3 Search for the Neutrinoless Double Beta Decay with GERDA

L. Baudis, A. Ferella, F. Froborg, R. Santorelli, M. Tarka

in collaboration with:
INFN Laboratori Nazionali del Gran Sasso LNGS, Institute of Physics, Jagellonian University, Cracow, Institut für Kern- und Teilchenphysik Technische Universität Dresden, Joint Institute for Nuclear Research, Dubna, Institute for Reference Materials and Measurements, Geel, Max Planck Institut für Kernphysik, Heidelberg, Germany, Università di Milano Bicocca e INFN Milano, Milano, Institute for Nuclear Research of the Russian Academy of Sciences, Institute for Theoretical and Experimental Physics, Moscow, Russian Research Center Kurchatov Institute, Max-Planck-Institut für Physik, München, Dipartimento di Fisica dell'Università di Padova e INFN, Physikalisches Institut, Eberhard Karls Universität Tübingen

(GERDA Collaboration)

Neutrino oscillation experiments have established that neutrinos have non-zero masses, with a lower limit for one of the masses at $\sqrt{\Delta m^2_{atm}} \simeq 0.05$ eV. However, these experiments can not determine the absolute mass scale and the charge conjugation properties of these particles. The observation of neutrinoless double beta ($0\nu\beta\beta$) decay would prove that neutrinos are Majorana particles, that lepton number is violated in Nature and would give us information on the so-called effective Majorana neutrino mass, m_{ee} (1). Current experimental limits on m_{ee} are of the order $m_{ee} \leq 0.3 - 1.0$ eV, with the most stringent upper limits from ^{76}Ge coming from the Heidelberg-Moscow (2) and IGEX (3) experiments.

GERDA is an experiment to search for the $0\nu\beta\beta$ decay in enriched ^{76}Ge detectors in Hall A of LNGS. The aim of GERDA Phase I and II is to reach a sensitivity for m_{ee} of 270 meV and 110 meV, respectively. This is achieved by operating bare HPGe crystals in a large volume (70 m^3) of liquid argon (LAr), which serves as a passive shield (in Phase I) against the external radioactivity. The liquid argon is surrounded by a water shield instrumented with PMTs.

GERDA is under construction at LNGS: the double walled stainless steel LAr cryostat, the water Cerenkov shield, the superstructure around the outer tank and the electrical systems have been installed. Figure 3.1 shows the water tank for the Cerenkov shield along the superstructure during its installation at LNGS. Currently the clean room on top of the superstructure is under construction. Next the lock system used to insert the crystals with their holders into the LAr and the gas handling system will be installed. The detector commissioning is planned for fall 2009, after which the science run will start.

Figure 3.1: The GERDA water tank for the Cerenkov shield and the superstructure during its installation.

GERDA Phase I will operate 17.9 kg of existing enriched ^{76}Ge detectors in LAr. These detectors are currently at LNGS, where they have successfully been tested in more than 40 cooling cycles in LAr in the GERDA Detector Lab. The cryostat and infrastructure being built for Phase I will also be used in Phase II. An additional 14 (25 for BEGe detectors) enriched HPGe detectors are planned for this second phase. The baseline design so far has been to produce highly segmented n-type detectors. Based on first, promising tests at the MPIK Heidelberg of p-type, broad-energy, point-contact Ge detectors (BEGe), it was realized that these detectors could be a viable alternative to segmented detectors for GERDA phase II. The final decision will be based on overall performance of both detector types and on costs.

At present, the GERDA collaboration is in the possession of 37.5 kg of enriched Ge material (in the form of GeO_2), with an additional 20 kg of enriched material needed. This material will be cleaned by the process of polyzone refinement at PPM Pure Metals in Germany. After this step, crystals will be grown at the Institut fuer Kristallzuechtung (IKZ) Berlin (until end of 2009, the period including test runs with natural, and depleted Ge) in the case of the segmented n-type detectors, and at Canberra USA in the case of BEGe detectors. The actual detectors will be produced at Canberra (until end 2010). All these steps will occur under close collaboration with the GERDA collaborating Institutions, including UZH.

