Search for neutrinoless double-beta decay of Ge-76 with GERDA

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GERDA, the GERmanium Detector Array experiment, is a new double beta-decay experiment which is currently under construction in the INFN National Gran Sasso Laboratory (LNGS), Italy. It is implementing a new shielding concept by operating bare Ge diodes - enriched in Ge-76 - in high purity liquid argon supplemented by a water shield. The aim of GERDA is to verify or refute the recent claim of discovery, and, in a second phase, to achieve a two orders of magnitude lower background index than recent experiments. The paper discusses motivation, physics reach, design and status of construction of GERDA, and presents some R&D results.

1. INTRODUCTION

Neutrino physics can help to answer fundamental questions in subatomic physics, astrophysics and cosmology. The recent discovery of non-zero neutrino masses has provided already first evidence for new physics beyond the standard model. However, many neutrino properties remain to be measured and even the absolute neutrino masses are still unknown. The GERDA experiment will search for neutrinoless double-beta (0νββ) decay in 76Ge, a lepton number violating process in which the nucleus 76Ge of charge Z=32 decays into 76Se with charge Z=34 and two electrons. It can be viewed as the familiar 2νββ decay, Z→(Z+2) + 2e− + 2νe, where the two anti-neutrinos annihilate. The observation of 0νββ decay would establish the neutrino to be its own anti-particle, or Majorana particle. Its half-life, \( T_{1/2}^\nu = 10^{25} \text{y} \), depends on a phase space factor \( G_0 \), the lepton mixing matrix \( |M_{\nu e}|^2 \), the effective Majorana mass \( |m_{\beta\beta}| = \Sigma_i U_{\nu i}^\dagger U_{\nu i} \) where \( U_{\nu i} \) are elements of the neutrino mixing matrix and \( m_i \) the masses of the neutrino mass eigenstates. So, a measurement of the 0νββ half-life will yield information about the absolute neutrino mass scale if the left-hand weak current is the dominant source for 0νββ decay.

The experimental signature for 0νββ decay is the observation of a peak at the endpoint \( Q_{\beta\beta} \) in the energy spectrum of the 2e− final state. Diodes fabricated from high purity Ge (HPGe) material enriched in 76Ge are outstanding ββ detectors being simultaneously the 0νββ decay source and a 4π detector with the excellent energy resolution of a few keV at \( Q_{\beta\beta} = 2039 \text{keV} \). The best limits for 0νββ decay in 76Ge are due to the Heidelberg-Moscow (HDM) and IGEX experiments yielding lower half-life limits of about \( T_{1/2}^\nu > 1.6 \cdot 10^{25} \text{y} \) and corresponding effective Majorana masses of \( |m_{\beta\beta}| < 0.33 - 1.35 \text{eV} \) where the range of \( |m_{\beta\beta}| \) values reflects the estimated uncertainties in the nuclear matrix elements needed to convert \( T_{1/2}^\nu \) into \( |m_{\beta\beta}| \). A fraction of the HDM collaboration has claimed recently the observation of 0νββ decay in 76Ge with a half-life of \( T_{1/2}^\nu = 1.2^{+3.0}_{-0.5} \cdot 10^{25} \text{y} \) (3σ range), implying a \( |m_{\beta\beta}| \) value between 0.1 and 0.9 eV with the central value of 0.44 eV. In view of the controversial aspects of this result, see e.g. refs. [3, 4], scrutiny by other more sensitive experiments is needed. The ongoing experiments CUORICINO [8] and NEMO3 could confirm the 0νββ decay signal with 130Te and 100Mo but cannot refute the claim in case of a null result [5] due to the uncertainties of the nuclear matrix elements, see [6] for discussion. The GERDA experiment aims at probing 0νββ decay of 76Ge with a sensitivity of \( T_{1/2}^\nu > 1.4 \cdot 10^{26} \text{y} \) at 90% confidence level corresponding to a \( |m_{\beta\beta}| \) range from 0.1 to 0.3 eV. Using in its first phase the refurbished 76Ge detectors of the previous HDM and IGEX experiments, a total of about 18 kg, GERDA will be able to scrutinize the recent claim for the 0νββ decay observation with high statistical significance after one year of running. GERDA will reach its ultimate sensitivity in phase II where the total 76Ge mass will be increased beyond 30 kg by adding custom made detectors.

