu\beta\beta$ decay for ^{76}Ge has been measured after collecting an exposure of 5.04 kg·yr (see ref. [5]). Above 4000 keV the background is dominated by α decays of ^{210}Po and ^{226}Ra . The energy spectrum from semi-coaxial and BEGe detectors is fitted to a background model in the range between 570 and 7500 keV (for further details see ref. [6]): the background is mainly due to sources close to the detectors or on the detector surface and no peak is expected to appear in the region of interest. In this region, with the exclusion of ± 5 keV around the expected position of the single escape peak from ^{208}Tl (2104 keV) and of the γ line from ^{214}Bi (2119 keV), the interpolated value for the background index (BI) is $\text{BI} = 1.75_{-0.24}^{+0.26} \times 10^{-2}$ cts/(keV·kg·yr) for semi-coaxial detectors and $\text{BI} = 3.6_{-1.0}^{+1.3} \times 10^{-2}$ cts/(keV·kg·yr) for the BEGe detectors. Detector signals are read out independently by a charge sensitive amplifier; the signal is then digitized by 100 MHz Flash ADCs and physical parameters like energy and risetime of the signal are reconstructed by digital filters [7]. The specific pulse shape of $0\nu\beta\beta$ events in GERDA detectors is used to discriminate them from background events. In GERDA Phase I two different methods for Pulse Shape Discrimination (PSD) have been developed, according to the different characteristics of the pulses and electric field distributions of semi-coaxial and BEGe detectors [8]. For a review of the GERDA experiment see also ref. [9].

² manufactured by Canberra in Olen, Belgium

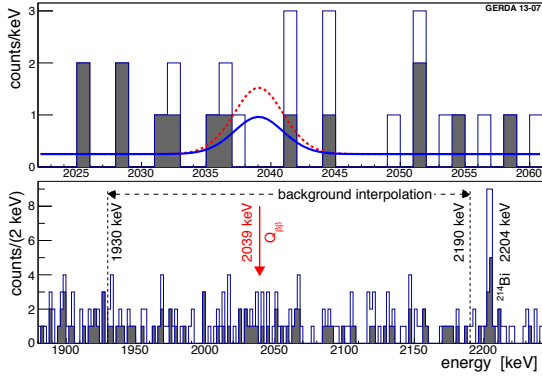


Figure 2. Energy spectrum from all ^{enr}Ge detectors before (filled) and after (open) the PSD selection. In the upper panel the expectation based on the central value of the half-life estimated by ref. [12] is also shown (red), together with the 90% C.L. limit estimated by GERDA Phase I (blue). In the lower panel the energy window used for the background interpolation is indicated. Plot from ref. [4].

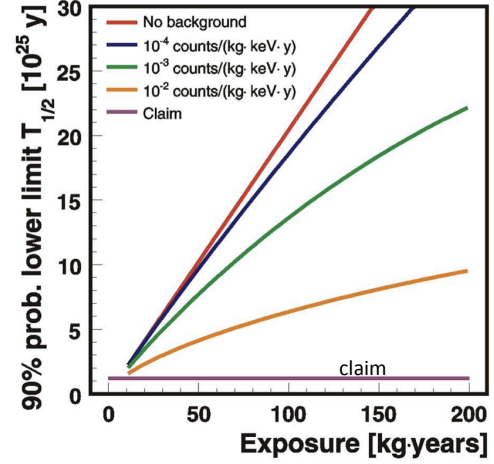


Figure 3. GERDA sensitivity on $0\nu\beta\beta$ half-life as a function of the collected exposure. The different lines correspond to different values of the background level. The expected background for GERDA Phase II is 10^{-3} counts/(keV·kg·yr).

