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Experience from operating germanium detectors in GERDA.

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Abstract. Phase I of the Germanium Detector Array (GERDA) experiment, searching for the neutrinoless double beta ($0\nu\beta\beta$) decay of $^{76}\text{Ge}$, was completed in September 2013. The most competitive half-life lower limit for the $0\nu\beta\beta$ decay of $^{76}\text{Ge}$ was set ($T_{0\nu}^{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L.). GERDA operates bare Ge diodes immersed in liquid argon. During Phase I, mainly refurbished semi-coaxial high purity Ge detectors from previous experiments were used. The experience gained with handling and operating bare Ge diodes in liquid argon, as well as the stability and performance of the detectors during GERDA Phase I are presented. Thirty additional new enriched BEGe-type detectors were produced and will be used in Phase II. A subgroup of these detectors has already been used successfully in GERDA Phase I. The present paper gives an overview of the production chain of the new germanium detectors, the steps taken to minimise the exposure to cosmic radiation during manufacturing, and the first results of characterisation measurements in vacuum cryostats.

1. Introduction
GERDA [1] is an experiment looking for the neutrinoless double beta decay of $^{76}\text{Ge}$. The observation of $0\nu\beta\beta$ decay would imply lepton number violation by two units, indicating physics beyond the Standard Model of particle physics. Additionally, it would prove that neutrinos have a Majorana mass component. Assuming the exchange of light Majorana neutrinos an effective neutrino mass can be evaluated by using predictions for the nuclear matrix elements. The experimental signature of $0\nu\beta\beta$ decay is a peak at the Q-value of the decay at 2039 keV, which lies above the continuous energy spectrum of the neutrino accompanied double beta ($2\nu\beta\beta$) decay. GERDA operates bare germanium diodes inside liquid argon which serves as a coolant and as shielding. The Phase I of GERDA was completed successfully, setting the most competitive limit on the half-life of $0\nu\beta\beta$ decay for $^{76}\text{Ge}$, $T_{0\nu}^{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L. [2, 3].

The efficiency to detect the $0\nu\beta\beta$ decay is increased by the fact that germanium serves both as the source of the decay and as the detector. Additionally, operating the diodes bare in liquid argon provides reduced background from cladding material. Finally, germanium is intrinsically pure and germanium diodes provide excellent energy resolution, while their production chain is well-established. This paper describes the experience obtained by operating germanium diodes in GERDA Phase I as well as the first characterisation results for a subset of the Phase II detectors.

In section 2, an overview of the semi-coaxial detectors used in Phase I and their performance is presented. The description of the broad energy germanium (BEGe) detectors that will be
used in Phase II, their production chain as well as their performance and characterisation in vacuum and in liquid argon are discussed in section 3.

2. Overview of Phase I semi-coaxial detectors

The main detectors used during GERDA Phase I were 8 enriched semi-coaxial p-type high purity germanium detectors, taken from the previous HdM [4] and IGEX [5] experiments. They are enriched to $\sim 86\%$ in $^{76}\text{Ge}$ and have a total mass of 17 kg. The non-enriched detectors have an abundance of $\sim 7.8\%$ in $^{76}\text{Ge}$ [1].

The BEGe detectors have a wrap around n+ electrode and a boron implanted p+ contact, separated by an insulated groove (see figure 2). No passivation layer was used on the groove. The masses of the individual detectors range between 0.98 and 2.9 kg. Apart from these 8 coaxial detectors, 5 BEGe detectors [6] were used and tested during Phase I. The energy resolution of the semi-coaxial detectors at 2.6MeV, determined with a $^{228}\text{Th}$ calibration source, is 4-5 keV (FWHM) [1]. Two detectors developed high leakage current at the beginning of Phase I and were removed from the analysis, however, they were used as a veto to suppress multi-site events.

A long term study of the leakage current of bare natural germanium detectors operated in LAr and LN$_2$ under varying gamma-irradiation conditions was performed. A continuous increase of the leakage current was observed during irradiation for the detector in LAr but not in LN$_2$, as shown on the left panel in figure 1. After removing the source, the leakage current would stabilise again, but at a value higher than before the irradiation. The leakage current could be completely restored to its initial value by warming up the detector in methanol baths. The right plot of figure 1 shows measurements with three prototype detectors using different sizes of groove passivation, namely large area, reduced and none. Reducing the size of passivation layer suppresses the effect while there is no leakage current induced when there is no passivation layer.

