3 GERDA: Neutrinoless Double Beta Decay in ^{76}Ge

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(GERDA Collaboration)

All results from neutrino oscillation experiments indicate that neutrinos are massive [1]. Such experiments are insensitive to the absolute mass scale of neutrinos, but this can instead be extracted from kinematic studies of beta decays, and from the neutrinoless double beta ($0\nu\beta\beta$) decay. Moreover, the observation of this decay would prove that the neutrino is a Majorana fermion and that lepton number is violated in nature.

The most stringent upper limit on the half-life of this decay for ^{76}Ge comes from the Germanium Detector Array (GERDA) [2], as detailed below. Existing and future neutrinoless double beta decay experiments should be able to probe the so-called degenerate and inverted mass hierarchy regions, testing the effective Majorana neutrino mass down to ~10-50 meV (see [3] for a recent review, including future projects).

[1] M. Gonzalez-Garcia, Phys. Dark Univ **4** (2014) 1-5.

[2] M. Agostini *et al.*,Nature **544** (2017) 47-52.

[3] R. Henning, Rev. Phys. **1** (2016) 29-35.

3.1 The GERDA Experiment

The GERDA experiment aims to detect $0\nu\beta\beta$ decay of ^{76}Ge, and is currently acquiring science data at Laboratori Nazionali del Gran Sasso (LNGS). GERDA uses high-purity germanium diodes, enriched in ^{76}Ge. The diodes, arranged in seven strings, act simultaneously as the detector and source material and are submerged in liquid argon (LAr). A water Cherenkov veto surrounds the LAr cryostat, to reject interactions from cosmic muons. Filled with ultra-pure water, the water tank also provides shielding against external radiation.

In the first stage of the experiment (Phase I), which lasted from 2011 to 2013, ten detectors with an active mass of 15 kg were used, resulting in a total exposure of 21.6 kg·y. A tenfold lower background than in previous experiments was obtained, with 1×10^{-2} events/(keV·kg·y) at the Q-value of the decay ($Q_{\beta\beta}$). No $0\nu\beta\beta$-decay signal was observed in Phase I, and a lower limit of $T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}$ y at 90% C.L. for the half-life of the decay was derived [4].

During the experiment's upgrade (Phase II) in the spring of 2015, new, enriched Broad Energy Germanium (BEGe) detectors were built, extensively tested and mounted into the LAr cryostat [5], and an active LAr veto system was installed at LNGS. The aim of this stage is to reach a sensitivity of $T_{1/2}^{0\nu\beta\beta} = O(10^{26})$y with a background index of 10^{-3} events/(keV·kg·y) after an exposure of ~100 kg·y. By December 2015, all 40 detectors were installed and characterised, and the Phase II data taking of GERDA started. Our group has contributed to the tests of the BEGe detectors, to the liquid argon veto [6], to the upgraded calibration system hardware and software and to new, low-neutron-emission ^{228}Th sources.

The LAr veto, shown in Fig. 3.1, left, is equipped with photomultiplier tubes and silicon photomultipliers (SiPMs) to detect the scintillation light induced by interactions in the argon, triggered by an event in a germanium detector. All channels are working and the LAr veto's performance is stable in time. Figure 3.1, right, shows the acquired background energy spectrum, including the effect of the argon veto.

The first five months of GERDA Phase II data were unblinded in June 2016. In the analysis, the Phase I data were considered as well, including a data period that was not used in the first publication. Hence the total exposure is 34.4 kg·y. The background level in the BeGe detectors in Phase II is $0.7^{+1.1}_{-0.5} \times 10^{-3}$ events/(keV·kg·y), meaning that the background goal of Phase II has been reached. There was no signal for $0\nu\beta\beta$ decay in the combined data set, and we thus place an improved lower limit on the half-life of $T_{1/2}^{0\nu\beta\beta} > 5.2 \times 10^{25}$ y (90% C.L.) [7].

