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The search for $0\nu\beta\beta$ decay with the GERDA experiment

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The status of the GERDA experiment for the search of $0\nu\beta\beta$ decay is reviewed. The background index in the energy region of interest after 6.1 kg·y of measurement is shown to be $0.02^{+0.006}_{-0.004}$ cts/(keV·kg·y). The measurement of $2\nu\beta\beta$ decay results in a preliminary half life of $T_{1/2}^{2\nu\beta\beta}(^{76}Ge)=(1.88\pm0.10)\cdot10^{21}$ yr. The status of the preparations for the upgrade of GERDA with additional 30 BEGe detectors with a total mass of 20.8 kg made from germanium enriched to ≈87% in ^{76}Ge is given.

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Figure 1: Left: Model of the GERDA experiment. Right: Three detector strings. Three detectors are mounted per string. They are surrounded by a copper shroud.

1. Introduction

Since oscillations between neutrino flavors could be detected unambiguously [1] it is clear that neutrinos must have a tiny but non vanishing mass. Massive neutrinos could be their own CP conjugates, ie. antiparticles, so called Majorana particles. This property would allow to attribute a non vanishing Majorana mass term to neutrinos that could be naturally tiny thanks to the seesaw mechanism.

Neutrino accompanied double beta ($2\nu\beta\beta$) decay is a second order weak process. Two neutrons coherently decay to two protons under the emission of two electrons and two electron anti-neutrinos. In case neutrinos have Majorana character, the decay could be induced by an exchange of a neutrino and hence happen without the emission of neutrinos.

Observation of neutrinoless double beta ($0\nu\beta\beta$) decay would hence reveal Majorana character of neutrinos and imply Lepton number violation in the neutrino sector, a key ingredient for the explanation of the baryon asymmetry of our universe by baryogenesis via leptogenesis.

While $2\nu\beta\beta$ decay has been observed for many isotopes, the neutrinoless mode could not yet be observed without doubt. The most stringent limits have come for more than a decade from experiments using High Purity Germanium (HPGe) detectors that are enriched in the double beta emitting isotope ^{76}Ge ($Q_{\beta\beta}$=2040keV) to ≈86%: The Heidelberg-Moscow and the IGEX collaboration give lower limits for $0\nu\beta\beta$ decay of ^{76}Ge with $1.9\cdot10^{25}$ yr [2] and $1.6\cdot10^{25}$ yr [3], respectively. A subgroup of the Heidelberg Moscow collaboration has claimed evidence for observation of $0\nu\beta\beta$ decay of ^{76}Ge with a half life of $T_{1/2}^{0\nu\beta\beta}=(1.2^{+3.0}_{-0.5})\cdot10^{25}$ yr [4], which would be consistent with an effective Majorana neutrino mass of $0.44^{+0.14}_{-0.20}$ eV (3σ) .

The KamLAND-Zen experiment and the Enriched Xenon Observatory (EXO) have recently published lower limits of $0\nu\beta\beta$ decay of ^{136}Xe $1.9\cdot10^{25}$ yr and $1.6\cdot10^{25}$ yr, respectively [5],[6]. In [5] a combined analysis is done. It is claimed that a 90%C.L. lower limit of $3.4\cdot10^{25}$ yr can be set, excluding an effective Majorana neutrino mass of >0.12 eV – 0.25 eV, depending on the nuclear matrix element calculation. While this refutes with 97.5%C.L. $0\nu\beta\beta$ decay induced by the exchange of a light Majorana neutrino consistent with the claim [4], $0\nu\beta\beta$ decay consistent with

