GERDA - a new neutrinoless double beta experiment using $^{76}$Ge

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Abstract. The search for neutrinoless double beta decay ($0^{\nu}\beta\beta$) has been a very active field for the last decades. While double beta decay has been observed, $0^{\nu}\beta\beta$ decay still waits for its experimental proof. The GErmium Detector Array (GERDA) uses $^{76}$Ge, an ideal candidate as it is acting as source and detector simultaneously. Germanium detectors, isotopically enriched in $^{76}$Ge are submerged directly into an ultra pure cryo liquid, which serves as coolant and radiation shield. This concept will allow to reduce the background by up to two orders of magnitude with respect to earlier experiments. GERDA has been constructed in hall A of the underground laboratory LNGS of the INFN in Italy. The experiment started recently with a test run.

1. Introduction
Neutrinoless double beta decay ($0^{\nu}\beta\beta$) is the only experimentally feasible way to determine whether the neutrino is a Dirac or a Majorana particle. The observation of $0^{\nu}\beta\beta$ decay would be proof of the Majorana nature [1], implying the violation of lepton number conservation. Neutrinoless double beta decay is only possible, if the neutrino is not massless, in contradiction to the standard model. The observation of neutrino oscillations from several experiments requires at least two of the neutrino mass eigenvalues to be nonzero. The lowest upper limit on the neutrino mass is given by cosmic observations, combining cosmic microwave background, supernova neutrinos, baryon acoustic oscillations and photometric redshift survey data. An upper limit on the sum of neutrino mass of $\Sigma m_\nu = 0.28 \text{ eV}$ (95\% C.L.) was derived, depending on several assumptions [2]. Experiments measuring the upper end of the energy spectrum of the electron in the tritium decay obtain a mass limit of $m(\nu_e) < 2 \text{ eV}$ [3]. The KATRIN experiment, currently under construction, will reach with the same direct approach a sensitivity $m(\nu_e) = 0.2 \text{ eV}$ for the electron neutrino mass [4].

From $0^{\nu}\beta\beta$ decay the effective neutrino mass can be derived from the measured half-life time, if the nuclear matrix element is precisely known from theory and the only mechanism for $0^{\nu}\beta\beta$ decay is light Majorana neutrino exchange. A large number of experiments searching for $0^{\nu}\beta\beta$ decay were performed in the last few decades, resulting in lower limits for the half-life times. The best limit for $^{76}$Ge is given currently by the Heidelberg-Moscow experiment (HdM) with $T_{1/2} = 1.9 \times 10^{25} \text{ y}$ (90\% C.L.). This half-life corresponds to an effective neutrino mass of 0.35 eV [5]. The $0^{\nu}\beta\beta$ decay experiments starting in near future will probe the effective neutrino mass to values down to the range of 100 meV.
A part of the HdM collaboration claims the observation of $0
\nu\beta\beta$ decay with $4.2\sigma$ confidence and a half-life of $T_{1/2} = 1.19^{+2.99}_{-0.50} \times 10^{25}$ y ($3\sigma$ range) [6]. The effective mass corresponding to this half-life is $0.30$ eV - $0.53$ eV [7]. [8] shows that the ratios of single-site events to all events given by the HdM experimental data can be explained if the peak at $2039$ keV is a superposition of 3 lines.

2. Experimental setup

The GERmanium Detector Array (GERDA) [9] is a new experiment that started its operation with a test run recently. GERDA is located in hall A of the underground laboratory LNGS of the INFN in Italy. The LNGS features an overburden of 3800 m.w.e., reducing the flux of cosmic muons by a factor of $10^6$. Like the HdM and IGEX [10] experiments germanium detectors are used which are isotopically enriched in $^{76}$Ge (86%), i.e. the source and the detector are the same. The basic idea of the GERDA design is the immersion of bare Ge detectors directly into an ultra-pure cryo liquid which acts as cooling medium for the diodes and as shielding against external radiation. Materials with high $Z$ are avoided in the vicinity of the diodes to reduce background produced by secondary effects of cosmic radiation. GERDA operates the germanium diodes in a cryostat of 2 m radius filled with liquid argon. To screen radioactive impurities in the steel of the cryostat, a 6 cm thick copper inlet is mounted on its inner wall. The cryostat is housed in a water tank of 10 m diameter and 9 m height (figure 1). The water is a passive shield against $\gamma$-rays and neutrons and it acts also as an active Cherenkov muon veto. On top of the water tank sits a cleanroom from where the detectors are lowered through the neck of the cryostat (figure 2).

