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The GERDA Experiment: Status and Future Plans

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Abstract. The GERDA experiment is searching for the neutrinoless double beta decay of ^{76}Ge. An observation of the neutrinoless double beta decay will not only prove lepton number violation by two units, but also that the neutrino is its own anti-particle, thus of Majorana type. The status of the experiment will be presented.

Keywords: neutrinoless double beta decay, Majorana neutrino, low background experiment, germanium 76.

1. Introduction

Neutrino oscillations proved that a neutrino has a mass. Then new questions arise. Is the neutrino a Dirac particle or a Majorana particle? What is the absolute neutrino mass scale? An experimental way to approach these questions is to search for a particular nuclear decay, the neutrinoless double beta decay (0νββ), which can be summarized as

$$(A, Z) \to (A, Z + 2) + 2\mathrm{e}^-$$

where Z and A are, respectively, the atomic and the mass numbers. In contrast with the predicted and observed double beta decay with the emission of two neutrinos (2νββ)

$$(A, Z) \to (A, Z + 2) + 2\mathrm{e}^- + 2\bar{\nu}_\mathrm{e},$$

the 0νββ violates the lepton number by two units, so it is not predicted by the Standard Model. The Schechter–Valle theorem states that 0νββ implies that the neutrino is a Majorana particle [1]. Moreover, if it is a real decay, it is possible to evaluate the effective mass of the electron neutrino

$$m_{\beta\beta} = \left|\sum_i U_{\mathrm{e}i}^2 m_i\right|$$

which contains information on the absolute mass scale (U is the neutrino mixing matrix, m_i are the mass eigenvalues) from the half life by the relation

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \frac{m_{\beta\beta}^2}{m_\mathrm{e}^2}$$

where $G_{0\nu}$ is the phase space factor and $M_{0\nu}$ is the nuclear matrix element.

GERDA (GERmanium Detector Array) [2] is an underground ultra-low background experiment located in the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, designed to search for the neutrinoless double beta decay of ^{76}Ge

$$^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se} + 2\mathrm{e}^-.$$

Figure 1. Strings of detectors inside the minishrouds.

^{76}Ge has a particular importance because the only claim of observation of 0νββ comes from a part of the Heidelberg–Moscow (HdM) collaboration in an experiment with this isotope. The final result obtained by Klapdor et al. is [3]

$$T_{1/2}^{0\nu\beta\beta,{}^{76}\mathrm{Ge}} = 2.23^{+0.44}_{-0.31} \times 10^{25}\,\mathrm{yr}$$

for an effective neutrino mass

$$m_{\beta\beta} = 0.32^{+0.03}_{-0.03}\,\mathrm{eV}.$$

2. GERDA design

The key components in the GERDA experiment are the High Purity Germanium (HPGe) detectors. The detectors are made of enriched material, so that the isotope of interest can reach up to 86 % of the mass, when the natural abundance is only 7 %. The idea

