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Phase II upgrade of the GERDA experiment for the search of neutrinoless double beta decay

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Abstract

Observation of neutrinoless double beta decay could answer the question regarding the Majorana or Dirac nature of neutrinos. The GERDA experiment utilizes HPGe detectors enriched with the isotope ^{76}Ge to search for this process. Recently the GERDA collaboration has unblinded data of Phase I of the experiment. In order to further improve the sensitivity of the experiment, additionally to the coaxial detectors used, 30 BEGe detectors made from germanium enriched in ^{76}Ge will be deployed in GERDA Phase II.

BEGe detectors have superior PSD capability, thus the background can be further reduced. The liquid argon surrounding the detector array will be instrumented in order to reject background by detecting scintillation light induced in the liquid argon by radiation. After a short introduction the hardware preparations for GERDA Phase II as well as the processing and characterization of the 30 BEGe detectors are discussed.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: $0\nu\beta\beta$ decay, neutrino mass, Lepton number violation, Majorana neutrino

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1. Introduction

Since the unambiguous observation of neutrino oscillations [1] it is clear that they must have a small but non vanishing mass. The property that neutrinos are their own CP conjugate, ie. Majorana particles, could explain naturally why they have a tiny mass. In this case neutrinoless double beta ($0\nu\beta\beta$) decay, a lepton number violating process, would be allowed and could be observable for some isotopes like ^{76}Ge or ^{136}Xe. While $2\nu\beta\beta$ decay, allowed in the standard model of particle physics, has been observed for many isotopes, the neutrinoless mode could not yet be observed without doubt. The presently most stringent limits for $0\nu\beta\beta$ decay come from experiments using ^{76}Ge or ^{136}Xe. The GERDA experiment utilizes high purity germanium (HPGe) detectors enriched with the isotope ^{76}Ge to search for $0\nu\beta\beta$ decay of ^{76}Ge. In the upcoming Phase II of the experiment special HPGe detectors, so called broad energy germanium (BEGe) detectors will be used. In the following the design of the GERDA experiments is shortly discussed and the special properties of BEGes leading to enhanced pulse shape discrimination power are described. The status of the preparations for the upgrade to Phase II of the experiments are presented.

2. GERDA Phase II with BEGe detectors

The design of the Germanium Detector Array (GERDA) experiment is based on the idea of operating bare HPGe detectors in a cryogenic liquid [2]. The cryogenic liquid acts as ultra low background shielding

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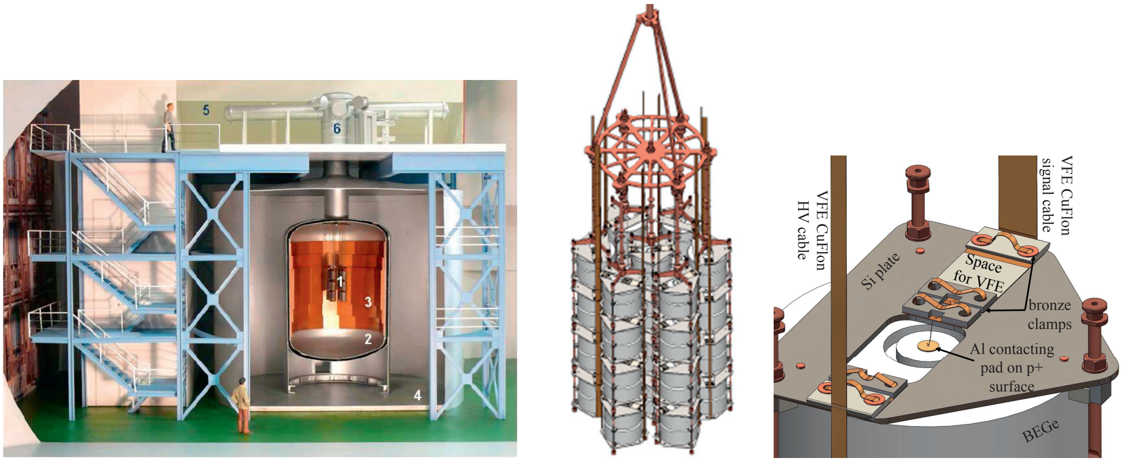

Fig. 1. *left*: Schematic model of the GERDA experiment. Some components are labelled with numbers. 1: Detector array, 2: cryostat, 3: copper lining, 4: water tank, 5: clean room, 6: lock system. *center*: Drawing of the detector array for Phase II. *right*: Schematic drawing of contacting scheme on the Si plates of the detector holders.