It is believed that the leakage current increase is induced by the collection and trapping of charges produced by the ionisation of LAr on the passivated surface of the detectors. Therefore, all GERDA Phase I detectors were reprocessed without the evaporation of a passivation layer [1].

Figure 1. Left: Leakage current induced by $\gamma$-radiation in a detector operated in liquid argon and liquid nitrogen. Right: Leakage current induced by $\gamma$-radiation in 3 detectors with different passivation layers. Taken from [1].
Figure 2. Profile and weighting potential of a BEGe diode. The weighting potential is strongest close to the p+ read-out electrode. The p+ electrode (centre, bottom) is separated from the n+ electrode by a groove, covered with an insulating passivation layer. The inactive dead layer (DL), the transition layer (TL) and the active volume (AV) are indicated. Examples of SSE and MSE events by means of hole trajectories are also shown. Taken from [7].

3. Phase II BEGe detectors
BEGe detectors consist the majority of the detectors to be used during Phase II of GERDA. These detectors are made from p-type germanium enriched to 88% in $^{76}$Ge, they have a wrap around n+ electrode, and a p+ electrode acting as an electron blocking contact. A reduced passivation layer was used for the BEGE detectors. Five out of the 30 new detectors were deployed and tested during Phase I. Compared to the Phase I coaxial detectors, the BEGe detectors have a smaller size, lower noise and better energy resolution as well as enhanced pulse shape discrimination capability.

A schematic of a BEGe diode, along with the weighting potential profile is shown in figure 2. The potential peaks strongly close to the p+ electrode. The hole trajectories of individual energy depositions for a single-site event (SSE) and a multi-site event (MSE) are illustrated.

In Phase II, electrical contacts to the point contact are made using ultra sonic wire bonds. This has the advantage of having low mass electrical contact, allowing the reduction of the mass of the detector holders, consequently lowering the background contribution from excess cladding material. For the bonding, a 600 nm thin Al film is deposited on the diodes to provide a metallic surface for ohmic contact and good bonding. This contacting scheme requires stability of the wires in LAr, as well as their survival during warming and cooling cycles. Special care during bonding is necessary to prevent damaging the p+ contact.

3.1. BEGe detector production
The enrichment in $^{76}$Ge was performed in 2005 at ECP in Zelengorsk, Russia [8], where 53.3 kg of enriched germanium oxide powder were produced. Improvements of clean conditions at work places and the use of de-ionised water for hydrolysis led to a purity level of 99.99%. The first step in the enrichment procedure is the fluorination of natural germanium, i.e. binding of Ge in gaseous GeF$_4$ compounds, followed by enrichment via gas centrifuge process and finally production of the enriched germanium oxide powder after hydrolysis, drying and calcination. Reduction and zone refinement was done in 2010 by PPM in Langelsheim, Germany [9], resulting in 37.5 kg of 6N purity grade germanium. The germanium oxide powder was reduced to metallic germanium in H$_2$ atmosphere, followed by cleaning, etching and zone-refinement of the metal ingots. The low resistivity tails of the ingots underwent additional zone refinement. Finally,
crystal pulling and cutting took place in Canberra, Oak Ridge [10], where 9 crystal ingots were cut into 30 slices, with a total mass of 20.8 kg.

The conversion of the germanium crystal slices to detectors was done in 2012 at Canberra Semiconductors N.V., Olen, Belgium [11]. Thirty enriched germanium diodes were produced, corresponding to 20 kg. This is a mass yield of 53.3% from the original germanium oxide. Prior to delivery, Canberra tested the diodes in liquid nitrogen bath for basic parameters. The requirements set on energy resolution (< 2.3 keV), operational voltage (< 3 kV) and leakage current (< 50 pA) were met for 29 out of 30 detectors. The energy resolution for all 30 detectors as a function of their mass is shown in figure 3. The mean energy resolution at 1333 keV is 1.74 keV (FWHM). One of the detectors could not reach full and stable depletion voltage and therefore had a deteriorated charge collection efficiency in some parts of the crystal.

3.2. Cosmic activation

An important background for 0νββ searches originates from cosmic activation of germanium during the production and handling of the germanium diodes. At sea level, secondary cosmic rays consisting mainly of fast nucleons, muons and muon induced neutrons produce long lived radionuclides via spallation reactions. The subsequent decays of these isotopes are a source of background in a germanium 0νββ experiment. The relevant isotopes produced in germanium are 68Ge and 60Co, with half-lives of 270 days and 5.2 years respectively.