2. Experimental Setup

The GERDA experiment implements an earlier proposal to operate bare Ge diodes in an ultra-pure liquefied gas, liquid nitrogen (LN\(_2\)) or argon (LAr). The cryogenic liquid acts not only as cooling medium for the diodes

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but represents also an unsurpassed shield against the **external gamma background** that has dominated in previous experiments. Figure 1a) shows a schematic of the experimental setup that is being built in Hall A of LNGS, below about 3800 meter water equivalent of rock of the Gran Sasso mountain. A superinsulated cryogenic vessel of 4 m diameter is immersed in a water tank with a diameter of 10 m and an effective height of 8.5 m. A similar graded shield has been discussed in the GEM proposal [11]. The 3 m thick layer of highly purified water reduces the radioactivity of the rock and concrete (∼3 Bq/kg $^{228}$Th) well below that of the cryostat walls which is then reduced by the 2 m thick cryogenic shield to the desired background index (BI) of a few $10^{-4}$ counts/(keV·kg·y) [12]. The water buffer serves also as a neutron shield and, instrumented with photomultipliers, as Cherenkov detector for efficiently vetoing cosmic muons [13]. The Ge detector array, Fig. 1b), has a hexagonal structure and is made up of individual detector strings. A detector string is assembled from up to five independent Ge detector modules. Designs of such modules are shown in Fig. 1c) and d) for p-type (phase I) and segmented true coaxial n-type Ge diodes (phase II). A cleanroom and lock on top of the vessel assembly allow to insert and remove individual detector strings without contaminating the cryogenic volume. Similarly, calibration sources can be brought close to the array. Radon tightness throughout the experimental volume is achieved by the exclusive use of metal seals in all relevant components.

The **intrinsic backgrounds** of the Ge diodes need also to be reduced in order to yield the desired level of sensitivity. The most relevant contributions are known to come from $^{60}$Co and $^{68}$Ge since their lifetimes are in the order of years and their decay chains exhibit Q-values above the $Q_{\beta\beta}$ value. Among others, these isotopes are produced by cosmogenic spallation in the germanium. An obvious way for their reduction is to limit the exposure of the enriched Ge material to (hadronic) cosmic rays as much as possible. This recipe is being followed in the procurement of new enriched detectors. Other methods for intrinsic background suppression will exploit that $\beta\beta$ decay has a point-like energy deposition while the $^{60}$Co and $^{68}$Ge decays lead to extended events due to multiple Compton interactions. Such ‘multi-site’ events will be suppressed by anti-coincidence of detectors within the array or, due to higher granularity even more efficiently, in segmented detectors. Another complementary method is to identify multi-site events from the time structure of the signal. With LAr as cryogenic fluid, these backgrounds can additionally be suppressed very efficiently by detecting the scintillation light of LAr.
3. R&D ACTIVITIES

Major mechanical engineering has been devoted to the design and clean manufacture of the cryostat which is realized as a double-walled super-insulated pressure vessel with a nominal volume of 64 m$^3$. Originally, the cryostat was planned to be fabricated from special OFE copper (\(< 20\mu\text{Bq/kg }^{228}\text{Th}\)) by electron beam welding. However, an unexpected increase of cost forced the implementation of the backup option, a stainless steel (1.4571) cryostat whose inner cylindrical shell is covered by ultrapure OFE copper, see Fig. 2(left). This approach implies the use of LAr to limit the mass of the copper shield. A detailed screening of all steel plates yielded an unexpectedly low radioactivity from less than 1 to 5 mBq/kg $^{228}$Th \[14\]; hence the copper shield of only 6 cm thickness includes even a safety margin \[12\]. Various acceptance tests of the cryostat include its certification as a pressure vessel according to AD2000, the measurement of its thermal loss (<300 W), and the verification that the eight pads supporting the inner vessel share all the same load. The Rn emanation rate has been measured to be \((14 \pm 2)\) and \((34 \pm 6)\) mBq before and after the mount of the copper shield, respectively. Since 10 mBq of Rn, homogeneously distributed in the cryogenic volume, contribute \(10^{-4}\) counts/(keV·kg·y) to the BI, a final cleaning cycle will be done. To avoid contamination by frequent refills, the cryostat is equipped with an active cooling system (Fig. 2 left)). As the cryostat is operated in a tank filled with water, special safety measures have been taken including a detailed risk analysis, earth-quake tolerance up to 0.6 g, the ban of penetrations within the cryogenic volume, thermal insulations at inner and outer shells to limit the evaporation rate in case of leakage of one wall, and, last not least, a nominal design for 1.5 bar overpressure while the operating pressure will be 0.2 barg.