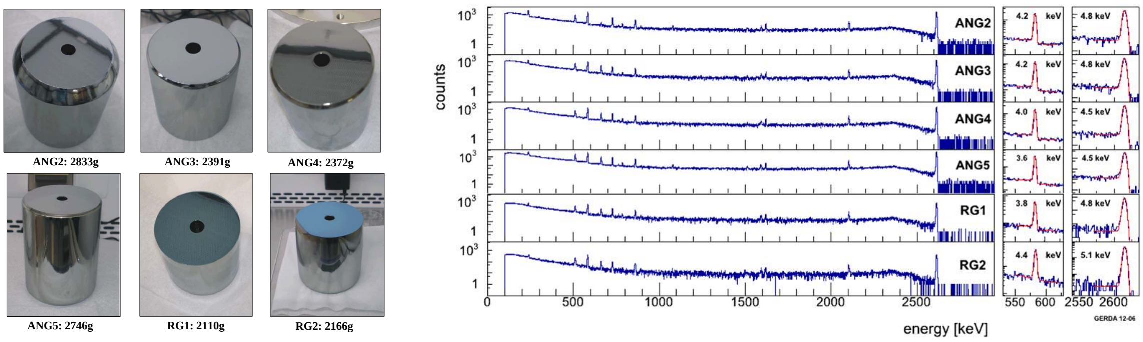

Figure 2: Left: Bare HP^{enr}Ge detectors from the Heidelberg-Moscow and IGEX experiments. Right:Energy spectra of a calibration measurement of the six working HPGe detectors enriched in ^{76}Ge. The calibration peaks at 2615 keV and 583 keV are shown in separate windows.

the claim induced by other scenarios such as SUSY, leptoquarks, compositness can be tested only by germanium based experiments.

The GERmanium Detector Array (GERDA) experiment is designed to confirm or refute the claim for evidence in the first phase of the GERDA experiment. In a second phase the available target mass and the background identification possibilities will be significantly increased, increasing the overall sensitivity to the half life of $0\nu\beta\beta$ decay to $2{\cdot}10^{26}$ yr (90% C.L.).

2. The experimental setup

The design of the GERDA experiment bases on the concept to operate bare HPGe detectors directly in a cryogenic liquid [7]. The ultra clean cryogenic liquid acts as shield against external radiation and cooling medium for the HPGe detectors simultaneously. A sketch of the setup is shown in Fig. 1. The array with HPGe detectors is submersed into the center of a liquid Argon (LAr) cryostat with 4 m diameter. The cryostat itself is surrounded by a water tank with 10 m diameter that is instrumented with Photo Multiplier Tubes (PMTs). The water shields against external γ radiation, moderates and captures neutrons and serves as a muon Cerenkov veto in connection with the PMTs. On top of the tank a clean room houses the lock system through which the HPGe detectors can be manipulated and lowered into the tank.

For the first phase eight reprocessed HPGe detectors of the Heidelberg-Moscow and IGEX experiments are used. The available HPGe detectors after dismounting from the vacuum cryostats are shown in Fig. 2. The overall mass of the six working HPGe detectors is 14.6 kg corresponding to 165 moles of ^{76}Ge.

The detectors are mounted together with a reference detector made from germanium with natural abundance in three strings. In a second string two more HPGe detectors with natural abundance were installed. The individual strings with enriched detectors are surrounded by shrouds made from 60 μm copper foil (see Fig. 1 right). The copper shroud is needed to shield the detectors against ^{42}K ions generated from the decay of ^{42}Ar. ^{42}K decays with a Q-value of 3.54 MeV via β decay with 81.9% probability to the ground state of ^{42}Ca. If drifted close to the surface of the HPGe detectors by the present electrical fields ^{42}K can thus lead to background events in the energy region of interest around $Q_{\beta\beta}$.