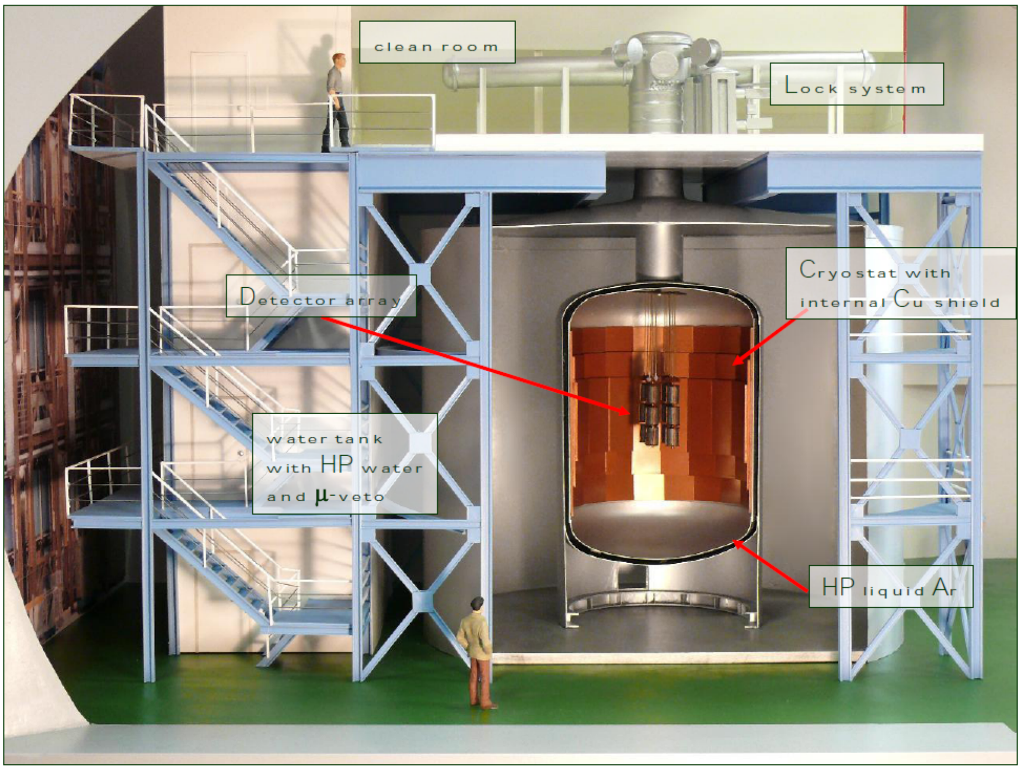

FIGURE 2. Sketch of the GERDA experiment, which is located in the Laboratori Nationali del Gran Sasso.

is to detect $0\nu\beta\beta$ decays taking place in the detectors themselves. The measured quantity is the sum of the kinetic energy of the electrons. For a $0\nu\beta\beta$ decay, this sum is equal to the Q-value of the decay ($Q_{\beta\beta} = 2039\,\mathrm{keV}$). Instead, part of the energy released in a $2\nu\beta\beta$ decay is carried away by the neutrinos, thus producing a continuous spectrum.

If $0\nu\beta\beta$ exists, its half life is longer than 10^{25} yr. Then very high exposure is required to achieve a significant result. In the meantime, background events induced by other physics processes may release energy near $Q_{\beta\beta}$. Then it is important to minimize the background in the region of interest (ROI).

In GERDA, the detectors are operated in a cryostat filled with liquid argon (LAr), in direct contact with it. The liquid argon acts as a cooling medium and as a passive shield. In the future, the LAr will be instrumented to detect its own scintillation light for further background suppression.

Around the cryostat, a water tank acts as a Cherenkov veto, designed to identify muon events which may induce a signal in the Ge detectors.

A scheme of the experiment is sketched in Fig. 2.

The detectors are arranged in strings with low mass holders, to minimize the mass inside the cryostat. The detector strings are surrounded by thin copper foils, minishrouds, as shown in Fig. 1. The minishrouds prevent the drift of ions near the detectors not only as a physical barrier but also because electric field lines which start from the detectors close on the minishroud; then it is possible to create a field-free configuration in the cryostat.

3. GERDA ROADMAP

The goal of Phase I of the experiment is to check Klapdor's claim. For a design background index (BI) of 10^{-2} cts/(keV kg yr), an exposure of ~ 15 kg yr is needed to reach a 90 % C.L. In Phase I, most of the mass comes from the detectors which were previously operated in the HdM [4] (five detectors, the detectors of the claim!) and in the IGEX [5] (three detectors) experiments.

A second phase of the experiment is already planned and funded. For Phase II, the goal is a background index of 10^{-3} cts/(keV kg yr). To reduce the Phase I background, most of the mass will be provided by custom-made Broad Energy Germanium (BEGe) detectors [6], made of enriched material. It has been proved that detectors of this kind provide better pulse shape discrimination than the coaxial detectors which were operated in the HdM and IGEX experiments [7]. Another improvement will be the detection of the LAr scintillation light. R&D is ongoing to choose the optimal solution (good detection without introducing new background in the cryostat). With the planned exposure of 100 kg yr, in Phaser II GERDA will be able to scrutinize an effective mass of the electron neutrino of ~ 0.2 eV.

