3 GERDA: Neutrinoless Double Beta Decay in ^{76}Ge

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When neutrinos propagate over macroscopic distances they can change their observed flavor eigenstate (so lepton flavor is not conserved). Neutrino oscillations demonstrate that neutrinos have mass but to explain these observations, it is necessary to understand a number of other properties of neutrinos and their interactions. The following issues are to be addressed:

- the absolute mass scale of the neutrinos,
- the full neutrino mixing matrix (including CP-violating phases), and
- are neutrinos Dirac or Majorana particles?

The Majorana nature of neutrinos can be studied in experiments searching for neutrinoless double beta decay ($0\nu\beta\beta$), which would involve a nucleus emitting two electrons that share the full Q-value of the decay. If the neutrino is a Majorana particle, this process is allowed in all isotopes that undergo the standard double beta decay ($2\nu\beta\beta$).

GERDA is an experiment searching for the $0\nu\beta\beta$ decay in ^{76}Ge ($Q = 2039.01 \pm 0.05$ keV). The source material is enriched in ^{76}Ge, which simultaneously acts as detector with an energy resolution of 0.1-0.2 % FWHM at 2 MeV. A novel shielding concept features bare germanium diodes operated in a 65 m^3 cryostat filled with liquid argon and surrounded by a 3 m thick water Cerenkov shield which moderates and captures external and muon-induced neutrons. The argon is used for cooling of the diodes and as a passive shield against the residual environmental background.

The experiment proceeds in two phases. Phase I uses eleven HPGe detectors, eight enriched in ^{76}Ge and three detectors made of ^{nat}Ge, with total masses of 17.7 kg and 7.6 kg, respectively. The goal at this stage is to improve the current limits and scrutinize the results of the Heidelberg-Moscow experiment [2]. Phase II, to start in the summer of 2013, will use additional enriched broad-energy germanium (BEGe) detectors, aiming for a total exposure of 100 kg·yr. With a background goal of 10^{-3} counts/(keV·kg·yr), the half-life sensitivity is $T_{1/2} = 2 \times 10^{26}$ yrs. The corresponding range of effective neutrino masses, taking into account the uncertainty in the matrix element and neglecting new lepton number violating interactions, is $0.09-0.15$ eV.

The operation of GERDA Phase I started in November 2011. Soon after, two enriched detectors showed an increase in the leakage current, and have been excluded from the analysis, resulting in a reduced total mass of the enriched detectors of 14.63 kg. Energy calibration for each detector is made with a ^{228}Th source assuming second-order polynomials. The average energy resolution at $Q_{\beta\beta} = 2039$ keV is 4.5 keV at FWHM.

The $2\nu\beta\beta$ decay in ^{76}Ge was measured with unprecedented signal-to-background ratio using an initial exposure of 5.04 kg·yr (126 live days acquired in the period November 2011 - March 2012), resulting in

$$T^{2\nu}_{1/2} = 1.84^{+0.14}_{-0.10} \times 10^{21}\ \text{yr [3].}$$

A much larger dataset with an exposure of 18.4 kg·yr reached in March 2013 is currently under analysis, and a precise background model is under development. The background level in the energy region of interest ($Q_{\beta\beta}\pm$100 keV) is 1.7×10^{-2} counts/(keV·kg·yr), one order of magnitude lower than in the Heidelberg-Moscow and IGEX experiments. The energy window $Q_{\beta\beta}\pm$20 keV is masked, with the unblinding scheduled for June 2013.

3.1 Data analysis in Zurich

We have implemented an automated calibration routine in the general GERDA analysis framework (GELATIO) and are responsible for the analysis of the weekly calibration runs and monitoring the stability of the energy calibration and resolution of the Ge diodes. For each detector we extract the position of the various peaks and the corresponding calibration curves.

FIG. 3.1 – Source Insertion System.

FIG. 3.2 – Control Box.

We are also involved in the selection of the final datasets for the $0\nu\beta\beta$ physics analysis, focusing on quality cuts applied to raw data signals, and in the development of the statistical analysis. We are developing cuts removing saturated and pile-up events and events with nonstandard rise-times and determine the associated efficiency factors.

3.2 Phase II calibration system

As a leader of the calibration working group, we are responsible for the calibration system hardware. The weekly calibration is performed using three motor-controlled source insertion systems (SISs, designed and built at UZH), which lower encapsulated ^{228}Th sources on tantalum holders into the cryostat on steel bands.

In Phase II, 30 new BEGe detectors will be deployed at LNGS in a new, single-arm lock system which can house seven detector strings. One string will consist of four pairs of BEGe detectors mounted back-to-back in a single holder system made from low-background copper and silicon plates. In order to evaluate the required number of SISs and of calibration positions for each detector string, we perform Monte Carlo simulations with GEANT4, where we study how to reach sufficient statistics for energy and pulse shape calibrations within a reasonable amount of time.

