GERDA - THE GERMANIUM DETECTOR ARRAY FOR THE SEARCH OF NEUTRINOLESS DOUBLE BETA DECAY OF Ge-76

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GERDA, a new underground experiment at the Laboratori Nazionali del Gran Sasso (LNGS), is designed to search for neutrinoless double beta ($0\nu\beta\beta$) decay of ^{76}Ge at background levels $<10^{-3}$ counts/(keV·kg·y) at $Q_{\beta\beta} = 2039$ keV that are more than two orders of magnitude lower than presently achieved. After an exposure of 100 kg·y, the sensitivity will be $T^{0\nu}_{1/2} > 1.4\cdot 10^{26}$ y at 90% confidence level; this corresponds to an effective Majorana mass between 0.1 and 0.3 eV.

1 Introduction

Neutrino physics has become a most attractive research topic since it might be a key for answers to 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 still to be measured, and even the absolute neutrino masses are still unknown. The GERDA experiment [1,2] will search for neutrinoless double beta ($0\nu\beta\beta$) decay in ^{76}Ge, a lepton number violating process in which the nucleus ^{76}Ge of charge Z=32 decays into ^{76}Se with charge Z=34 and two electrons. It can be viewed as the familiar $2\nu\beta\beta$ decay, $Z \rightarrow (Z+2) + 2\,e^- + 2\,\bar{\nu}_e$, where the two anti-neutrinos annihilate. The observation of $0\nu\beta\beta$ decay would establish the neutrino to be its own anti-particle, or Majorana particle. Its half-life, $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\cdot|M_{0\nu}|^2 \cdot |m_{\beta\beta}|^2$, depends on a phase factor $G_{0\nu}$, the nuclear matrix element $M_{0\nu}$, and the effective Majorana mass $|m_{\beta\beta}| = |\Sigma_i\, U^2_{ei} m_i|$, where U_{ei} are elements of the neutrino mixing matrix and m_i the masses of the neutrino mass eigenstates. Hence, a measurement of the $0\nu\beta\beta$ half-life will yield information about the absolute neutrino mass scale if left-hand weak currents are dominant for $0\nu\beta\beta$ decay.

The experimental signature for $0\nu\beta\beta$ decay is the observation of a peak at the endpoint $Q_{\beta\beta}$ in the energy spectrum of the $2\,e^-$ final state. Diodes fabricated from high purity Ge material enriched in ^{76}Ge are outstanding $0\nu\beta\beta$ decay detectors being simultaneously the $0\nu\beta\beta$ decay source and a 4π detector with the excellent energy resolution of a few keV at $Q_{\beta\beta} = 2039$ keV. The best limits for $0\nu\beta\beta$ decay in ^{76}Ge are due to the Heidelberg-Moscow (HDM) and IGEX enriched ^{76}Ge experiments [3,4] yielding lower half-life limits of about $T^{0\nu}_{1/2} > 1.6 \cdot 10^{25}$ y and corresponding effective Majorana masses of $|m_{\beta\beta}| < 0.33$ - 1.35 eV where the range of $|m_{\beta\beta}|$ values reflects the estimated uncertainties in the nuclear matrix elements needed to convert $T^{0\nu}_{1/2}$ into $|m_{\beta\beta}|$. A fraction of the HDM collaboration has claimed recently the observation of $0\nu\beta\beta$ decay in ^{76}Ge with a half-life of $T^{0\nu}_{1/2} = 1.2^{+3.0}_{-0.5}\cdot 10^{25}$ y (3σ range), implying a $|m_{\beta\beta}|$ value between 0.1 and 0.9 eV with the central value of 0.44 eV [5]. In view of the controversial aspects of this result, see e.g. refs. [6,7], scrutiny by other more sensitive experiments is needed. The ongoing experiments Cuoricino and Nemo3 could confirm the $0\nu\beta\beta$ decay signal for ^{130}Te and ^{100}Mo but cannot refute the claim in case of a null result due to the uncertainties of the nuclear matrix elements, see e.g. ref. [8] for discussion. Indeed, Cuoricino has reported a null result with the upper bound of $|m_{\beta\beta}| < 0.2$ - 1.1 eV [9]. The Gerda experiment aims at probing $0\nu\beta\beta$ decay of ^{76}Ge with a sensitivity of $T^{0\nu}_{1/2} > 1.4 \cdot 10^{26}$ 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 ^{76}Ge detectors of the previous HdM and Igex experiments, a total of about 15 kg, Gerda will be able to scrutinize the recent claim for the $0\nu\beta\beta$ decay observation with high statistical significance after one year of running. Gerda will reach its ultimate sensitivity in phase II where the total ^{76}Ge mass will be increased beyond 30 kg by adding custom made detectors that are truely coaxial and segmented.