Figure 2: LAr cryostat with copper shield and active cooling system (left), the cryostat mounted on the water tank’s bottom plate in Hall A (middle), and the construction of the Gerda building around the finished water tank which houses the cryostat.

A clean underground detector test facility has been installed at LNGS for detector R&D. There all HdM and Igex diodes to be used in phase I of Gerda have been characterized \[15\], and refurbishment and handling procedures have been developed and verified. The observed reversible radiation-induced increase of leakage current in LAr can be reduced to an insignificant effect by reducing the size of the passivation layer. By now, all enriched diodes as well as those from the Genius test facility have been successfully refurbished. Moreover, the formerly reported problem of a 'limited long-term stability of naked detectors in liquid nitrogen' \[16\] could not be verified. Studies with three non-enriched p-type HPGe diodes during two years of operation with more than 50 warming and cooling cycles have led to the definition of an optimum detector handling procedure. By following this procedure, the detector performance has been proven to be stable over the long-term measurements. - For phase II detectors, material (37.5 kg) has been enriched (> 86% of $^{76}$Ge) in Russia, transported in a shielded container to Munich and stored underground in order to minimize the cosmogenic production of radionuclides. Test purifications of natural GeO$_2$ and its reduction to 6N metal have yielded \[17\] the outstanding yield of 90%. For crystal pulling and characterization a collaboration has
been started with the Institut für Kristallzüchtung in Berlin, and a first natural Ge crystal has been pulled with the dedicated puller. For phase II, a 3x6 fold segmented n-type true-coaxial diode of natural Ge has been tested; with a novel low mass contacting scheme it exhibits a resolution of 3 keV at 1.3 MeV for both core and segments. The functioning of these contacts has been verified also in LN₂. Detailed studies have established its power for discriminating single- and multi-site events. For inside \(^{60}\)Co and \(^{68}\)Ge impurities, the suppression factor is more than an order of magnitude. As pointed out recently, also a modified electrode HPGe detector can exhibit very good pulse shape discrimination properties without any segmentation. Pursuing this line, first tests have shown that a standard commercial product, the Canberra Broad Energy Ge (BEGe) Detector, exhibits similar characteristics and might be indeed a cost-effective alternative to a segmented detector.

**Electronic engineering** has produced ASIC charge sensitive preamplifiers for readout of the HPGe diodes at 77 K. 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 fulfills all requirements including a bandwidth of 20 to 30 MHz, an equivalent noise charge of less than 150e at 30 pF and a rise time of 15 ns after a coaxial cable of 10 m length. A second fully integrated version is under test.

### 4. STATUS AND OUTLOOK

Constituted in February 2004, the GERDA collaboration comprises now about 95 physicists from 17 institutions of six countries. The Letter of Intent was submitted to LNGS in March followed by the Proposal in September 2004. LNGS has approved GERDA in February 2005, allocated space for it in Hall A in front of the LVD detector, and acknowledged the safety concept of GERDA. After the delivery of the cryostat in March 2008, the construction of the GERDA experiment continued with the construction of the water tank and the GERDA laboratory building including the platform for cleanroom and lock (Fig. 2). The installation of these latter parts is expected early in 2009. It will be followed by the commissioning of the GERDA experiment and the start of phase I data taking.

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