Development and installation of the GERDA experiment

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Abstract. The progress in the development of the GERDA (GERmanium Detector Array) experiment is presented. The goal of the experiment is the search for neutrinoless double beta decay of \(^{76}\)Ge with considerable reduction of background in comparison with predecessor experiments. GERDA will operate bare germanium semiconductor detectors (enriched in \(^{76}\)Ge) submerged in high purity liquid argon supplemented by a water shield. The experimental set up is currently under construction in the underground facility of LNGS, Italy. The results of various R&D efforts and the main steps of the GERDA set up design and installation are given as well as several novel methods for background reduction are described.

1. Introduction
The goal of the GERDA (GERmanium Detector Array) experiment [1] is to search for neutrinoless double beta decay \((0\nu\beta\beta)\) of \(^{76}\)Ge. The \(0\nu\beta\beta\) decay is one of the most sensitive probes of still unknown neutrino properties such as neutrino type and their mass scale. So far the best limits on \(0\nu\beta\beta\) decay half-life \(1.9 \times 10^{25}\) y and \(1.6 \times 10^{25}\) y have been obtained with HPGe detectors enriched in \(^{76}\)Ge in the predecessor Heidelberg-Moscow [2] and IGEX [3] experiments at the background \(\sim 10^{-1}\) counts/keV·kg·y. Moreover, the part of the Heidelberg-Moscow collaboration, after additional data treatment, claimed the presence of an excess of events in ROI, which they interpreted as the evidence of \(0\nu\beta\beta\) observation with the best fit \(T_{1/2} = 1.2 \times 10^{25}\) y, \(\langle m_{\beta\beta} \rangle = 0.44\) eV at the value of a nuclear matrix element \(NME = 4.22\) [4]. The aim of GERDA is to achieve the considerable reduction of background and thus better sensitivity in comparison with previous experiments.

GERDA will operate bare germanium detectors (enriched in \(^{76}\)Ge) submerged in liquid argon (LAr) for shielding against external radiation. By removing most of the cladding and contact materials and immersing the detectors in an ultra-pure environment, one can reduce the detector background dramatically. Provided that the background can be reduced to \(10^{-3}\) counts/keV·kg·y, it will be possible to operate detectors free of background within the planned exposure. The experimental GERDA strategy is based on three phases. In Phase I all 8 existing and reprocessed enriched HPGe detectors \((18\) kg of \(^{76}\)Ge in total) from the Heidelberg-Moscow and IGEX experiments and 6 reprocessed HPGe detectors made from natural Ge \((15\) kg of \(^{76}\)Ge) from Genius TF [5] will be used. After 1 year of data taking (an exposure of \(15\) kg·y with the background level \(10^{-2}\) cts/keV·kg·y) GERDA can scrutinize the existing claim at the high statistical level without problems with uncertainties of NME or improve the limit on the half life up to \(T_{1/2} > 3 \times 10^{25}\) y, translated into an effective neutrino mass \(\langle m_{\beta\beta} \rangle < 0.2 - 0.5\) eV for the range of NME values from \(5.46\) to \(2.22\) according to the set of more recent calculations (see Table IV from [6]). In Phase II new segmented or BEGe detectors \(>20\) kg of \(^{76}\)Ge will be added. In total 40 kg of \(^{76}\)Ge + \(15\) kg of \(^{76}\)Ge will be used in this phase. In addition several detectors from material depleted in \(^{76}\)Ge will be incorporated. After exposure of \(100\) kg·y with the background reduced up to \(10^{-3}\) cts/keV·kg·y, the limit on \(T_{1/2}\) would improve to \(2 \times 10^{26}\) y leading to \(\langle m_{\beta\beta} \rangle < 0.08 - 0.21\) eV and Phase II will cover the degenerate neutrino mass hierarchy.

If no signal for the \(0\nu\beta\beta\) decay is found, a ton scale \(^{76}\)Ge experiment (Phase III) with further background reduction to \(10^{-4}\) cts/keV·kg·y undertaken in a worldwide collaboration GERDA-MAJORANA will be required to cover the inverted hierarchy region.
2. R&D performed for Phase I

Due to the main GERDA conceptual design aimed to operate bare HPGe detectors in LAr the success of the experiment depends strongly on the long-term stability of detector parameters in a cryogenic liquid. To verify the ability of a bare detector operation in LN\(_2\) and LAr, three p-type non-enriched HPGe detectors (with masses 1.6 kg, 2.5 kg, and 2.5 kg of \(^{70}\)Ge) were produced as the prototypes for Phase I with different designs, namely, 1) with a passivation layer covering all the borehole side, 2) with a passivation layer limited to a groove, 3) without a passivation layer at all. The detectors are mounted in the low-mass holders made of selected low-activity copper, PTFE and silicon (80 g in total per each detector) [7]. For three years of R&D and testing in the underground GERDA Detector Laboratory (GDL) at LNGS the detector handling and mounting procedures have been defined and the Phase I detector technology has been tested successfully [8].

