GERDA and the search for neturinoless double-β decay

M. Agostini, B. Bode, D. Budjas, E. Engelmann, J. Janicsko, A. Lazzaro, S. Schönert, and C. Wiesinger

INTRODUCTION

Many extensions of the Standard Model of particle physics predict the existence of a lepton-number-violating nuclear transition called neutrinoless double-β decay ($0\nu\beta\beta$). In this transition, two neutrons decay simultaneously into two protons emitting only two electrons: $(A, Z) \rightarrow (A, Z+2) + 2e^-$. The observation of this process would prove the existence of physics beyond the Standard Model and, in particular, that neutrinos have a Majorana mass component.

For about a decade, the most stringent constrains in $0\nu\beta\beta$ search had been set by the Heidelberg-Moscow (HdM) and the IGEX experiments, respectively $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr [1] and $T^{0\nu}_{1/2} > 1.6 \cdot 10^{25}$ yr [2]. These results are in tension with a successive claim for a positive signal reported by a subgroup of the HdM experiment, $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr [3].

The GERDA experiment [4] pursues a staged implementation. The goal of Phase I (concluded in 2013) was to probe the claim for a positive signal. The experimental apparatus is currently being upgraded to increase the target mass and install new hardware components for a further background reduction. In the next data taking phase (Phase II), GERDA will start a pioneering exploration of $T^{0\nu}_{1/2}$ values in the range of 10^{26} yr.

CONCEPT AND DESIGN OF GERDA

GERDA searches for the $0\nu\beta\beta$ of ^{76}Ge using an array of high-purity Ge (HPGe) detectors produced from isotopically-modified material (87% ^{76}Ge). The detectors are mounted into strings and immersed directly in ultra radio-pure LAr. LAr acts as coolant material, passive shielding against external natural radioactivity and active veto-system when its scintillation light is detected. The shielding is complemented by a 3 m layer of water instrumented with photo-multiplier to detect the Cherenkov light produced by the passage of muons. The experiment has been assembled deep underground at the "Laboratori Nazionali del Gran Sasso" of INFN in Italy. A sketch of the apparatus is shown in Figure 1.

HPGe detectors are a well consolidated technology that ensures excellent energy resolution, long term stability and optimal radio-purity. These detectors are typically used as calorimeters but pulse shape discrimination (PSD) techniques can also be applied to enhance the signal to background ratio. As the ^{76}Ge decays occur inside the Ge crystal, the experimental signature of $0\nu\beta\beta$ would be a peak in the energy spectrum at the Q-value of the decay ($Q_{\beta\beta} = 2039$ keV).

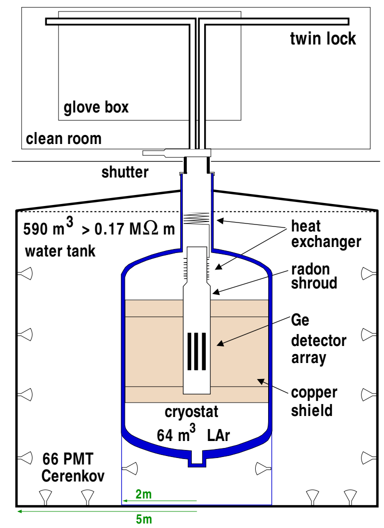

Figure 1: Schematic drawing of the experiment.

RESULTS OF PHASE I

Phase I data were collected between November 2011 and May 2013. Ten detectors have been used for analysis, providing 17.6 kg of enriched-Ge target mass. The stability of the energy scale and resolution was monitored separately for each detector with ^{228}Th calibration runs performed every one or two weeks. Shifts of the energy scale were found to be $< 0.05\%$ at $Q_{\beta\beta}$, much lower than the exposure-weighted energy resolution of the dataset: 4.6 ± 0.3 keV (full-width half maximum).

The background level of the data set at $Q_{\beta\beta}$ is about 0.02 cts/(keV$\cdot$ kg$\cdot$ yr), rather stable over the data taking period. Comprehensive background models capable of accurately reproducing the data have been developed [5]. The background at $Q_{\beta\beta}$ is attributed mostly to gamma-rays from close ^{208}Tl and ^{214}Bi sources, ^{226}Ra and ^{210}Po contaminations on the detector surfaces, and ^{42}K decays in the LAr volume surrounding the detector array.

To further reduce the background, pulse shape discrimination techniques (PSD) based on the analysis of the time-structure of the digitized signals were developed and tuned before the actual $0\nu\beta\beta$ analysis [6]. The cuts were tuned to ensure a high signal acceptance ($\gtrsim 90\%$) and provide a background suppression at $Q_{\beta\beta}$ of about a factor $\sim$2.