3. Results on $0\nu\beta\beta$ decay of ^{76}Ge

After the collection of an exposure of 21.6 kg·yr from GERDA Phase I, a limit on the half-life of $0\nu\beta\beta$ decay in ^{76}Ge was established [4]. Phase I data were divided into three different sets: data from the BEGe detectors (“BEGe” set), data from semi-coaxial detectors in the time period when the BEGe detectors were deployed (“silver” set) and remaining data from semi-coaxial detectors (“golden” set). “Unblinded” data showed a flat background in the region of interest, with seven events observed while 5.1 ± 0.5 were expected from background interpolation. After the PSD was applied, three events from the semi-coaxial detectors and the one from the BEGe detector were classified as background. No event remains in the energy window $Q_{\beta\beta} \pm \sigma_E$ and the corresponding BI becomes 10^{-2} cts/(keV·kg·yr). The observed spectrum was fitted with a profile likelihood fit; the fitted function contains three constant terms for the background (for the three data sets) and a Gaussian peak, centered at $Q_{\beta\beta}$ and with standard deviation according to the energy resolution. The four corresponding parameters of the function were the three terms for the background and $1/T_{1/2}^{0\nu}$. The limit on the half-life is $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.) and the best fit value for the number of $0\nu\beta\beta$ events is $N^{0\nu} = 0$. The corresponding limit on the number of signal events is $N^{0\nu} < 3.5$ counts. The median sensitivity for the 90% C.L. limit, given the background levels and the efficiencies, is $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25}$ yr. The systematic uncertainties due to detector parameters, selection efficiency, energy resolution and energy scale, were folded into the half-life estimation; they weaken the limit by about 1.5%. A Bayesian analysis [10] was also performed (using the BAT toolkit [11]) with the same fit and a flat prior distribution for $1/T_{1/2}^{0\nu}$ between 0 and 10^{-24} yr $^{-1}$. The corresponding result for the limit is $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr, with a median sensitivity of $T_{1/2}^{0\nu} > 2.0 \cdot 10^{25}$ yr. The GERDA result does not support the previous claim of $0\nu\beta\beta$ decay observation in ^{76}Ge [12]. The Bayes factor, *i.e.* the ratio between the probability that the observed data D are produced according to the model H_1 ($0\nu\beta\beta$ with half-life $T_{1/2}^{0\nu}$ from ref. [12]) and the probability that they are produced according to the model

H_0 (only background), is $P(D|H_1)/P(D|H_0) = 0.024$. In fig. 2 the “unblinded” spectrum is shown, together with the likelihood fit and the expectation based on the claim from ref. [12]. A combined profile likelihood fit, when GERDA data are combined with data from the HdM [13] and IGEX [14] experiments, gives again $N^{0\nu} = 0$ as best fit and $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (90% C.L.). Considering this limit, the phase-space factor for the ^{76}Ge [15] and the nuclear matrix element calculations reported in refs. from [16] to [22] (scaling the different g_A and R_A parameters according to ref. [23]), the derived upper limits on the effective electron neutrino mass range between 0.2 and 0.4 eV. A Bayesian analysis gives the same limit and a Bayes factor equal to $P(D|H_1)/P(D|H_0) = 2 \cdot 10^{-4}$.

4. Phase II upgrades

The main goal of GERDA Phase II is to increase the sensitivity with respect to Phase I, by lowering the background level and increasing the total collected exposure. The background level will be reduced thanks to the implementation of a LAr scintillation veto and the procurement of 30 additional enriched BEGe detectors, to achieve a total mass of about 40 kg. The scintillation veto consists in the detection of the 128 nm scintillation light generated in liquid argon by radioactive background decays or cosmic muons, accompanied with the emission of gamma particles which eventually excite the argon. A curtain made of light-guiding fibers surrounding the detector strings will collect the light, eventually read out by Silicon Photo-Multipliers (SiPMs) on the top of the array. In addition, light will be also directly detected by PMTs coated by wavelength shifter and placed on top and bottom of the detector array. Residual background contamination will be rejected by the Pulse Shape Discrimination, as described in ref. [8]. The expected background index for GERDA Phase II, when the combination of LAr veto and Pulse Shape Discrimination is used, is of the order of 10^{-3} cts/(keV·kg·yr). The commissioning of the Phase II upgrade of GERDA is presently ongoing. The sensitivity of GERDA as a function of the total collected exposure is shown in fig. 3. With the increased total mass of enriched germanium an exposure of 100 kg·yr will be reached in about 3 years. The corresponding sensitivity on the half-life of $0\nu\beta\beta$ decay is $T_{1/2}^{0\nu} \simeq 1.4 \cdot 10^{26}$ yr.

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