The contribution of these decays to the background index (B.I.) of Phase II was studied with Monte Carlo simulations [12, 13]. Averaged over three years of data taking, 68Ge and 60Co contribute approximately $3.7 \times 10^{-3}$ counts/keV kg yr and $8.4 \times 10^{-4}$ counts/keV kg yr. This level of B.I. can be reduced by one to two orders of magnitude after applying pulse shape discrimination methods. The goal of GERDA Phase II is to reduce the background index by an order of magnitude compared to Phase I, reaching the level of $10^{-3}$ cts/keV kg yr.

Several actions were taken to minimise the exposure to cosmic radiation during the production of the diodes. Optimisation of the processing steps minimising the time the material was unshielded, on-site underground storage during the various processing steps and using a water- and steel-shielded container during transportation contribute to the reduction of cosmogenic-induced radioisotopes in the detectors. The expected reduction factor of cosmic activation due to the shielding was in the range of 10 and 15 for 68Ge and 60Co, respectively [14]. Figure 4 shows the history of the estimated number of cosmogenic-induced 68Ge and 60Co atoms in enriched germanium for a BEGe detector. The bulk of the activation occurred during enrichment (I), purification (II), crystal growth (III) and diode conversion (IV), while the material was above ground. 60Co was removed completely at the time of crystal growth.
energy resolution ∆E (FWHM at 1333 keV), peak position PP and peak integral PI as a function of the applied voltage. Taken from [7].

Figure 5. $^{60}$Co high voltage (HV) scans for detectors GD32A (left) and GD35B (right). Energy resolution ∆E (FWHM at 1333 keV), peak position PP and peak integral PI as a function of the applied voltage. Taken from [7].

3.3. Vacuum cryostat tests
The following characterisation measurements took place in the HADES underground laboratory in Mol, Belgium. High voltage scans, in steps of (50-100) V, using a point like $^{60}$Co source were performed to the first seven BEGe detectors in order to determine the depletion voltage. The depletion voltage of a germanium detector is defined as the reverse bias voltage that electrically full depleted the diode of free charge carriers. The peak position, the peak integral and the energy resolution in terms of FWHM of the two $^{60}$Co γ-lines were monitored at each intermediate voltage.

The HV scans for two detectors are shown in figure 5. As soon as the detector is electrically full depleted, the parameters become almost constant. The lowest voltage point on this plateau is the depletion voltage.

The measurements in HADES show energy resolutions which are in good agreement with the values provided by Canberra [7]. Additionally, the BEGe detectors show a 30% better energy resolution compared to the coaxial detectors operated in vacuum cryostats [15]. In particular, the average energy resolution (FWHM) at the recommended voltage for the 1333 keV and 2615 keV gamma lines are 1.73 keV and 2.47 keV respectively.

In figure 5 one sees that the detectors exhibit the so-called bubble or pinch-off effect [6, 16]. In a voltage interval of a few tens of kV below depletion voltage, the electric field in a region at the centre of the detector becomes zero. Some clouds drifting to the electrodes may get trapped in this region, giving rise to a broader energy resolution and a peak position instability right below the depletion voltage.

The active volumes of the seven BEGe detectors were determined by comparing calibration
Figure 6. Evaluation of the FCCD for detector GD32A. Left: Measured vs. simulated absolute count rate of the 1173 keV $^{60}$Co $\gamma$-line. Right: Measured vs. simulated ratio of two $\gamma$-line intensities for $^{241}$Am. Taken from [7].

data to simulated calibrations of the same experimental setup. Two different methods were used. In one case a $^{60}$Co source was used and the count rate for a subset of gamma-ray peaks was measured. In the second method, an $^{241}$Am source was used and count rate ratios were determined. Both observables are plotted as a function of the full charge collection depth (FCCD), i.e. the sum of transition layer and dead layer thicknesses [7], based on simulations (see figure 6). The transition layer surrounds the active volume (AV), has a reduced charge collection efficiency and a low electric field [17]. The intersection of the experimental data with the curves from the simulations provide the FCCD of the detector. The active volume fractions are determined by subtracting the FCCD volume from the overall detector volume. It is worth noting that the peak count rate method results depend on the precise knowledge of the activity of the source while this factor cancels out in the peak ratio method.