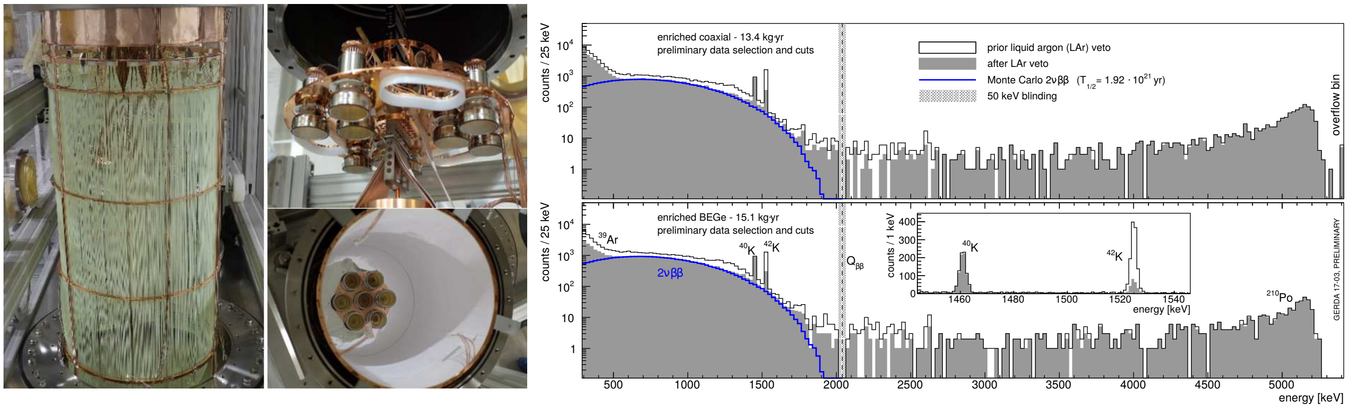

FIG. 3.1 – (Left): Picture of the liquid argon veto system: fibre curtain with SiPM readout at the top, and top and bottom arrangement of PMTs with the coated, wavelength shifting reflector foil. (Right): Energy spectra of Phase II data sets before (open histogram) and after the argon veto (filled histogram). The expected $2\nu\beta\beta$ spectrum (blue line) is also shown, as well as the sum spectrum around the two potassium lines (^{40}K peak at 1461 keV, and the ^{42}K peak at 1525 keV) in the insert.

GERDA-Upgrade is a step towards a 200 kg stage, to be constructed at LNGS by the new collaboration, LEGEND, (recently formed by GERDA, MAJORANA and other groups), which itself is the precursor of a future, ton-scale ^{76}Ge experiment. The aimed sensitivities are $T_{1/2}^{0\nu\beta\beta} > 10^{26}$ y and $T_{1/2}^{0\nu\beta\beta} > 10^{27}$ y for GERDA-Upgrade and the 200 kg stage, respectively.

In the following we detail our recent contributions to GERDA.

[4] Gerda Collaboration, M. Agostini *et al.*, Phys. Rev. Lett. **111** (2013) 122503.

[5] M. Agostini *et al.*, Eur. Phys. J. C75 **2** (2015) 39.

[6] L. Baudis, G. Benato, R. Dressler, F. Piastra, I. Usoltsev, M. Walter, JINST **10.09** (2015) P09009.

[7] M. Agostini *et al.*, Nature **544** (2017) 47-52.

3.2 Energy calibration

The GERDA experiment is calibrated by temporarily exposing the germanium detectors to ^{228}Th sources and evaluating the position of known emission lines in the recorded energy spectrum. Our group is part of the calibration team which performs the weekly calibrations, and we are responsible for analysing and evaluating the calibration data.

For the main result of GERDA Phase II, the $0\nu\beta\beta$-search, we determined the energy resolution for BEGe-type detectors and coaxial-type detectors to be 3.0±0.2 keV and 4.0±0.2 keV, respectively, with an estimated systematic uncertainty on the energy scale of 0.2 keV [8]. The combined data for evaluating the resolution is shown in Fig. 3.2. The evaluation of the full systematic uncertainties is an ongoing effort.