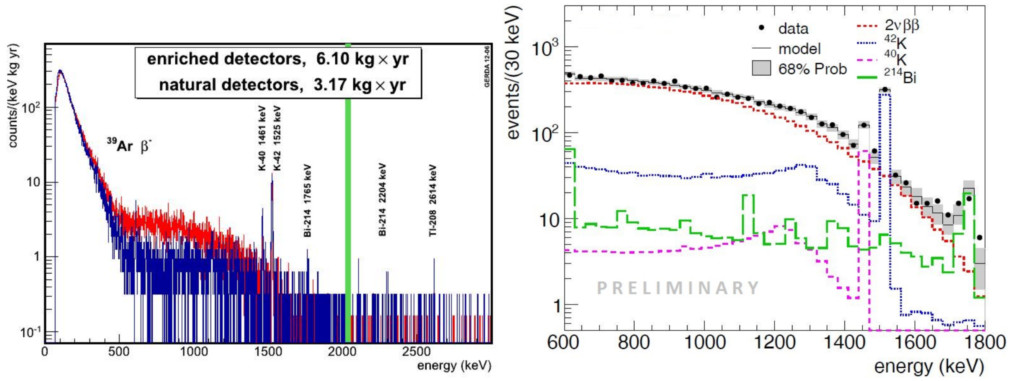

Figure 3: Left: Background spectra taken with the phase I HPGe detectors enriched in ^{76}Ge (red) and HPGe detectors made from natural germanium (blue). Prominent lines from identified background contributions are labelled. The energy region around the Q-value of $\beta\beta$ decay is blinded (green line). Right: Background spectrum of the enriched detectors in the energy region 600 keV – 1800 keV. A decomposition obtained by fitting simulated spectra to the prominent features is shown. Ohter identified background components are not considered as they are negligible in the shown energy range.

Since November 2011 the GERDA experiment is running in its phase I configuration. Calibration spectra of all enriched detectors are shown in Fig. 2. The energy resolution (FWHM) at 2.6 MeV of the detectors is between 4.5 keV (0.17%) and 5.1 keV (0.20%). Until June 2012 a total of 6.1 kg·yr of data has been taken with the enriched detectors.

3. First results from GERDA phase I

The energy spectrum of the enriched detectors after 6.1 kg·yr and of the HPGe detectors with natural abundance after 3.7 kg·yr are shown in Fig. 3 (left). In the energy region below ≈500 keV both spectra are dominated by events resulting from the β decay of cosmogenically produced ^{39}Ar. A clear excess due to $2\nu\beta\beta$ decay is seen between 600 keV and 1500 keV in the detectors enriched in ^{76}Ge. A preliminary analysis results in a half-life for $2\nu\beta\beta$ decay of ^{76}Ge $T_{1/2}^{2\nu\beta\beta}$=(1.88±0.10)·10^{21} yr [8].

Figure 3 right shows a decomposition of the energy spectrum in the energy range from 600 keV to 1800 keV into different observed components: The presence of the background components is inferred from peaks in the energy spectrum at 1460 keV (^{40}K), 1525 keV (^{42}K) and 1764 keV (^{214}Bi). Other contributions to the background index (BI) in the energy region of interest are due to ^{228}Th and ^{228}Po on the surface of the detectors.

The data is blinded in an energy region of (2040 ± 20) keV around the Q-value of the $\beta\beta$ decay of ^{76}Ge. No visible features are contained in the energy windows 1940 to 2140 keV. The BI is $0.020^{+0.006}_{-0.004}$ cts/(keV·kg·yr).

The BI reached with the GERDA experiment is by a factor of 8 (13) lower than the ones from the Heidelberg Moscow and IGEX experiments [9].

Under the current conditions a 90% lower limit on the half life of $2 \cdot 10^{25}$ yr can be obtained after 20 months of total running time.

4. Preparations for GERDA phase II

To bring the BI to a level of 10^{-3} cts/(keV·kg·yr). additional efforts are necessary. Hence, active veto technologies will be used for the second phase of GERDA.

When energy is deposited in LAr it scintillates at 128 nm. If LAr scintillation light can be detected coincident with an energy deposit in a HPGe detector, the event is very likely a background event. This allows for very efficient rejection of external background events. Measurements have shown that this technique works reliably [10].

The second phase of GERDA will exploit this background recognition technique. Two alternative designs are being prepared. In the low background photo multiplier tube (PMT) design a shroud with ≈ 500 mm diameter, lined with VM2000 reflecting foil is surrounding the detector array. The PMTs are mounted at a distance of $\approx$800 mm above and below the detector array at the top and the bottom of the shroud. A test setup is shown in Fig. 4. The second design foresees a containment created by a curtain of $\approx$ 1080 wavelength shifting fibers surrounding the detector array. The light transported by the fibers is detected using silicon photo multipliers coupled to the fibers. It has been shown in simulations that with both designs background rejection efficiencies of 100 can be reached for background induced by an external ^{228}Th source. The option to insert both designs simultaneously is also considered.

Complementarily background can be recognized for events depositing energy inside the detector only: The energy of the two electrons emitted in $\beta\beta$ decay are deposited mostly within 1 mm^3 in a single site event (SSE) while for Compton scattered background events the energy deposits will likely be separated by $\approx$ cm causing a multi site event (MSE) [11]. If event topologies can be distinguished by pulse shape analysis [12] or segmentation [13] a significant fraction of background events due to γ radiation can be rejected in the analysis. For phase II of the GERDA experiment detectors with special field configuration will be used [14]. The field configurations of BEGe detectors in conjunction with the surface properties allow for very efficient distinction of signal like SSEs from MSEs and surface events [15].