In a first phase 8 diodes made of isotopically enriched germanium (17.66 kg), previously used by the HdM and IGEX experiments, will be employed. The preamplifiers are placed about 30 cm above the detector array, cooled by the surrounding liquid argon. The long term stability of bare germanium detectors in liquid argon was tested in the GERDA test facility. No increase in the leakage current was observed if the diodes were warmed up in a proper atmosphere [11]. The goal of phase I is to reach an exposure of 15 kg y with a background level of $10^{-2}$ counts/(keV kg y). This exposure is sufficient to scrutinize the claim of $0\nu\beta\beta$ observation.
For a second phase additional detectors will be produced, increasing the total crystal mass to \(\sim 40\) kg. Two detector types were under consideration, 18-fold segmented n-type and BEGe p-type diodes. Recently a decision in favour of the BEGe geometry was reached. The amount of cabling needed for a BEGe detector compared to the segmented option is much smaller, i.e. the radioactive impurities close to the detectors are reduced. Furthermore BEGe detectors provide a precise spatial resolution by pulse-shape analysis (PSA) using the strong inhomogeneity of the electric field in the detector. PSA allows to distinguish between single- and multi-site events. While \(0\nu\beta\beta\) decays are single-site events due to the limited range of electrons in germanium, energy deposition by high energetic \(\gamma\)-rays is dominated by Compton scattering, resulting in multi-site events. Rejection probabilities of almost 89\% were reached in simulations and verified in an experiment using the 1620 keV \(\gamma\) of a \(^{228}\)Th source. At the same time the single-site energy deposition of the double escape peak of 2614 keV at 1592 keV has a survival probability of 90\% [12]. Equiping the cryostat with photo multipliers, the scintillation light of argon could be used to suppress photons scattered once in a Ge crystal and absorbed in the surrounding liquid. R&D is performed to make this technique applicable for phase II or a future extension.

For the detectors of phase II 53 kg of enriched GeO\(_2\) were purchased and reduced to Ge metal of 6N grade (37.5 kg). The detector production procedure was tested with isotopically depleted GeO\(_2\) (abundance of \(^{76}\)Ge: 0.60\%). Diodes made from depleted material might be deployed in the array as well to cross check the spectra of the enriched detectors. Six diodes of natural composition from GENIUS-TF will be deployed in the array to increase the background rejection capability by anti-coincidences between detectors. The goal for phase II is an exposure of 100 kg y at a background index of \(10^{-3}\) counts/(keV kg y). The lower limit on the half-life time to be reached in phase II is \(1.5 \times 10^{26}\) y, if no event is observed around 2039 keV. This half-life corresponds to an effective neutrino mass between 0.09 eV and 0.15 eV [7].

A third phase in cooperation with the MAJORANA collaboration [13] is planned, increasing the detector mass to the ton scale. Such an experiment is capable to probe a half-life time of \(10^{28}\) y or an effective neutrino mass of 25 meV [14].
3. Muon veto
Direct background by cosmic muons contributes $10^{-3}$ counts/(keV kg y) in the region of interest. To meet the required overall background level a muon veto was installed. The muon veto consists of the water tank equipped with photo multiplier tubes (PMT) for the detection of Cherenkov light of muons and 40 plastic scintillator panels on the roof of the clean room. Sixty PMTs are mounted on the wall and the bottom of the water tank. The volume below the cryostat is monitored by another 6 PMTs. Since only 0.5 % of the surface is covered by PMTs the detection efficiency for photons is enhanced by a high reflective foil (VM2000 by 3M). A veto efficiency of more than 99 % was reached in simulations, reducing the direct background contribution of muons to $10^{-5}$ counts/(keV kg y).