Furthermore, we maintain and develop the analysis framework used for calibration. Currently, we are optimising and parallelising it to meet the rising performance demands of the ever increasing amount of data and detector channels. In addition, we aim to improve the user interface and algorithm to more easily distribute calibration analysis work and monitoring, especially with regard to the upcoming, larger LEGEND experiment. We maintain the hardware of the existing calibration systems, and we produced the currently employed calibration sources [9]. For the upgraded phase of GERDA, we will produce another batch of 3-4 ^{228}Th sources with a low neutron-emission rate as a replacement for the existing ones, given the short ^{228}Th half-life of 1.9 yr.

[8] M. Agostini *et al.*, Nature **544** (2017) 47-52.

[9] L. Baudis, G. Benato, P. Carconi, C. M. Cattadori, P. De Felice, K. Eberhardt, R. Eichler, A. Petrucci, M. Tarka, M. Walter, JINST **10.12** (2015) P12005.

3.3 Pulse shape simulations and background model

Understanding and modelling the background of GERDA is key to the interpretion of physics data. We participate in the background modelling effort, based on Monte Carlo simulations of decays of radioactive isotopes in detector materials, using the measured activity levels [10]. Currently, these simulations are limited to the energy deposition inside the germanium detectors, and do not include the signal generation in the Ge diodes. Consequently, the impact of the detector response and signal processing, as well as the pulse shape properties required for pulse shape discrimination (PSD), cannot be accurately accounted for. We are implementing a code for pulse shape simulation, based on the ADL libraries [11], into the common simulation framework of the GERDA and MAJORANA collaborations, MaGe [12]. We have performed

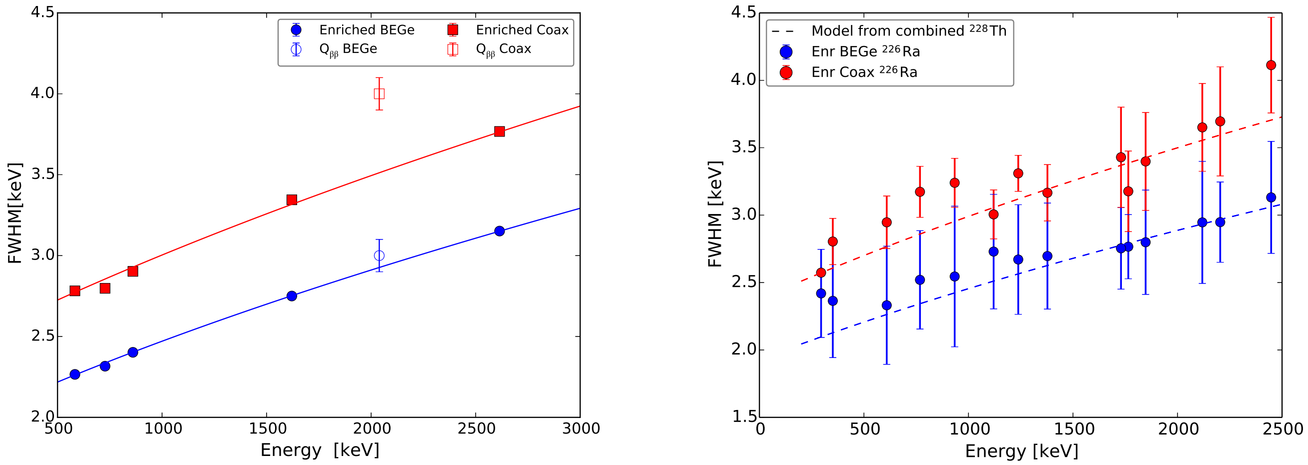

Fig. 3.2 – (Left): The energy resolution, determined from the combined calibration data set with ^{228}Th sources, for BEGe (blue) and coaxial (red) type detectors, respectively, as a function of energy. To explain the energy resolution of the physics data (hollow markers) at $Q_{\beta\beta}$, additional, systematic effects have to be taken into account. (Right): The resolution for BEGe (blue) and coaxial (red) detectors, obtained from calibration data with a ^{226}Ra source. The aim was to cross check the ^{228}Th calibration results, and extend the range to lower energies. The dashed lines represent the model obtained from ^{228}Th calibration data. Here the error bars reflect the spread in resolution over individual detectors.

simulations of the electric field and weighting potential, required for calculating the induced charge on the read-out electrode for BEGe detectors (examples are shown in Fig. 3.3, left and centre). Together with our interface to extract the detector geometry of individual germanium detectors and energy deposits directly from MaGe, pulse shape simulations can now be performed from individually simulated energy deposits. An example of a simulated signal in a BEGe type detector is shown in Fig. 3.3, right. Our immediate plan is to include static and dynamic noise components, and ultimately perform realistic end-to-end simulations of interactions in the BEGe detectors. After the development of the simulation software is completed, it will be validated by comparing it to calibration and science data.