The 37.5 kg of germanium enriched in ^{76}Ge to ≈ 87 % procured in 2005 [9] have been transformed into 29 working BEGe diodes with a total mass of ≈ 20 kg. During all processing steps great care has been taken to minimize the activation of the enriched germanium with cosmogenic isotopes such as ^{68}Ge and ^{60}Co. All transport has been performed in a specially designed container. Transport between Europe and the USA was done by ship, taking care to store the container at the lowest possible container slot as shown in Fig. 4 middle, thus ensuring optimal shielding of the enriched germanium against cosmic rays during the ≈ 10 day ship voyage. At all production sites the germanium was stored in underground sites while no processing was going on. The rigorous effort to minimize exposure of the material allows to keep the BI (without veto from the discrimination techniques) expected due to ^{68}Ge and ^{60}Co at a level of $1.8 \cdot 10^{-3}$ cts/(keV·kg·yr) in spring 2013, at this time dominated by the decay of ^{68}Ge ($T_{1/2}$=270.8 days).

Ensuring very low background surrounding, shielded transports together with the exploitation of the described background recognition techniques will allow to further significantly reduce the BI in the energy region of interest. The goal is to reach a BI of $<10^{-3}$ cts/(keV·kg·yr). This would allow to push the 90% C.L. half life exclusion limit sensitivity of the experiment to above 10^{26} years within three years of measurement as shown in Fig. 4.

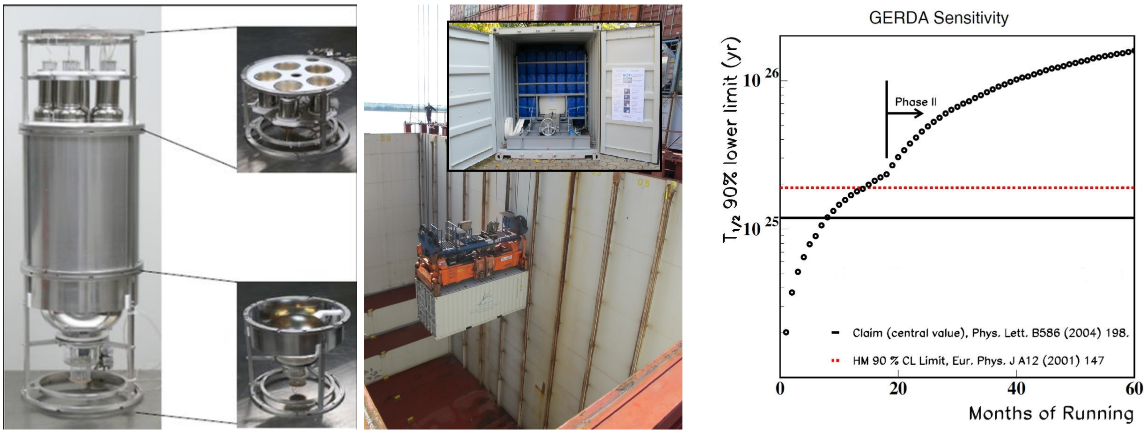

Figure 4: Left: LAr instrumentation test setup with PMTs. Middle: Shielding container being loaded into the bottom of a transatlantic ship. The shielding container is shown in the inlet. Right: Sensitivity reach of the GERDA experiment in terms of 90%C.L. half life limit.

5. Conclusions and outlook

Phase I of GERDA started data taking in late 2011. The experiment is running stably since with a BI of $0.020^{+0.006}_{-0.004}$ cts/(keV·kg·yr). A total of 6.1 kg·yr of data has been taken until June 2012. The measured preliminary half life of $2\nu\beta\beta$ decay is $(1.88\pm0.10)\cdot10^{21}$ yr. Preparations for phase II of the experiment are ongoing and the upgrade with LAr instrumentation, additional 30 BEGe detectors enriched in ^{76}Ge with a total of 20.8 kg are planned for 2013.

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