against external radiation and as a cooling medium for the HPGe detectors simultaneously. A schematic of the GERDA setup is shown in Fig. 1. The experiment is located in the INFN Gran Sasso National Laboratory with an overburden of 3500 mwe in order to protect against cosmic radiation. An array of HPGe detectors is placed inside a cryostat, 4 m in diameter, filled with liquid Argon (LAr). The cryostat is produced from specially selected steel. Its inner wall is covered with a layer of low background copper to shield against the non zero radio impurities of the steel [3]. The cryostat is placed within a water tank, 10 m in diameter serving as additional radio pure shield against external radiation. The water tank is instrumented with 66 photo multiplier tubes (PMTs) serving as detectors for Čerenkov light emitted by muons passing the water tank. An additional scintillator veto system is placed on the roof of the experiment. HPGe detectors can be deployed to the cryostat through a lock system housed on top of the cryostat inside a class ISO5 clean room. The technical details of the experiment can be found in [4].

In a first phase of the experiment the coaxial HPGe detectors from the Heidelberg-Moscow [5] and IGEX [6] experiments have been used. From the absence of a peak like structure at the Q-value at 2039 keV a lower limit on ${}^{0\nu\beta\beta}T_{1/2}$ of ^{76}Ge of $2.1 \cdot 10^{25}$ yr has been obtained [7].

In the upcoming second phase additionally to the Phase I detectors 30 BEGe detectors with a total mass of 20.1 kg will be used. The background index (BI) of the experiment will be reduced by using pulse shape discrimination (PSD) of the BEGe detectors and the additional readout of scintillation light in the liquid Argon surrounding the detectors. With a total exposure of 100 kg yr and a BI of 10^{-3}counts/(keV kg yr) the limit setting sensitivity on ${}^{0\nu\beta\beta}T_{1/2}$ of ^{76}Ge of the experiment can be improved to 10^{26} yr (90%C.L).

BEGe detectors have a pronounced weighting potential around the read out electrode. Due to the special electric field configuration inside the detector volume, charge carriers induced by interactions of radiation with the detector material drift towards the read out electrode on the same path through the volumes of the detector with significant weighting potential (see Fig. 2 *left* for an illustration). Hence, all current pulses from single site events (SSEs) taking place inside the detector with the same energy have the same amplitude, A. Events with more than one interaction inside the detector volume have pulse shapes that can be described by a superposition of pulse shapes of individual energy deposits. This allows to distinguish signal like SSEs from background like multi site events (MSEs) using the ratio A/E, where E is the total energy deposited in the detector. Charge carriers induced by events happening close to or on the electrode, the p^+ surface, have an increased displacement current, hence the A/E ratio of these pulses is increased. Charge carriers induced by events on the outer mantle, the n^+ surface, can reach the active volume by diffusion through the dead layer of the detector. The charge carrier diffusion time is longer than the drift time through the detector, hence these current pulses are longer and have smaller A/E ratio [8, 10]. Fig. 2 *right* shows schematically

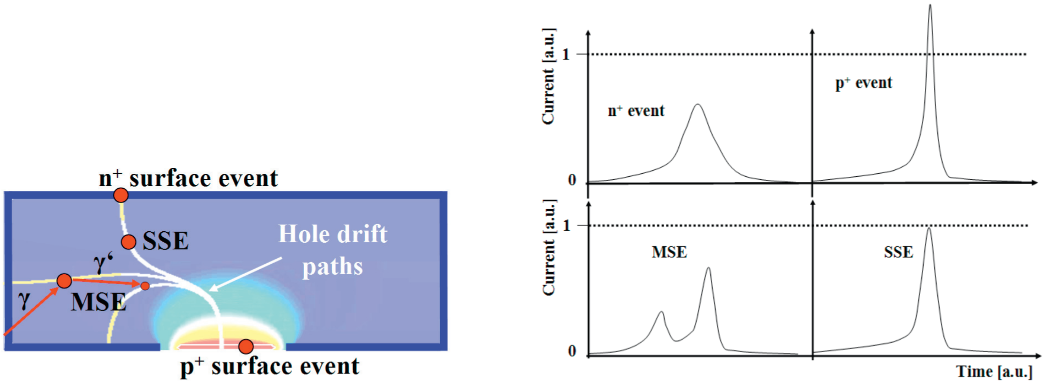

Fig. 2. *left:* Schematic view of a BEGe detector and the types of interactions that can be identified using PSA. *right*: Schematic pulse shapes from different type of events. For details see text.

the pulse shapes of different events.