4. PHASE I STATUS

Phase I started in November, 2011. This paper reports on the results of 194 days of data taking. During this period, the livetime was about 152 days, corresponding to a duty cycle of ~ 78 %.

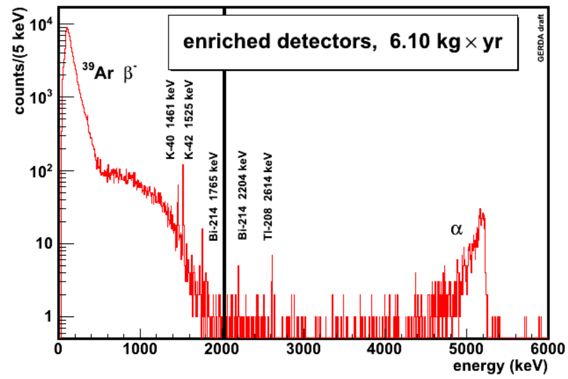

FIGURE 3. Full energy spectrum of enriched detectors. The most prominent lines are labeled.

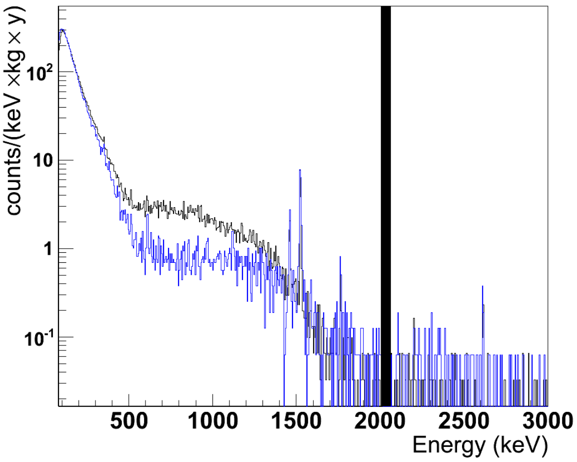

FIGURE 4. Energy spectra of natural and enriched detectors.

Physics data are continously collected, except during the calibrations with ^{228}Th sources, which are performed every 7–15 days. A calibration run takes a few hours. If problems occur, they are reported by the real-time slow control monitor and by off-line data analysis [8].

In this period a problem of stability of the temperature of the clean room arose. Some data are not considered in the analysis at the moment because the energy scale was not reliable. These data may be recovered in the future.

Presently, a blinding of the region $Q_{\beta\beta} \pm 20$ keV is applied. In the plots, it is represented as a black band. Events having a signal in the blinding energy window are automatically removed from the data stream which is used for analysis and stored in a separated area. The goal is to provide a first estimate of the background at $Q_{\beta\beta}$ without looking at the signal region, in order to be as unbiased as possible. The blinding will be removed when sufficient statistics to reach the Phase I goal is collected.

Only six enriched detectors have been considered in the current analysis, because two Phase I detectors showed problems with the leakage current. The total mass of the six enriched detectors is 14.6 kg, so the total exposure is 6.10 kg yr.

5. The energy spectrum

A new framework called GELATIO [9] has been developed for the energy reconstructions and the analysis of the charge pulses.

Figure 3 is a histogram of the sum of the spectra of enriched detectors, considering only non-muonic, single-detector events.

The low energy part of the spectrum is dominated by the ^{39}Ar beta decay. The released electron can have a kinetic energy up to 565 keV. This is not a problem for the 0νββ search, because 565 keV $< Q_{\beta\beta}$.

A second signature of Ar radioactivity is the peak at 1525 keV, which is due to a gamma emitted in the second step of the decay chain

$$^{42}\mathrm{Ar} \rightarrow {}^{42}\mathrm{K} \rightarrow {}^{42}\mathrm{Ca}.$$

From this peak the concentration of the ^{42}Ar in natural argon has been estimated, and it is found to be larger than the upper limit from the previous literature. This could be a problem, because a beta up to 3525 keV could be emitted in the ^{42}K decay, and it could release part of the energy in a detector (for example around $Q_{\beta\beta}$), if the decay takes place near the surface. The minishroud was developed to treat the ^{42}K problem. The ^{42}K is initially produced in a charged state, then it is important to have a field-free configuration in the cryostat, to avoid collection effects.