With accurate pulse shape simulations, we can treat our Monte Carlo simulations of the various background components in the same way as our physics data. By using the identical data analysis chain we can thus create a complete background model that includes PSD. Since PSD strongly affects the spectral shape of our remaining background, this variation must be reproduced by the background model, possibly leading to the identification of new components. We will also increase the accuracy of the model by re-simulating components strongly affected by the active volume size of the Ge diodes with improved knowledge of the dead-layer extent.

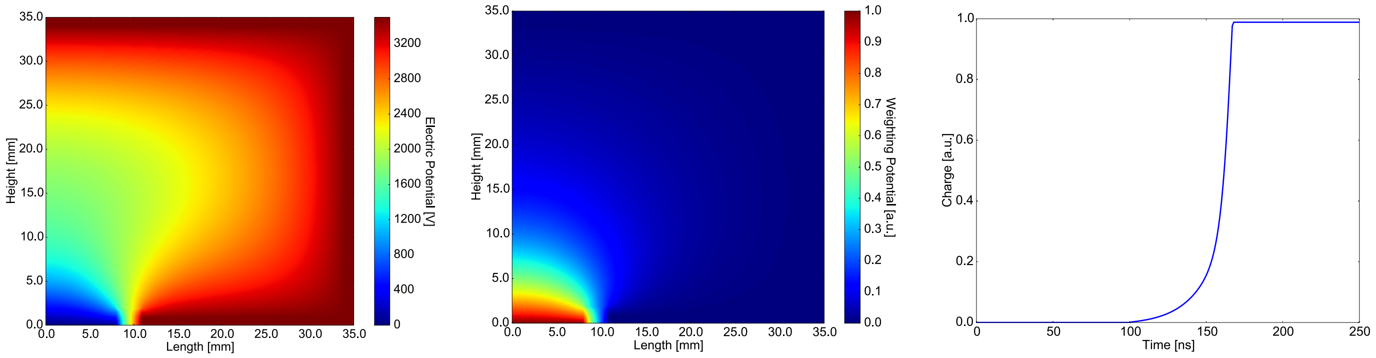

Fig. 3.3 – (Left, centre): Simulation of the electric field and weighting potential in a BEGe type detector. These potentials are used to calculated the drift paths of charge carriers and the induced charge on the electrodes for pulse shape simulations. (Right): Simulated charge signal on the read-out electrode of a detector.

[10] M. Agostini, *et al.*, Eur. Phys. J. C **74.4** (2014) 2764.

[11] B. Bruyneel, B. Birkenbach, P. Reiter, Eur. Phys. J. A **52.3** (2016) 70.

[12] M. Boswell, *et al.*, IEEE Trans. Nucl. Sci. **58** (2011) 1212-1220.

3.4 PMTs for direct detection of scintillation light in liquid argon

One of the distinctive features of GERDA is the liquid argon veto. It enables detection and rejection of background events with an energy deposit in the liquid argon. Liquid argon scintillation light has a wavelength of 128 nm and cannot easily be detected, as there are very few materials transparent to this light, including the quartz windows of the PMTs used in the experiment. Instead, we wavelength shift the light to optical wavelengths using foils surrounding each detector string and a curtain of fibres, coated with a wavelength shifting material. The downsides of this technique are the limited geometrical coverage, and the introduction of additional materials into the LAr cryostat.