3.1 GERDA calibration system

For GERDA Phase I, our group is responsible for the calibration system (we are leading the Calibrations Task Group in the collaboration): calibration sources, collimators, hardware for insertion/parking in the LAr cryostat, Monte Carlo simulations of possible configurations, source strengths and efficiency of pulse shape discrimination, as well as long-term maintenance and data analysis. We have simulated various source and collimator configurations using the Geant4 based framework MaGe (4) which was designed for the GERDA (5) and Majorana (6) projects. The scope was to determine which sources will be used, in which configuration, position and strength, and how often. The sources will be employed to determine and monitor the stability of the energy scale and resolution of the detectors with time, as well as to establish and monitor the efficiency of the pulse shape analysis method which will be used to distinguish single-site interactions (as expected from a double beta decay event) from multiple scatters (for instance, multiple Compton scatters, or neutron interactions). The best source in terms of energy range is ^{228}Th, with $T_{1/2}$=1.9 yr, providing several lines around the region of interest, as well as a population of single-site events with the double-escape peak of the 2615 keV ^{208}Tl line. Our simulations show that we will need three sources in different positions around the detector arrays, each of about 50 kBq. Figure 3.2 shows ^{228}Th calibration spectra of two detectors in the Phase I array, the detector with the highest and lowest statistics in one layer, respectively. We are developing a dynamic data base to store the calibration parameters after each run and to feed them into the data processing software.

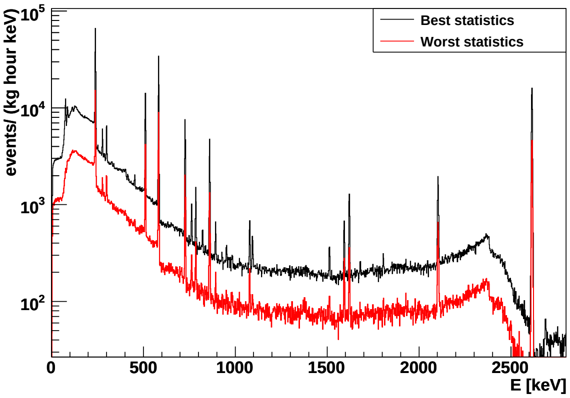

Figure 3.2: ^{228}Th calibration spectra of two detectors in the Phase I array, the detector with the highest and lowest statistics in one layer, respectively.

Since the sources will be parked inside the LAr cryostat, a proper shielding by the source collimator is required. We have studied pure tungsten, a W-compound (Densimet, 92% W, rest is Ni and Fe) and pure tantalum. All offer sufficient shielding against the source activity in the parking position, the pure tungsten is however harder to machine, being brittle. So far we have screened the pure tungsten and the Densimet with Gator, obtaining the activities for U/Th/K/Co of 300/30/8.1/40 mBq/kg and 180/70/7/57 mBq/kg, respectively. We are currently screening the tantalum and will then decide which material to use (any of these will give a background which is at least a factor thousand below the background from the source itself, and thus negligible).

A problem with custom-made ^{228}Th sources is the neutron yield via (α,n) reactions in the ceramic pallet ($NaAlSiO_2$) containing the radioactive element. A calculation of the n-spectra and yields for our required source activities gave a neutron rate of about 1.9 n/s for a 50 kBq source, with a mean energy of 1.5 MeV. Subsequent neutron transport simulations in MaGe show that the background in the 1.5-2.5 MeV region is about 1.6×10^{-3} events/(kg yr keV) for all 3 sources, which is higher than the GERDA phase II goal of 1×10^{-3} events/(kg yr keV). We have thus started a collaboration with PSI to fabricate sources embedded in gold, which has a 9.9 MeV threshold for (α,n) reactions, much higher than the light materials in ceramics and above the maximum α energy of the ^{228}Th chain. A solution of ThCl in 1 M HCl will be heated and then mixed with melted gold, yielding a pure Th source embedded in Au. This procedure is first being tested with a lower activity (20 kBq) solution. The resulting source will be tested in a mock-up collimator (see Fig. 3.3) immersed in our LAr cryostat containing a small HPGe detector (see next Section) in our lab at UZH.

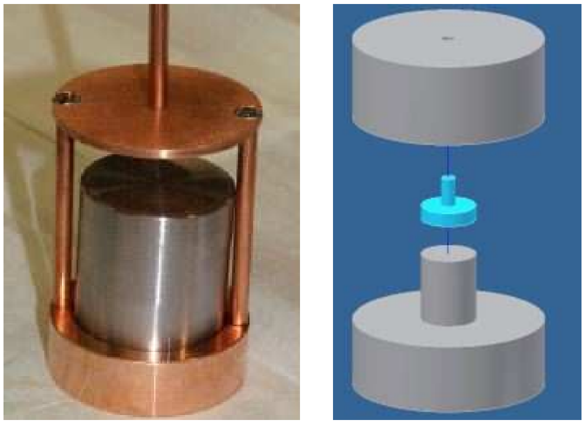

Figure 3.3:
Mock-up W collimator for testing the GERDA calibration source at UZH and a possible source/collimator configuration considered for the final design.