In preparation for GERDA Phase I the IGEX and HdM detectors were removed from their parent copper cryostats and all detectors were reprocessed by Canberra Semiconductor NV, Olen [9] without passivation layer. The detectors were stored underground during reprocessing with less than 1 week exposure above ground. The main results achieved during modification and testing of bare HPGe detectors are the following: 1) it was shown that bare Ge detectors can work directly in LN\(_2\) and LAr with the leakage current (< 20 pA) and energy resolution (< 3 keV at 1.3 MeV) corresponding to their standard values in traditional cryostats; 2) their parameters are stable after more than 50 cooling/warming cycles in LAr; 3) the detector parameters do not deteriorate after one year of continuous operation in LAr even after irradiation with intensive gamma sources (modification without passivation layer). This shows the feasibility of the overall GERDA project and closes the question about “limited long-term stability of naked detectors in liquid nitrogen” arisen as a result of the GeniusTF investigations [10].

The other important part of the Ge detector assembly is the front-end electronics which should operate perfectly inside LAr in a distance 30 – 60 cm from the bare detectors. Several versions of ASIC charge sensitive preamplifiers were produced and investigated with the prototype detectors inside test bunches filled with LAr. The PZ-0 circuit is built in the AMS HV 0.8 \(\mu\)m CZX process and has discrete input FET and feed-back components. It fulfils all requirements including a bandwidth of 30 MHz, an equivalent noise charge of less than 150e\(^-\) r.m.s for \(C_{\text{det}} = 30 \text{ pF}\) and a rise time of 15 ns after a coaxial driving cable of 10m length. With one of the latest PZ-0 versions totally equipped for Phase I and coupled with 37 cm cable to the bare HPGe detector placed in the center of the test cryostat filled with 100 kg of LAr, an energy resolution of 2.9 keV at 1.3 MeV has been achieved.

Several MC programs have been developed for background analysis [11]. It was shown that the proposed set up allows to suppress the background from external (rocks) and internal (cryostat and crystal support elements) gamma activity to the level required for Phase I.

The radioactivity of a large fraction of the construction materials was measured by several low-background Ge gamma-spectrometers situated in different underground laboratories [12] as well as by the high sensitive systems for Rn emanation measurements [13]. The most important result is that samples of stainless steel with a \(^{228}\)Th activity of less than 1 mBq/kg were found. This gave the possibility to build a low background stainless-steel cryostat which satisfies all GERDA requirements. The main part of construction development and mechanical engineering has been devoted to the design and manufacture of the cryostat which is realized as a double-walled super-insulated pressure vessel from stainless steel 1.4571 [14].

The performance of the water Cherenkov veto was studied and the encapsulated photodetectors were developed. The muon veto modules on the base of plastic scintillator have been developed with a light collection non-uniformity less than 15 % for the 200 x 50 x 3 cm\(^3\) dimensions. The effective approach to discriminate multi-site deposits in the Ge detectors by using a pulse shape analysis of the signal from Phase I detectors as well as to use anticoincidence between nearby detectors assembled in several strings have been carefully investigated and quantified.
3. Installation of the GERDA setup
The construction and assembling of the experimental set up is practically completed in Hall A of the Gran Sasso National Laboratory (3800 m w.e.), Italy. A schematic drawing of the complex GERDA setup is shown in figure 1, left. A stainless steel (U/Th ≤ 5 mBq/kg) cryostat of 4.2 m diameter and total height (including the neck) of 8.9 m with the inner vessel volume of 64 m³ contains 90 tons of LAr. The inner cylindrical shell of the cryostat is covered by a OFE Cu (U/Th ≤ 16 μBq/kg) shield with maximum thickness of 6 cm and total mass of about 20 tons (see figure 1, middle). During various acceptance tests the cryostat has been certified as a pressure vessel with a thermal loss of about 200 W. The cryostat is immersed in a water tank with a diameter of 10 m and a total height of 9 m. For a successful long term operation of the cryostat in a tank filled with water, special safety measures have been performed. The cryostat is equipped with an active cooling system using LN₂ which due to subcooling of LAr provides minimal losses of evaporated argon (< 0.1 m³ / 10 days). The ultra pure water buffer (565 tons) serves as a gamma and neutron shield and, instrumented with 66 photomultipliers, as Cherenkov detector for efficiently vetoing cosmic muons. Performed MC simulations show that an efficiency of more than 99 % can be achieved reducing the muon induced background to a level of 10⁻⁵ cts/ keV·kg·y. Plastic scintillator panels on top of the detector with the total area of 20 m² will tag muons which enter the dewar through the neck with the vetoing efficiency of about 98 %.