One material transparent to liquid argon scintillation light is MgF_2. We tested one 3-inch R11065 PMT from Hamamatsu with a MgF_2 window during operation at room temperature, and in cryogenic nitrogen and liquid argon environments using our PMT testing facilities. (LArS and Sandbox), measuring the PMT's characteristic properties: gain, dark count rate and after-pulse rate. We obtained a gain of 6.5×10^6 at a nominal operating voltage of 1500 V, similar to values for the regular version of this PMT. To confirm the detection of liquid argon scintillation light, measurements with an alpha-emitting ^{241}Am source inside LArS were taken. The mean recorded waveform is shown in Fig. 3.4. It displays the intensity of light after the first detected photon. Its form is characteristic for the liquid argon scintillation light, as the intensity follows the exponential de-excitation rates of the short (here ∼7.8 ns) and long (here ∼1.4 µs) lived excited states responsible for the scintillation.

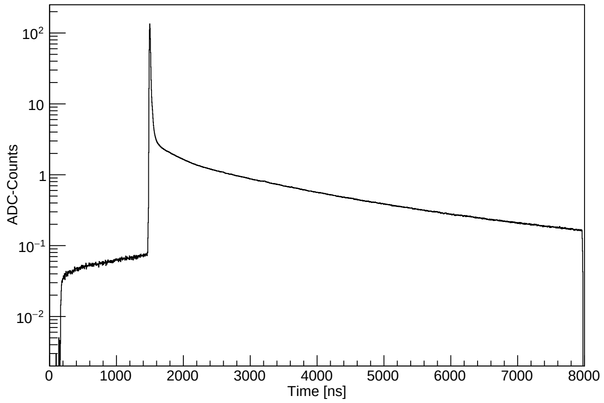

FIG. 3.4 – Average waveform, recorded with the PMT with MgF_2 window in liquid argon with an alpha-emitting source.

We also tested the leak tightness of the tube, by observing the rate of after-pulses and in particular ion-initiated after-pulses in several measurements in nitrogen and argon over the course of about a year. Ion-initiated after-pulses were identified by their characteristic delay relative to the trigger pulse. The after-pulse rate was acceptable, even after several cool-down/warm-up stress cycles, and did not degrade over time: as an example, the relative rate (per triggered photoelectron) in the nitrogen peak was 7.2×10^{-4}% and 8.8×10^{-4}% a year ago and in a recent measurement, respectively, while the total relative after-pulse rates were 0.37% and 0.34%.

We aim to confirm these results, and test for micro-light emission (observed in some of the R11410 PMTs) by operating at least two units face-to-face, over a longer period of time to prove their applicability in liquid argon cryostats. This is of interest to several planned experiments in the low-background community, including LEGEND. If successful, we plan to investigate the possibility to realise a liquid argon veto, where the standard PMTs are replaced by those with MgF_2 windows.

3.5 Super-WIMP search

With its unprecedented low background, GERDA may be sensitive to bosonic super-WIMPs [13] with masses up to 1 MeV in the low energy region of the energy spectrum. Bosonic super-WIMPs can be completely absorbed by a germanium atom via the axio-electric effect and result in a peak in the energy spectrum, centred around their rest mass. Existing limits, obtained by other germanium- and xenon-based experiments, reach up to 145 keV [14, 15]. With this analysis, we aim to extend the direct search range for bosonic super-WIMPs to 1 MeV. In Fig. 3.5 examples of expected event rates for various couplings in the pseudo-scalar particle case, and of the corresponding signatures in the GERDA energy spectrum are shown.

For this analysis, the performance of the Ge detectors, currently optimised on the high-energy range around 2039 keV, has to be evaluated at low energies. We performed a special calibration with a ^{226}Ra source to determine the quality of the energy reconstruction and resolution down to the low energy threshold around 175 keV. No hints of a significant degradation of the energy reconstruction were found towards low energies and the resolution (at FWHM), shown in Fig. 3.2, right, is in the range 2-3 keV. Furthermore we plan to extend the background model, currently limited to an energy threshold of 600 keV, to low energies and investigate the possibility to reduce the background in this region by means