3.2 R&D for GERDA Phase II detectors

GERDA Phase II will use an additional 14 (25 for BEGe) enriched HPGe detectors. Before these detectors can be manufactured, it is essential to test all the steps in the fabrication process using non-enriched Ge material. Two options are currently being considered by the collaboration: 18-fold segmented n-type detectors, or non-segmented, p-type, broad-energy, point-contact Ge detectors (BEGe). Long-term tests of a segmented detector at MPI Munich has yielded an energy resolution of the single segments between 2 keV-3 keV (FWHM) at the 1332 keV ^{60}Co line (7). Motivated by (8), first studies with a 800 g BEGe detector at MPIK Heidelberg were performed, showing a good discrimination of single-site versus multiple-site interactions. This is achieved through a gradient in the impurity concentration level, yielding an electric field distribution which enhances the difference in charge carrier drift times depending on the interaction site (8). This type of detector is thus a viable, possibly cheaper and lower-background alternative for GERDA Phase II detectors. We have engaged in an R&D program together with a few of the GERDA institutions (MPIK, Tuebingen, Milano and Geel) and

Figure 3.4: Our n-type HPGe detector before tests in liquid argon.

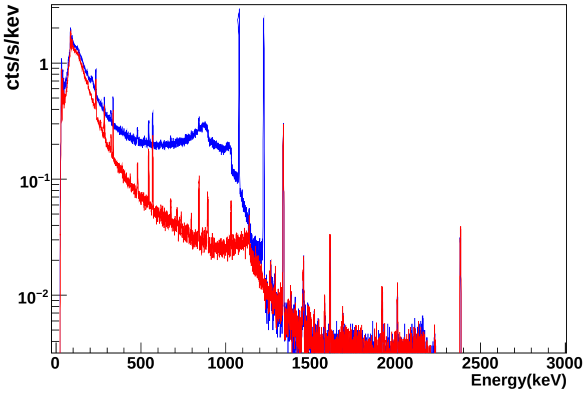

Figure 3.5: Calibration spectrum with a ^{60}Co source (blue) and background spectrum (red) in the UZH lab. The energy resolution of the detector is 2.0 keV at the 1.3 MeV ^{60}Co line.

Canberra USA on the production and tests of BEGe detectors from the available enriched Ge material, with a high yield and at reasonable costs. We will be responsible for the zone refinement and crystal pulling steps (together with Milano), and for the tests of one BEGe detector (3 will be fabricated in this step). All these steps will be tested with depleted Ge material first; 20 kg of this material will be delivered to Canberra in June 2009.

We have also committed to test one of the n-type detectors produced by Canberra France from non-enriched Ge material, in order to verify the quality of crystals from the Institut for Kristallzuechtung (IKZ) which is responsible for pulling crystals for the n-type detectors. This will allow us to directly compare the two type of detectors in the same facility.

We have built a detector test facility, in which we operate a commercial, n-type, naked HPGe-crystal (~300 g) immersed in liquid argon. The aim of this first step was to develop the infrastructure for the detector storage in vacuum, to test the cooling and warming-up procedures avoiding any condensation on the detector surfaces, to test low-noise electronics for detector operation and to validate the Monte Carlo simulations of calibration sources. A picture of our HPGe detector and a calibration spectrum with a ^{60}Co source is shown in Figs. 3.4 and 3.5.

[1] S. R. Elliott and P. Vogel,
Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002).

[2] L. Baudis et al. (Heidelberg-Moscow collaboration), Phys. Rev. Lett. **83**, 41 (1999).

[3] I.G. Irastorza et al. (IGEX Collaboration),
Phys. Rev. D **65**, 092007 (2002).

[4] Y.-D. Chan et al., arXiv:0802.0860v1 [nucl-ex] (2008).

[5] I. Abt et al, GERDA: The GERmanium Detector Array for the search of neutrinoless $\beta\beta$ decays of ^{76}Ge at LNGS, Proposal to LNGS P38/04, September 2004.

[6] C.E. Aalseth et al. (Majorana Collaboration), Phys. Atom. Nucl. **67** 2002 (2004).

[7] I. Abt et al.,
Nucl. Instrum. Meth. **A577**, 574-584 (2007).1

[8] Barbeau et al., JCAP **0709**, 009 (2007).