Other gamma lines which are clearly visible come from ^{40}K, ^{214}Bi and ^{208}Tl.

The estimated rate for the ^{208}Tl signal at 2614 keV is 1.6 ± 0.5 cts/(kg yr), and it is an order of magnitude lower than the rate in the HdM experiment, 16.5 ± 0.5 cts/(kg yr) [10]. This validates the GERDA concept.

Another important signature in the spectrum comes from the 2νββ decay, which is dominant above the ^{39}Ar region and below $Q_{\beta\beta}$ (Fig. 3). The 2νββ signature is clearly more evident in the enriched detector, see Fig. 4.

Figure 5 presents a decomposition of the spectrum in the range where 2νββ (red) is dominant. According to the current background model, in this region there is a significant contribution of ^{42}K (blue). The contribution from ^{214}Bi is shown in green, and the contribution of ^{40}K is shown in pink. Other components are negligible. The component spectrum shapes have been obtained using MAGE [11], a simulation framework based on Geant4 [12], and a precise model of the GERDA geometry. The amplitudes have been fitted to the data.

To complete the discussion, it is important to quote the current estimate for the background index around $Q_{\beta\beta}$. By choosing a window of $Q_{\beta\beta} \pm 100$ keV, excluding the blind region (for an effective window size of

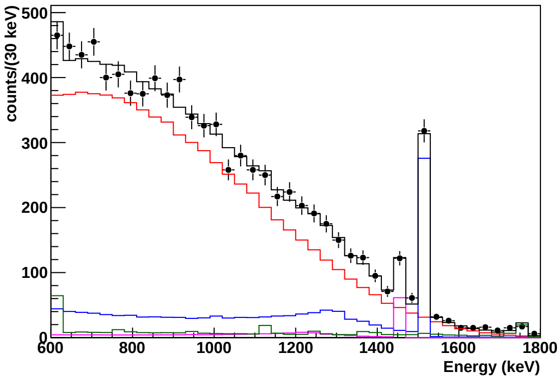

FIGURE 5. Zoom of the $2\nu\beta\beta$ region, and component decomposition ($2\nu\beta\beta$, ^{42}K, ^{214}Bi, ^{40}K; black line: component sum, black dots: data).

160 keV), and by considering the quoted exposure, it is possible to estimate for enriched detectors

$$\mathrm{BI} = 0.020^{+0.006}_{-0.004}\ \mathrm{cts/(keV\ kg\ yr)}.$$

This result has been obtained without pulse shape discrimination. Multi-detector events and events in coincidence with a signal from the muon veto have been discarded.

The pulse shape discrimination is clearly important, but it is also one of the most controversial topics in the Klapdor analysis. At least for Phase I, a more conservative approach is planned concerning pulse shape discrimination.

The background in the HdM experiment, without pulse shape discrimination, is 0.11 cts/(keV kg yr) [13], and this provides further proof of the quality of the GERDA design.

6. Conclusions

GERDA is steadily taking data and working well. The background is very low compared to previous experiments with Ge detectors. In the next year, GERDA will probably be able to achieve the first goal, i.e. a check on Klapdor's claim. Phase II is in an advanced state of preparation.

Acknowledgements

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Discussion

Claudia Tomei — The minishrouds are really close to the detectors. Could they be a possible background source?

Paolo Zavarise — In GERDA, tests with and without the minishrouds have been performed. Best results have been obtained with the minishrouds. Each minishroud is made of radiopure copper. Its thickness is only 60 µm, so its mass is low. Until now, no indications of a contribution to the background have been found.

Carlo Gustavino — In one plot, you have overlapped the energy spectrum of natural and enriched detectors, to show the characteristic shape of $2\nu\beta\beta$ decay. To improve this plot, why haven't you applied pulse shape discrimination?

Paolo Zavarise — Simply because our pulse shape approach is a work in progress, expecially for Phase I detectors. Presently we are more interested in minimizing the "raw" background, and showing the quality of our design.