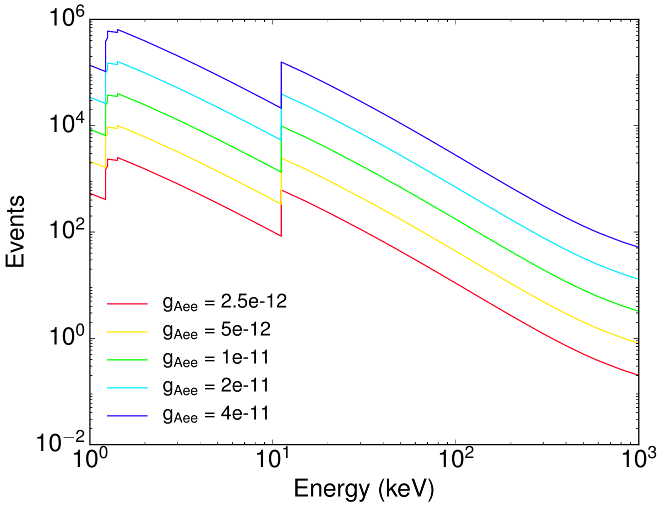

FIG. 3.5 – Expected total number of events from pseudoscalar super-WIMPs of various coupling strengths to electrons, with a GERDA exposure of 5.8 kg·yr.

of PSD. While above 1 MeV the background rejection by PSD is well established [16], it was suggested that its performance breaks down below these energies, due to the higher impact of noise. By adding measured noise traces to signal traces and analysing the impact on the PSD, we found the background rejection, for example for multi-site events, degrades due to noise from 80-90% at high energies to around 50% at the low energy threshold. This must be cross-checked by detailed pulse shape simulations, as mentioned above. We thus plan to adapt and use the PSD methods developed for high energies at the lower end of the energy spectrum.

[13] M. Pospelov, A. Ritz, M. B. Voloshin,
Phys. Rev D **78** (2008) 115012.

[14] K. Abe, *et al.*,
Nucl. Instrum. Meth. A **716** (2013) 78-85.

[15] N. Abgrall, *et al.*, arXiv[nucl-ex] (2016) 1612.00886.

[16] M. Agostini, *et al.*, Eur. Phys. J. C **73.10** (2013) 2583.

3.6 The GERDA Upgrade

Considering the initial results from Phase II, only a fraction of a background event is expected in the region of interest in the entire exposure of this phase. Thus, GERDA is the first "background-free" experiment in the field, and sensitivity grows linearly with time. It will reach $T_{1/2}^{0\nu\beta\beta} \sim 10^{26}$ y in three years of continuous operation. GERDA has validated the concept of background suppression by the use of a liquid argon veto and pulse shape analysis, and shown that it is suitable to reach an extremely low background level with a high discovery potential.

The background at the Q-value of the $0\nu\beta\beta$-decay is world-best: it is lower by a factor of ten compared to experiments using other isotopes, after normalisation by the energy resolution and the total efficiency. Hereby, the GERDA half-life sensitivity is similar to that of KAMLAND-ZEN for ^{136}Xe, despite KAMLAND-ZEN experiment's 10-fold larger exposure. Thus, it is well-motivated to increase the overall GERDA detector mass, in order to increase sensitivity, and reach the 10^{26} y half-life goal on a faster timescale. A discovery of $0\nu\beta\beta$ decay would have far-reaching implications for cosmology and particle physics. To make a convincing case for such a discovery, an ultra-low background level, an excellent energy resolution as well as the possibility to distinguish a signal-like event from an unknown gamma-line from a nuclear transition is mandatory. The latter is achieved in GERDA by pulse shape analysis and a potential signature in the liquid argon.

The cryostat used by GERDA can house up to 200 kg of detectors, and such an arrangement would be background-free up to an exposure of 1000 kg·y. The first step (GERDA-Upgrade) is to replace the inner detector string made of detectors with natural Ge composition with 7–8 new, enriched Ge detectors. The subsequent step, in the framework of the new collaboration LEGEND, is to operate a total of 200 kg of Ge diodes in an upgraded infrastructure at LNGS. This would be a first step towards a ton-scale ^{76}Ge experiment, to be constructed within a larger international collaboration. GERDA-Upgrade would demonstrate another milestone in background reduction, since a level of $\sim 10^{-4}$ events/(keV·kg·y) is required for the 200 kg stage. This is to be achieved by replacing the cables with existing, lower-radioactivity versions, and by improving the light yield of the liquid argon veto.