The muon veto installation was finished in summer 2009. In figure 2 the inside of the water tank lined with reflective foil is shown. After filling the water tank, all PMTs and the trigger logic were tested. Figure 3 presents an event hitting the volume below the cryostat. All the six PMTs in this volume plus two PMTs in the water tank detected photons. The (hardware) trigger window is 60 ns wide and a minimum of 4 responding PMTs is required. The analysis window considers a wider time range to include all PMTs hit by photons.

4. Neutron capture on $^{76}$Ge
Neutrons produced by cosmic muons in the underground laboratory may be captured on the $^{76}$Ge nuclei in the germanium detectors. The excitation energy of the produced $^{77}$Ge nucleus (6072 keV) is released by a cascade of prompt $\gamma$-rays (figure 4). The following $\beta$-decay of $^{77}$Ge to $^{77}$As ($T_{1/2} = 11.3$ h) emits photons and electrons with energies above the Q-value for double beta decay. An isomeric state populated after neutron capture decays by isomeric transition (branching: 19 ± 2 %) or $\beta$-decay to $^{77}$As (81 ± 2 %) with a half-life of $T_{1/2} = 52.9$ s [15]. The strongest transition in the latter case is the direct $\beta$-decay into the ground state of $^{77}$As with $Q = 2.86$ MeV. While photons and $\beta$-decays into excited states (because of accompanying $\gamma$-rays) can be efficiently rejected by PSA, the electrons emitted by the direct $\beta$-decay from $^{77m}$Ge to the ground state of $^{77}$As have the same signature (single-site event) as $0\nu\beta\beta$. Therefore they cannot be rejected by this method. A possible veto strategy for such events is the introduction of a dead time after neutron capture. This veto can be trigged by the observation of prompt $\gamma$-rays. The veto efficiency depends mainly on the knowledge of the prompt transitions in $^{77}$Ge [15].
For a quantitative estimation of the neutron capture rate in GERDA, the cross section of the $^{76}\text{Ge}(n,\gamma)$ reaction is one of the main input parameters. Since the values for the thermal capture cross sections in the literature vary over a wide range a new measurement was carried out using the activation method. Samples of enriched GeO$_2$ were irradiated with cold neutrons at the Prompt Gamma Activation Analysis (PGAA) instrument of the FRM II near Munich, Germany [16]. To monitor the neutron flux a piece of gold foil was used. The cross section of $^{76}\text{Ge}$ was then derived relative to the well known cross section of $^{197}\text{Au}$. The total cross section obtained for the isomeric state is $\sigma_m = (115 \pm 16)$ mb, the ground state is populated with $\sigma_t = (68.8 \pm 3.4)$ mb. The reliability of the new values is higher than those from previous measurements due to the application of HPGe detectors compared to NaI-crystals or $\beta$-particle detection. However, the analysis has shown, that the emission probabilities of the $\gamma$-rays in the $^{77}\text{Ge}$ decay in the literature used to derive the cross sections do not agree with the new measurements [17]. Further measurements to fix the disagreement are planned.

5. Status
After the cryostat was filled with liquid argon at the end of 2009, the lock system to lower the detectors was installed and the water tank filled in the first half of 2010. In June, GERDA was ready to lower and operate the first detectors. Currently one string of 3 diodes of natural

**Figure 4.** Decay spectrum of $^{77}\text{Ge}$.

**Figure 5.** Calibration spectrum of the $^{228}\text{Th}$ source measured with a detector of natural composition. The energy resolution for the 2.6 MeV peak of $^{208}\text{Tl}$ is 4.2 keV (FWHM).
composition is operated in liquid argon to test the background level. Every week the stability of the detectors and the read out system is checked by short calibration runs with a $^{228}$Th source. One calibration spectrum is shown in figure 5. The experiment is expected to start data taking with enriched germanium detectors soon.

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