In the second phase of Gerda 30 BEGe detectors and the 8 Phase I coaxial detectors will be arranged in 7 strings housing up to 8 BEGe detectors or 3 Phase I detectors each. Fig. 1 *center* shows a drawing of the detector array. In order to mount all detectors and to move the array with a total weight of 60 kg (including LAr instrumentation) and a total of 238 cables inside one cable chain into the cryostat a new lock system had to be designed and constructed.

37.5 kg of germanium isotopically enriched in the isotope ^{76}Ge to ≈ 88% has been procured in the form of GeO_2 from ECP, Zelenogorsk in Russia.

The GeO_2 has been reduced and zone refined to electronic grade 6N material in form of 35.5 kg of metallic bars by PPM Pure Metals GmbH in Langelsheim, Germany (see Fig. 3, *left*). This corresponds to an efficiency of 94%. No isotopic dilution is expected as in an earlier test using isotopically shifted gerrmanium no change in isotopic abundances could be detected at the level of 0.01% using ICPMS measurements [9].

At Canberra Industries Inc., Oak Ridge, TN, USA this material was used to grow HPGe crystals suitable for producing crystal slices for BEGe detector production. In total 30 slices with an average diameter and height of of (73.3±2.8) mm and (29.7±3.1) mm, respectively, were obtained. The combined mass of the crystal 30 slices was 20.77 kg with the weight of individual slices ranging from 470 g to 835 g. The 30 germanium crystal slices have been converted to working BEGe detectors at Canberra Semiconductors N.V., Olen, Belgium.

All 30 detectors have been characterized by calibration measurements in vacuum at the HADES underground facility. All are fulfilling the specified requirements: The energy resolution was better then 2.3 keV at 1333 keV, while the leakage current was less then 50 pA at an operational voltage of less then 4 kV for all 30 detectors. The overall mass of the detectors is 20.0 kg, corresponding to an overall mass yield from GeO_2 to working BEGe detectors of 53.4%.

All detectors are presently stored at the LNGS underground laboratory. In total 8.8 kg of material in form of crystal remainders and 5.5 kg of material in form of kerf (sawdust mixed with water and lubricants) have been collected. This material will be reprocessed to electrical grade 6N material and can later be converted to BEGes.

During the whole production sequence great care was taken to shield the enriched germanium against cosmic activation. The production times at the different unshielded sites were minimized. Whenever the material was not processed or needed at the production site it was stored in locations shielded against cosmogenic radiation. Transport of the enriched germanium happened inside a container with 70 cm steel and an additional 70 cm of salt water shield (see Fig. 3 *center*). The history of exposure to cosmic rays was recorded in a data base for each individual germanium sample for all processing steps. Fig. 3 *right* shows the history of activation of one of the detectors with ^{68}Ge with the assumption of a constant activation rate at sea level as calculated in [11] and shielding efficiencies of the different shielded sites obtained by MC

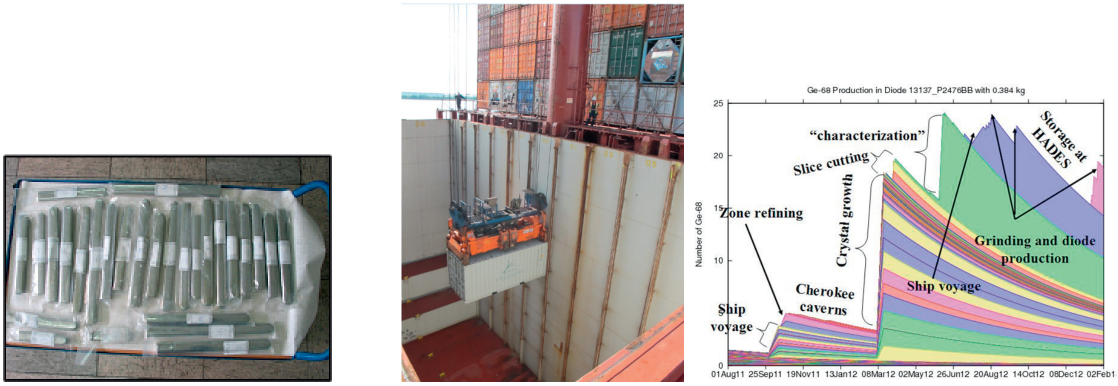

Fig. 3. *left*: Bars of zone refined germanium used for crystal growth. *center*: Shielding container being loaded to the bottom most storage place of the container ship transporting the zone refined bars across the Atlantic ocean. *right*: History of activation of one of the BEGe detectors as derived from tracking of the exposure of the enriched materials to cosmic rays.