A blinded analysis was performed for the search of the $0\nu\beta\beta$ signal [7]. All analysis parameters have been fixed before processing the data in the energy range of $Q_{\beta\beta} \pm 5$ keV. The energy spectrum around $Q_{\beta\beta}$ after the data unblinding is shown in Figure 2. The number of counts observed (expected from background) in the energy window $Q_{\beta\beta} \pm 5$ keV after PSD is 3 (2.5).

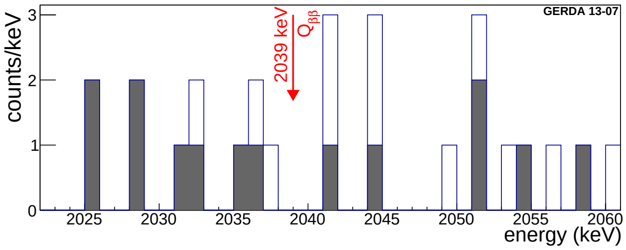

Figure 2: Combined energy spectrum from all detectors before (empty histogram) and after (filled) PSD.

To derive a limit on the $0\nu\beta\beta$ signal strength, a (extended) profile likelihood fit was used with a pdf given by a Gaussian peak for the signal over a constant distribution for the background. All systematic uncertainties due to detector parameters, $0\nu\beta\beta$ acceptance, energy scale have been evaluated by using a Monte Carlo based approach. The best fit value is for no signal counts – i.e. no excess of signal events above the background – and the derived limit on the $0\nu\beta\beta$ half-life is $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L. This result lies below the median sensitivity of GERDA expected for no signal ($T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr at 90% C.L.).

A hypothesis test has been performed to compare the GERDA data with the signal claim of Ref. [3]. The probability of our experimental result given the claimed signal strength is 1% (p-value computed using the profile likelihood). Consistently, the Bayes factor computed for the model "$0\nu\beta\beta$-signal plus background" and "background only" is $2.4 \cdot 10^{-2}$.

ACTIVITIES OF THE LOCAL GROUP

In the years 2011-2013, the GERDA group at TUM included eight members: three seniors and five students. We provided remarkable contributions to Phase I analysis and to the development of new hardware for Phase II, in particular to:

- Phase I data reduction, including the development of the official analysis framework and of the algorithms for digital signal processing [8, 9];
- background modeling in Phase I and PSD techniques for background reduction [6];
- modeling, design, production and characterization of new Ge detectors for Phase II [10, 11, 12, 13];
- design and production of wavelength shifting fibers readout with Si photo-multipliers to detect the LAr scintillation light;
- detector array assembly for Phase II and integration tests.

In addition, using the MLL Tandem Accelerator, we produced radioactive isotopes of great interest for GERDA.

As previously mentioned, one of the main background components of GERDA Phase I is ^{42}K, progeny of ^{42}Ar cosmogenically activated in LAr. Its distribution inside the GERDA cryostat was observed to be affected by electric fields. The study of this effect was complicated by the relatively low concentration of ^{42}Ar. To improve the accuracy of the measurements, two samples of ^{42}Ar were produced at the Tandem Accelerator from ^{40}Ar through (^{7}Li, α-p) reactions by using a $^{7}Li^{3+}$ beam hitting a gas cell target. The samples have been finally injected into a dedicated LAr cryostat (LArGe setup [14]), increasing the natural ^{42}Ar concentration of more than two orders of magnitude.

Recently, also ^{56}Co has been activated using ^{56}Fe(p,n) reactions. ^{56}Co emits high energy gamma-rays up to 3.5 MeV and can be used to create a sample of $0\nu\beta\beta$-like energy deposition at the $Q_{\beta\beta}$ energy. The source has been deployed inside GERDA to accurately assess the efficiency of the PSD cut which is a parameter of paramount importance for the $0\nu\beta\beta$ analysis.

THESES

- A. Lazzaro, "Studies of high-purity Ge detector signals", Master thesis, 2012
- R. Kneißl, "Investigations of liquid argon scintillation read out with scintillating fibres for the GERDA neutrino-less double beta decay", Bachelor thesis, 2012
- C. Weinberger, "Development of high-purity front end electronic components for the neutrino-less double beta decay experiment GERDA", Bachelor thesis, 2012
- E. M. Sicheneder, "Characterization of the Silicon Photomultipliers for the liquid argon veto for GERDA" Bachelor thesis, 2012
- M. Agostini, "Signal and background studies for the search of neutrinoless double beta decay in GERDA", PhD thesis, 2013

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