The GERmanium Detector Array, GERDA

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Abstract. The GERmanium Detector Array, GERDA, is a new experiment which is currently being built at the INFN LNGS Laboratory in Italy with the aim to search for neutrinoless double beta-decay of \(^{76}\)Ge. Unique features of the experiment are (1) to operate germanium detectors directly inside a bath of liquid argon, and (2) to use segmented germanium detectors. The background level is expected to be two orders of magnitude below that of recent experiments. This results in an estimated sensitivity to the half-life of \(T_{1/2} > 13.5 \times 10^{25} \text{y}\) for the envisioned exposure of 100 kg y, corresponding to an effective Majorana neutrino mass of approximately 130 meV.

1. Introduction
Neutrinoless double beta-decay \((0\nu\beta\beta)\) is a second order weak process which is predicted to occur if and only if the neutrino is a Majorana particle. The final state of the decay consists of the recoiling nucleus, two electrons and no neutrinos. The half-life of the decay is inversely proportional to the square of the effective Majorana neutrino mass, \(\langle m_{\beta\beta} \rangle\), i.e. the coherent sum over the neutrino masses times the square of the corresponding PMNS matrix element. Thus, an observation of the decay would not only reveal the nature of the neutrino but could also give information about the absolute neutrino mass scale. 35 isotopes are known for which \(0\nu\beta\beta\)-decay is energetically allowed. However, the decay has not been observed yet. For a review of the current experimental status, see e.g. [1].

Several experiments have been carried out to search for \(0\nu\beta\beta\)-decay of the germanium isotope \(^{76}\)Ge. Germanium has semi-conductor properties and can be used as source and detector simultaneously resulting in a high signal efficiency. The germanium used for the detectors is enriched in \(^{76}\)Ge to a level of about 86\% compared to a natural abundance of 8\%. Lower limits on the half-life were inferred from the two most recent experiments, IGEX [2] and Heidelberg-Moscow (HdM), with \(T_{1/2} > 1.9 \times 10^{25} \text{y} \) (90\% C.L.) [3]. Parts of the HdM collaboration claimed an evidence for an observation of the decay with a half-life in the 3-\(\sigma\) range of \((0.69 - 4.18) \times 10^{25} \text{y}\) [4].

The GERmanium Detector Array, GERDA [5], is a new experiment which is being build with the aim to search for \(0\nu\beta\beta\)-decay of \(^{76}\)Ge. Its main design feature is to operate bare germanium detectors directly in a bath of ultra-pure liquid argon. The experimental goal is to reduce the background by two orders of magnitude below that of recent experiments to a level of \(10^{-3} \text{counts/(kg}\cdot\text{keV} \cdot \text{y)}\). In the first phase of the experiment (Phase I) the recent

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claim of discovery will either be verified or rejected. In the second phase (Phase II) the current lower limit on the half-life is expected to be improved by one order of magnitude. The concept and the technical realization of the experiment are described in the following section. Background rejection techniques are summarized in Section 3 where also an estimate of the expected background level is given. The estimated sensitivity of the experiment to 0νββ-decay is presented in Section 4. A section on the current status of the experiment follows.

2. Concept and technical realization

![Diagram of detector array](image1)

**Figure 1.** Detector array indicating the possible positions for the Phase I and Phase II detectors as well as for calibration sources.

![Graph of 90% prob. upper limit on effective Majorana neutrino mass](image2)

**Figure 2.** Expected 90% prob. upper limit on the effective Majorana neutrino mass, \( \langle m_{\beta\beta} \rangle \), using the nuclear matrix elements presented in [14] with \( \langle M^{0\nu} \rangle = 3.92 \).

In GERDA, enriched high-purity germanium detectors will be operated directly in a bath of cryogenic liquid, based on ideas presented in [6]. The baseline design foresees liquid argon as liquid which serves as coolant for the detectors and as shield against external photons simultaneously. It can be produced with much higher purity compared to lead and copper which is traditionally used as shielding material. Also, the production of background from cosmic rays is smaller. The amount of background from radio-impurities close to the detectors can thus be reduced.

The cryogenic liquid will be contained inside a copper-lined steel cryostat of about 4.2 m diameter and a height of 5.6 m holding about 98 t of liquid argon. The cryostat itself will be placed inside a water tank filled with ultra-pure water. The water tank has a diameter of 10 m and a height of 8 m. The walls of the tank will be equipped with 66 photo multipliers acting as Cherenkov muon-veto.

An independent super-structure around the water tank will house three levels of laboratory cabins. A platform on top of the structure will hold a class 10,000 clean-room. It will house a lock through which detectors will be lowered into and removed from the cryogenic liquid, and a storage facility for detectors. Flow-boxes and a detector mounting station will reach class 100.