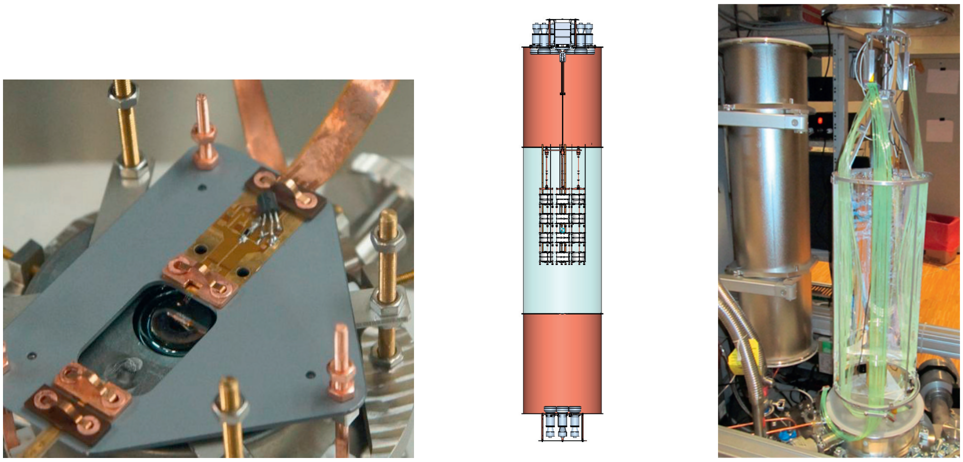

Fig. 4. *left*: BEGe detector contacted by bonding to prototype front end electronics on a silicon holder board. *center*: Schematic sketch of detector string surrounded by the PMT LAr instrumentation setup. *right*: Picture of a SiPM fiber test setup.

simulations. With the mentioned precautions in September 2014 only 4.9 ^{68}Ge and 21.4 ^{60}Co nuclei are expected per kg of germanium. This should be compared to the saturation activity of 1600 and 10.000 ^{68}Ge and ^{60}Co nuclei per kg germanium, respectively.

For detector contacting aluminum (Al) pads have been evaporated onto the p^+ and n^+ surfaces of the detectors using low background Al. Signal and HV contacts are established by bonding Al wires onto the detector surfaces and CuFlon flex cables attached to the silicon detector holder by CuSn6 springs. All used materials have been specially selected and screened prior to production. Fig. 1 *right* shows a schematic drawing of the holder and contacting scheme. Fig. 4 *left* shows a picture of the signal and HV contacts established between a BEGe detector and the CuFlon flex cables attached to a prototype silicon holder. A new version of the Phase I CC2 preamplifier with the JFET and the feedback resistor placed in the direct vicinity of the detector will be used. A prototype setup with close to final front end electronics and holder configuration has been successfully tested and an energy resolution of 2.6 keV at 2.6 MeV has been reached.

The volume directly surrounding the detector array will be instrumented with photo multipliers to detect the 128 nm scintillation light emitted if energy is deposited inside LAr. This allows to identify background events resulting from Compton scattered photons with partial energy deposit in the HPGe detector and partial

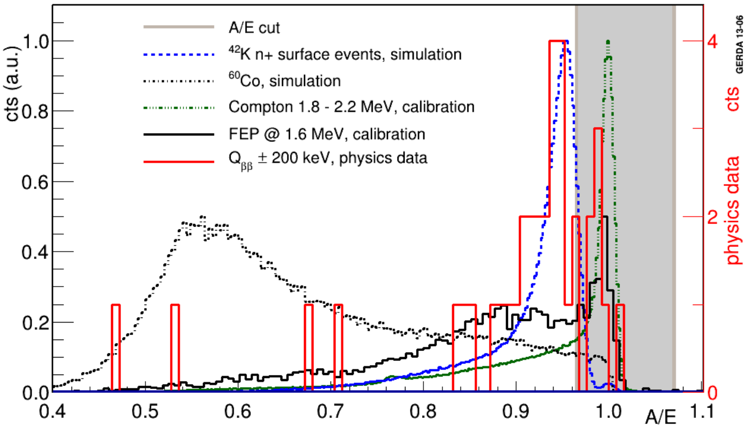

Fig. 5. A/E distribution of signal like SSEs and different background components. The distributions have been obtained by Gerda calibration measurements, Gerda background data and simulations.

energy deposit inside the LAr. Two independent systems will be implemented: 16 three inch PMTs with the wavelength shifter Tetraphenyl butadiene (TPB) deposited on their entrance window will be mounted above (9 PMTs) and below (7 PMTs) the detector array facing the LAr surrounding the detectors (see Fig. 4 *center*). Additionally, a curtain made from light guide fibers with TPB deposited on their surface will surround the detector array. 128 nm photons reaching the light guides are wavelength shifted by the TPB and are guided to the end of the fibers, where they can be detected by SiPMs optically coupled to the fibers (see Fig. 4 *right*). It has been shown in proof of principle test stands that sufficient amount of light can be collected with both techniques to efficiently identify background events [12, 13].