Since the height of the new Phase II lock will be considerably increased (the distance from the top of the lock to the center of the cryostat will be 8.5 m), the existing steel belts holding the calibration sources will be replaced. We have constructed a new SIS at UZH (Fig. 3.1), along with the control unit for three systems offering redundancy in case of failure (Fig. 3.2). The system is currently under test and fine tuning for best agreement between the position determinations with the two encoders is in progress.

3.3 Tests of enriched BEGe detectors

From 37.5 kg of available enriched ^{76}Ge, thirty working BEGe detectors were produced, with a total mass 20.1 kg. We have participated in the characterization of all detectors at the Hades underground facility in Belgium. A dedicated study of germanium detectors depleted in ^{76}Ge content, to which our group contributed [4], was crucial in verifying all the production steps. We also contributed to the optimization of the acceptance protocol which considers parameters such as depletion and operational voltage, energy resolution, and leakage current. Measurements were performed to study the charge collection features of each diode and to determine the detector active volume and mass, as well as the dead-layer thickness and the uniformity over the crystal surface.

We are involved in the analysis of the ^{228}Th calibration data regarding pulse shape discrimination and estimation of the dead-layer of the diodes. The dead-layer is found by comparing measured energy spectra from ^{133}Ba and ^{241}Am sources with simulated spectra with varying dead-layer thickness. The dead-layer thickness at the n^+ contact ranges from 0.7 mm to 1.2mm, and the active volume fractions are between 86% and 92%.

3.4 Liquid argon instrumentation

In Phase II of the GERDA experiment, the background level in the region of interest (ROI) is to be reduced by one order of magnitude compared to Phase I. Some background events in the ROI occur in coincidence with a signal in the liquid argon (LAr) surrounding the Ge detectors. The LAr scintillation signal (λ = 128 nm) produced in such events will be detected and used in an active veto system which is presently being designed.

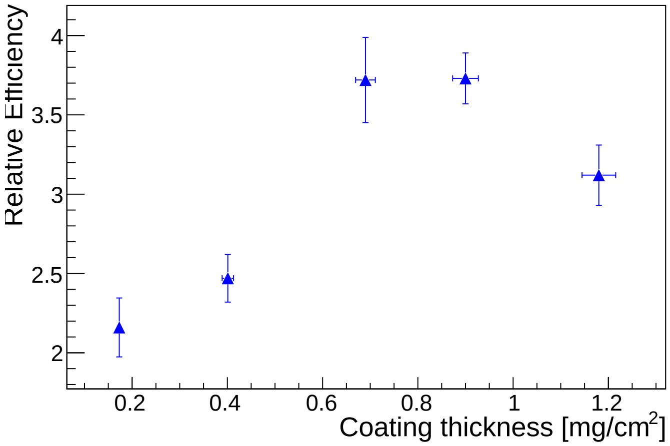

FIG. 3.3 – Wavelength shifting efficiency of Tetratex coated with TPB relative to uncoated VM2000 as a function of the coating thickness.

FIG. 3.4 – Coated foil in our LAr setup, illuminated with a UV lamp.

The LAr instrumentation system will consist of both low-radioactivity Hamamatsu R11065 PMTs and of SiPMs coupled to an optical fiber curtain for the light readout. Since the quartz windows of the PMTs and the optical fibers absorb light at 128 nm reflector foils with wavelength-shifting (WLS) coatings will surround the instrumented LAr volume.

The WLS coatings should meet the following requirements: high conversion efficiency, long-term stabiliy in LAr, and high radio-purity. We have studied several WLS solutions consisting of a polymer coated with the WLS in our LAr detector at UZH, equipped with an R11065-10 Hamamatsu PMT. The WLS is usually tetraphenyl butadiene (TPB), but can also be a plastic scintillator, as well as BCF-10 fiber dissolved in toluene. The studies have been performed on a specular highly reflective multilayer polymer foil VM2000, and on Tetratex, a diffuse highly reflective PTFE fabric. The fabric nature of Tetratex allows coatings with pure TPB which would otherwise not be stable. The best results were obtained (Fig. 3.3) for a combination of 0.8 mg/cm^2 of pure TPB wet-coated onto Tetratex, showing efficiency which is about 3 times higher than for VM2000 alone. This coating-reflector foil combination also showed high mechanical stability during thermal cycling between room and LAr temperatures. Final tests on the optimal thickness and the long-term behavior study in LAr are ongoing (see Fig. 3.4).

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[3] M. Agostini *et al.*, J. Phys. G40, 035110 (2013).

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