The active volume fractions of the detectors lie on the range of 89-94% of the detector volume [7]. The results from the $^{241}$Am measurements are in good agreement, within 1%, with the values provided by the manufacturer, determined also with Am surface scans. The results from $^{60}$Co measurements are systematically lower than the $^{241}$Am results by 1.9% on average. Details on the systematic uncertainties of these measurements are reported in [7].

For the determination of background rejection efficiencies through pulse shape analysis, $^{228}$Th calibration sources were deployed on the outer surface of the vacuum cryostat. As an SSE proxy, the 1593 keV double escape peak (DEP) from the 2614 keV line of $^{208}$Tl was used. Events from the full energy peak (FEP), the single escape peak (SEP) and Compton continua are taken as MSE proxies. The pulse shape discrimination (PSD) method used for the BEGe detectors utilises a single parameter, i.e. the maximum amplitude of the charge pulse, A, over the energy deposited, E [18].

Figure 7 shows the A/E distributions of DEP events from $^{208}$Tl decays for three BEGe detectors. Ideally, as shown in black, the distribution is Gaussian with a tail component from underlying MSE background. Five BEGe detectors showed anomalous A/E distributions, with multiple or unusually broad peaks. The A/E distributions for two of these detectors are shown in red and blue in figure 7. Investigations indicated that this behaviour is not caused by the set-up configuration (e.g. electronic components) [7]. However, positively charged compounds can be deposited in the groove between the p+ and n+ electrodes after diode production leading to the distortion of the electric field configurations and in turn distorted drift paths. The grooves of two detectors underwent chemical treatment by the manufacturer followed by thermal heating. This led to improvement of the PSD behaviour for one of the two detectors.
3.4. Performance in liquid argon

The performance of four BEGe detectors operated in LAr during Phase I of GERDA is shown in figure 8. The leakage current, shown on the left plot, is stable. The energy resolution, determined with $^{228}$Th calibration sources, is also stable, with values in the range between 2.8 to 3 keV. This resolution is 30% worse than what was determined with the detectors operating in vacuum. This is due to the longer signal cable between the readout electrode and the field effect transistor (FET) in liquid argon. Compared to the coaxial detectors, the resolution of the BEGes is 30% better [12]. Finally, the peak position of the 2615 $^{208}$Tl line is stable over time, with relative deviations of 0.1%.

During Phase I, a drift of the mean of the A/E distributions was observed. First, a long term exponentially decreasing behaviour, shown in figure 9, varying from 1 to 5% depending on the detector. Second, a shift of 1% to higher values was observed during $^{228}$Th calibrations. The instabilities were quantified and time-corrections were applied to the A/E distributions. The
A/E drift might be due to the presence of charges on the passivated groove, neutralising or dissolving in liquid argon after months of operation.

Finally, in order to examine the pulse shape anomalies observed in vacuum, tests were performed in liquid argon in the GERDA Detector Laboratory (GDL) in LNGS. In liquid argon tests, the width of the A/E distributions improved and the non-Gaussian features disappeared [7]. The PSD survival efficiencies were also improved for the detectors without passivation layer and no A/E anomaly present. Figure 10 shows the A/E distributions for a detector with passivation layer in vacuum and without passivation layer in LAr.

4. Conclusions
The goals of GERDA Phase I were reached with well-type non-passivated coaxial detectors, setting a limit on the half-life of $^{76}$Ge $0\nu\beta\beta$ decay, as well as demonstrating the successful operation of bare germanium detectors in LAr. Irradiation induced leakage current was investigated and was found to be strongly suppressed by reducing the size of the passivation layer. For Phase II, 30 new BEGe detectors were produced. Careful steps were taken during production to minimise cosmic activation, that can lead to background at the region of interest. A new contacting scheme is being implemented for the BEGe detectors in Phase II. The new detectors have an improved energy resolution and high background identification capabilities. A possible origin of the anomalies related to pulse shape analysis is charge deposition in the groove. Improvement can be achieved by chemical and thermal treatment of the passivation layer or by removing the passivation and handling the detectors under clean nitrogen atmosphere. The BEGe detectors were proven to be very stable in their operation in liquid argon. The low expected background index in Phase II will allow the exploration of $0\nu\beta\beta$ half-life values of $^{76}$Ge above $10^{26}$ years.

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