Simulations of light propagation inside the LAr with an idealized geometry assuming that the LAr in the Gerda cryostat is not contaminated have shown that a large fraction of background events external to the detector assembly can be identified using this technology with high efficiencies. Thus, the BI expected from distant contaminations can be reduced to a tolerable level.

^{42}Ar ($T_{1/2}$=33 yr) is present in liquid argon in small amounts [14]. Its ionized decay product of ^{42}Ar, the β^- emitter ^{42}K with $T_{1/2}$=12.3 hours and a Q-value of 3.525 MeV, can be transported by electrical fields to the detector surfaces. In Phase I of the Gerda experiment the individual detector strings were surrounded by a copper shroud, minimizing the LAr volume from which ^{42}K ions can be collected on the detector surfaces. Additionally a quasi field free solution was chosen to minimize drift towards the detectors. This allowed to reduce the BI from ^{42}K (before PSD) on the BEGe detector surfaces to a level of $0.021^{+0.03}_{-0.14}$ tolerable for Phase I [14]. In order to take maximum advantage of the light instrumentation of the LAr, in Phase II the copper shroud will be exchanged by a transparent TPB coated shroud that allows to minimize the volume from which ^{42}K ions are collected, while allowing to detected scintillation light also from the volume inside the mini shroud. Low background nylon has been identified for this purpose. It could be shown experimentally in the LArGe facility [13] that a nylon shroud can reduce the BI due to ^{42}K by a factor of 17 with respect to the unprotected setup. The background suppression factors of the LAr instrumentation for different background components have been simulated for the configurations using no mini shroud, with a copper shroud and using a nylon mini shroud around the individual detector strings. The simulations suggest that a TPB coated nylon mini shroud does not deteriorate the preformance of the LAr instrumentation significantly.

Using information from Phase I of the Gerda experiment, available screening results, measurements of suppression factors with the LArGe setup and Monte Carlo simulations of the light collection efficiencies of the LAr instrumentation an estimate on the expected BI due to different background contributions can be made. Efficient PSD and LAr veto efficieny are required to reach the Gerda Phase II BI goal of 10^{-3}counts/(keV kg yr). The most critical background component is decay of the ^{42}Ar daughter ^{42}K on the

n^+ surface of the detectors. In order to reach the Phase II background goal of 10^{-3} counts/(keV kg yr) the separation of the A/E peak of bulk SSEs from the distribution of n^+ surface events needs to be sufficiently good. Fig. 5 demonstrates the A/E distribution of different background components as expected from GERDA calibration measurements (MSEs, ie. Compton events from full energy peak at 1.6 MeV, n^+ events), background data in GERDA Phase I (SSEs, n^+ events and MSEs), and simulations (^{60}Co and n^+ surface events). It is demonstrated that a clear separation of the signal like SSEs and the n^+ surface events is achievable using PSD with BEGes [15].

3. Conclusion

In the first phase of the GERDA experiment a lower limit on the half life of $0\nu\beta\beta$ decay in ^{76}Ge of $^{0\nu\beta\beta}T_{1/2}$ of ^{76}Ge of $2.1{\cdot}10^{25}$ yr was obtained. The GERDA experiment is presently being upgraded to its second phase, in which an additional 20 kg of BEGe detectors will be used increasing the total target mass to ≈35 kg. The LAr surrounding the detectors will be instrumented with PMTs and fibers connected to SiPMs to detect the 128 nm LAr scintillation light from background events. This will allow to decrease the background index to a level of 10^{-3}counts/(keV kg yr). 30 BEGe detectors with a total weight of 20 kg have been produced and successfully characterized. The infrastructure at LNGS is presently being upgraded. Integration tests with the close to final holder and contacting configuration in a test stand have been performed and an energy resolution of 2.6 keV at 2.6 MeV could be achieved. Commissioning of Phase II is expected to start within the year 2014.

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