2 Experimental Setup

The Gerda experiment implements an earlier proposal [10] 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 but represents also an unsurpassed shield against the external γ background that has dominated in previous experiments.

Figure 1a) shows a schematic of the experimental setup that will be located in Hall A of Lngs, below about 3300 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].

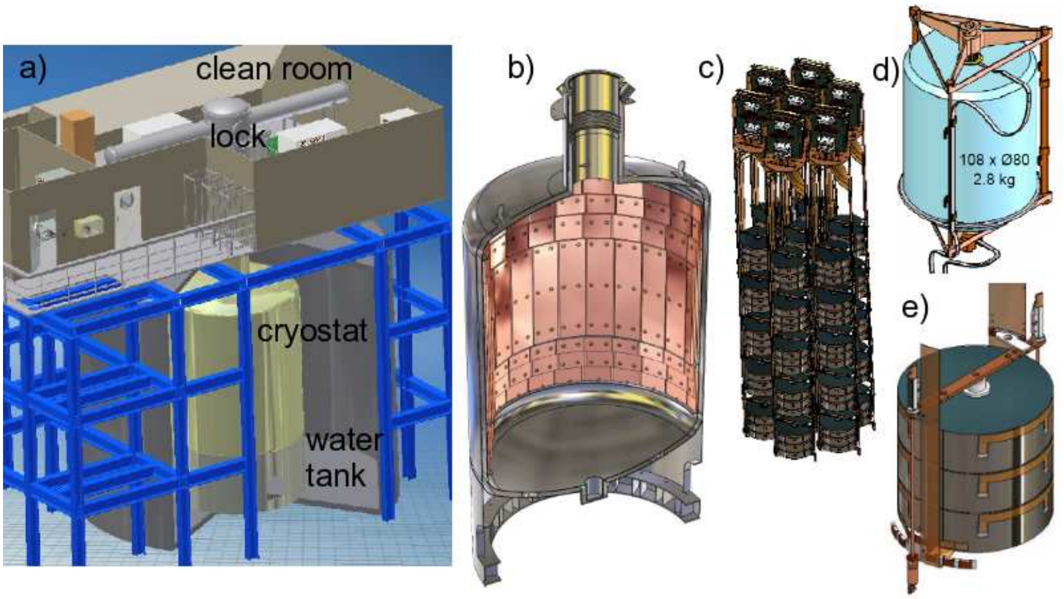

Figure 1: Artist's views of a) the Gerda experiment, b) the superinsulated stainless steel cryostat with internal high-purity copper shield, c) a 5×7 Ge detector array assembled from 7 strings of 5 diodes, d) p-type Ge diode for phase I and e) segmented true coaxial n-type Ge diode for phase II in low mass support and contact structures.

The 3 m thick layer of highly purified water reduces the radioactivity of the rock and conrete ($\sim$3 Bq/kg ^{228}Th) well below that of the cryostat walls which is then reduced by the 2 m thick cryogenic shield to the desired background index of a few 10^{-4} counts/(keV·kg·y). The water buffer serves also as a neutron shield and, instrumented with photomultipliers, as Cherenkov detector for efficiently vetoing cosmic muons [12]. Originally, the cryostat was planned to be fabricated from special OFE copper ($< 20\mu$Bq/kg ^{228}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. 1b). This approach implies the use of LAr to limit the mass of the copper shield; for stainless steel with less than 1 mBq/kg ^{228}Th, the maximum copper thickness will be about 6 cm. The Ge detector array, Fig. 1c), has a hexagonal structure and is made up of individual detector strings. A cleanroom and radon tight 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. A detector string is assembled from up to five independent Ge detector modules. Designs of such modules are shown in Fig. 1d) and e) for p-type (phase I) and segmented true coaxial n-type Ge diodes (phase II).

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, and so an obvious way for their reduction is to reduce 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 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. For ^{60}Co and ^{68}Ge inside segmented detectors, the suppression factor is more than an order of magnitude[13]. Another complementary method is to identify multi-site events from the time structure of the signal. With LAr as cryogenic fluid, these backgrounds can be suppressed very efficiently also by detecting the scintillation light of the LAr.

3 R & D Activities

A clean underground detector test facility has been installed at LNGS for *detector R&D*. A successful refurbishment procedure has been developed and verified for the HDM and IGEX diodes to be used in phase I of GERDA. Moreover, optimum procedures are being developed for the operation of bare Ge detectors in LAr; both the long term stability is investigated as well as the cycling between room and LAr (88 K) temperature. The same facilty is also used to study background suppression by LAr scintillation.

Mechanical engineering is focussed on the clean manufacture of the stainless steel cryostat as well as on the development of low-mass suspension and contact systems for the Ge diodes. For phase II detector modules, see Fig. 1e), the total amount of materials for support, insulation, and contacts - exclusively copper and teflon - will be less than 30 g.