Figure 1. Left: Schematic view of the GERDA setup. Middle: Stainless steel cryostat with copper shield and active cooling system. Right: The GERDA facility installed in the Hall A of LNGS.

The Ge detector array is made up of individual detector strings and is situated in the central part of the cryostat. A cleanroom and a radon tight lock on top of the vessel assembly allow insert and remove individual detector strings without contaminating the cryogenic volume. Radon tightness throughout the experimental volume is achieved by the exclusive use of metal seals in the components.

The main parts of the “nested type” assembly are already installed in the underground facility, see figure 1, right. Commissioning of the completed set up will start by filling the cryostat with LAr which is scheduled for November 2009.

4. R&D activities for Phase II
To reach the background level required for Phase II (<10⁻³ cts/keV·kg·y) novel methods are developed to suppress as much as possible the intrinsic background of the detectors which is mostly due to cosmogenically produced isotopes such as ⁶⁰Co and ⁶⁸Ge.

R&D are carried out to investigate performances of segmented and BEGe types of germanium detectors which can resolve multi-site energy deposits due to background events. The first version of
the Phase II detector design foresees 18-fold segmented detectors. The segmentation helps to identify multiple Compton-scattering background events in the region of interest. The 3x6 fold segmented n-type true-coaxial detector has been produced from natural Ge and tested with a novel “snap contact” scheme with very small amount of extra material (19g Cu, 7g PTFE, 2.5g Kapton) [15]. The detector was running successfully in LN$_2$ for 5 months without deterioration of the performance with a leakage current 30 ± 5 pA. A core resolution of 4.1 keV and segment resolutions between 3.6 keV and 5.7 keV at 1.3 MeV were achieved. Detailed studies have established its power for discriminating single- and multi-site events. For internal $^{60}$Co and $^{68}$Ge impurities, the suppression factor is of about 10 or even better depending of its location [16]. A long term test of this detector in LAr started recently.

A small-electrode Broad Energy Ge (BEGe) detector [17] is considered as the second candidate for the Phase II detectors. The largest BEGe detector (878 g, $\varnothing$80 x 32 mm) commercially available from Canberra Semiconductor, N.V. Olen, has the energy resolution 1.6 keV at 1.3 MeV and is used now for careful investigation of its performance. It was shown that such type of Ge detectors with the applied novel single-parameter PSD method can exhibit very good pulse shape discrimination properties [18] without any segmentation and might be a cost-effective alternative to a segmented detector. On the other hand, BEGe detectors are limited in the currently achievable mass to about 1 kg and a full 3D event reconstruction like in segmented detectors can not be realized.

For the Phase II detectors additional Ge material (37.5 kg) has been enriched (> 86% of $^{76}$Ge) in Russia, transported in a shielded container to Europe and stored underground in order to minimize the cosmogenic production of radionuclides.

The novel concept to use LAr scintillation light as anti-coincidence signal for further background suppression was developed. The pilot setup Mini-LArGe on the base of LAr scintillator (19 kg of LAr active volume) was developed and successfully operated. A long-term stability (about 2 years) with light yield of 1800 pe/MeV was achieved. About 95% of the background Compton events in the Ge detector are vetoed in this setup [19]. Suppression factors of 99% are expected for larger active argon volumes. The pulse shape analysis methods were developed, which allow to perform gamma / alpha / neutron selection with a strong discrimination factor ($>10^5$) for background suppression [20]. The results obtained with the Mini-LArGe have successfully proven the efficiency of the LAr scintillation as a powerful tool for background suppression and diagnostics. These investigations will be continued with the up-scaled (1.4 tons of LAr) low background LArGe setup recently installed in the GDL underground facility. A cluster up to 9 bare HPGe detectors can be operated in the LArGe setup. To detect the scintillation light of LAr nine low temperature PMTs are used. A vacuum insulated copper cryostat of 90 cm inner diameter and 205 cm height is lined with the TPB wavelength shifter and VM2000 reflector foil. The setup is surrounded by a graded shield consisting of 20 cm polyethylene, 23 cm steel, 10 cm lead and 15 cm electrolytic copper. A gas-tight lock serves as the access port for insertion of Ge detectors. After construction the cryostat was filled with LAr and the active cooling system was tested. LN$_2$ at an overpressure of 1 barg is transferred into the heat-exchanger integrated into the top of the cryostat. At a LN$_2$ flow rate of 2 kg per hour no mass loss was observed within one week of continuous operations. The commissioning of the LArGe setup is planned for autumn 2009.

5. Conclusion

In the framework of the extensive R&D program the main GERDA experimental concepts were proven and the methods of further background reduction were developed and tested. This gave a possibility to start a construction of the GERDA set up which is now practically completed. Commissioning of the set up will start with filling the cryostat with LA scheduled for November 2009.

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