2.1. Active components

The detector consists of two sub-systems, an array of germanium detectors and a muon veto. The detector array is depicted in Fig. 1 and consists of up to 19 hexagonally packed strings with
a maximum of five detectors per string. The distance between the centers of two strings is 9 cm, the vertical clearance between two detectors is 5 cm. The Phase I detectors were previously used in the IGEX and HdM experiments. They are p-type diodes with a closed-ended coaxial geometry with masses between 0.9 kg and 2.9 kg. The Phase II detectors will be n-type diodes with a true coaxial geometry and of similar dimensions as the Phase I detectors. Detectors with a 6-fold segmentation in the azimuthal angle and a 3-fold segmentation in the height are currently being studied.

The muon veto consists of the instrumented water tank operated as Cherenkov detector, and of a scintillator plate on top of the clean-room. The combined detection efficiency for traversing muons is expected to be 99%.

3. Signatures and background sources

The energy in a 0νββ-decay is transferred to the two electrons only (neglecting the nuclear recoil). The expected spectrum of the ionization energy, thus, has a sharp peak at the Q-value. The Q-value for 0νββ-decay of 76Ge is 2039 keV.

In processes other than 0νββ-decay an amount of energy can be deposited in an interval around the Q-value by e.g. photons and mimic the decay searched for. These processes are considered as background. Sources of background are (1) radioactive isotopes within the detectors produced by cosmic radiation (e.g. 60Co, 68Ge), (2) radioactive isotopes in the surrounding of the detectors (e.g. 228Th, 238U) and (3) muons, neutrons and their secondaries. Previous experiments were dominated by photons from sources close to the detector, and in particular from radioactive contaminations in the detector shielding.

3.1. Rejection techniques

Several techniques to reject background events are developed for the GERDA experiment. They are mostly focused on the rejection of photon induced events and based on measurements of the volume over which energy is deposited. Electrons in the MeV-energy region have a range of about 1 mm whereas photons in the same energy region lose their energy via Compton-scattering with energy deposits separated by several centimeters. In a 0νββ-decay event energy would thus be localized on a millimeter scale and could be distinguished from photon induced events.

Photonic events are rejected by (1) requiring anti-coincidences between detectors [7], (2) requiring anti-coincidences between the segments of a single detector [8], and (3) the study of the time-resolved detector response (pulse shape analysis) [9, 10]. These techniques have been studied in auxiliary experiments using a segmented prototype detector [11]. The results are well reproduced by Monte Carlo simulations. Studies using the scintillation light of liquid argon as an active veto against photons are currently being performed [12].

3.2. Background estimate

Monte Carlo simulations of the expected background sources have been performed for a simplified GERDA Phase II setup with the aim to estimate (1) the rejection of background events using the techniques introduced previously [7, 13], and (2) to estimate the background level of the experiment. The latter is done in conjunction with screening measurements of the materials to be used in GERDA. A summary of the expected background contributions for the first design is shown in Tab. 1. After the application of the background rejection techniques the most important background contributions are expected to be cosmogenically produced 68Ge and photons from 232Th in the detector cables and holders. The expected background level is estimated to be $3.7 \cdot 10^{-3}$ counts/(kg·keV·y). Further improvements are expected due to a redesign of the detector holder and the use of pulse shape analysis which has not been taken into account in the first estimate. Further R&D is ongoing within the collaboration.
Table 1. Estimate of the background level expected in the GERDA experiment for a simplified Phase II setup at the present level of R&D.

| Detector part                  | Contribution [10^{-4} counts/(kg·keV·y)] |
|--------------------------------|------------------------------------------|
| Germanium detector (cosmogenic $^{68}$Ge) | 10.8                                     |
| Germanium detector (cosmogenic $^{60}$Co)  | 0.3                                      |
| Germanium detector (bulk)               | 3.0                                      |
| Germanium detector (surface)            | 3.5                                      |
| Cabling                                 | 7.6                                      |
| Copper holder                           | 3.4                                      |
| Electronics                             | 3.5                                      |
| Cryogenic liquid                        | 0.1                                      |
| Infrastructure                          | 2.9                                      |
| Muons and neutrons                      | 2.0                                      |
| **Total**                                | **37.1**                                 |

4. Sensitivity to 0νββ-decay
The sensitivity of the GERDA experiment to 0νββ-decay was estimated for several background levels [15]. For a background level of $10^{-3}$ counts/(kg·keV·y) and an exposure of 100 kg·y the expected 90% prob. limit on the half-life is $T_{1/2} > 13.5 \times 10^{25}$ y. Using the nuclear matrix elements presented in [14] this translates into an upper limit on $\langle m_{\beta\beta}\rangle$ of 130 meV. Fig. 2 shows the 90% prob. upper limit on $\langle m_{\beta\beta}\rangle$ as a function of the exposure for background levels in the range of $0 - 10^{-2}$ counts/(kg·keV·y).

5. Status of the experiment
The GERDA experiment is currently being built at the INFN LNGS Laboratory, Italy, at a depth of about 3 400 meter water equivalent. The assembly of the water tank and the cryostat is expected to continue until 2008. The clean-room is expected to be installed in the same year. Commissioning of the detector is planned for 2008.

The Phase I detectors are currently being refurbished. First tests of the detectors in their new holder system yield positive results. A total of 37.5 kg germanium has been isotopically enriched for the Phase II detectors and will be prepared for crystal pulling.

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