Electronic engineering has developed several working frontend solutions for the few readout channels of phase I, using a cold FET close to the Ge diode and a available warm (cold) preamplifier outside (inside) the cryostat. For phase II with hundreds of readout channels, more compact physical dimensions and shorter rise times are required. Two ASIC CMOS chip projects have been launched to provide the required bandwith (20 to 30 MHz) and ENC ($<$ 150 e at 30 pF load) at liquid nitrogen temperature (77 K). The two CMOS designs are complementary: one approach has all components fully integrated on the ASIC chip while in the second approach the input FET and the feed-back components are not integrated. Chips from both projects are available and have been shown to be functional. The first test results from the latter project look very promising.

Extensive *Monte Carlo simulations* have been carried out within the GEANT4 based MAGE framework which has been developed in cooperation with the MAJORANA collaboration to support both experiments. The simulations are used to study the effects of the external γ, neutron and muon backgrounds[12], to determine the acceptable radioactivity for the materials used to mount, contact and cable the Ge diodes, or to find optimum detector segmentation and algorithms for background reduction[13].

The *radiopurity* of materials to be used for GERDA is assessed with γ spectrometry, inductively coupled plasma mass spectrometry, neutron activation and α counting. Most recent γ ray screening results have been obtained for all (> 10) relevant batches of the 30 tons of 1.4571 steel from which the cryostat will be fabricated. Material with less than 1 mBq(^{228}Th)/kg activity could be identified for the cryostat's cylindrical shells; this allows to use a much thinner internal copper shield than anticipated. Other investigations into the purity control of LN_2 and LAr in terms of ^{222}Rn have found that special but commercially available LAr meets the specifications of GERDA. Further work addresses purification procedures for LAr, surface impurity assessment and cleaning as well as the development of improved radon detection devices.

The *procurement* of new ^{76}Ge diodes has started with the production of 37.5 kg of enriched ^{76}Ge material in the form of GeO_2. Major effort is devoted to optimize its chemical purification, reduction, zone refinement and the crystal production. Test facilites and methods for the characterization of the new segmented n-type diodes are under development and have yielded already first positive results.

4 Status

Constituted in February 2004, the GERDA collaboration comprises now about 80 physiscists from 13 institutions of five countries. The Letter of Intent[1] was submitted to LNGS in March followed by the Proposal[2] in September 2004. LNGS has approved GERDA in February 2005 and allocated space for it in Hall A in front of the LVD detector. The safety concept of GERDA has been acknowledged by LNGS.

By December 2006, the water tank and the stainless steel cryostat with the ultrapure copper for its internal shield have been ordered. The design of auxiliary mechanics, readout electronics and data acquisition is well advanced. In particular, the full functionality of all HdM and IGEX enriched ^{76}Ge diodes has been established and their refurbishment for the new low-mass support structures is in progress. A prototype phase 2 detector, i.e. a 3×6 segmented true coaxial n-type Ge diode, has been successfully tested. Material (37.5 kg) for the phase 2 detectors 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 commissioning of the GERDA experiment and start of phase I data taking is planned for 2008.

References

1. The GERDA Collaboration, Letter of Intent (2004), [hep-ex/0404039].
2. The GERDA Collaboration, Proposal (2004), http://www.mpi-hd.mpg.de/GERDA/
3. H.V. Klapdor-Kleingrothaus *et al*, *Eur. Phys. J.* A **12**, 147-154 (2001), [hep-ph/0103062].
4. C.E. Alseth *et al*, *Phys. Rev.* D **65**, 092007 (2002), [hep-ex/0202026].
5. H.V. Klapdor-Kleingrothaus *et al*, *Phys. Lett.* B **586**, 198-212 (2004), [hep-ph/0404088].
6. A.M. Bakalyarov *et al*, *Phys. Part. Nucl. Lett.* **2**, 77-81 (2005), [hep-ex/0309016].
7. A. Strumia and F. Vissani, *Nucl. Phys.* B **726**, 294-316 (2005), [hep-ph/0503246].
8. V.A. Rodin *et al*, *Nucl. Phys.* A **766**, 107-131 (2006) [nucl-th/0503063].
9. C. Arnaboldi *et al*, *Phys. Rev. Lett.* **95**, 142501 (2005), [hep-ex/0501034].
10. G. Heusser, *Ann. Rev. Nucl. Part. Sci.* **45**, 543 (1995).
11. Yu.G. Zdesenko *et al*, *J. Phys* G **27**, 2129 (2001), [nucl-ex/0106021].
12. L. Pandola *et al*, *Nucl. Instrum. Methods* A **570**, 149-158 (2007).
13. I. Abt *et al*, *Nucl. Instrum. Methods* A **570**, 479-486 (2007).