STATUS AND PROSPECTS OF THE SEARCH FOR NEUTRINOLESS DOUBLE BETA DECAY OF $^{76}\text{Ge}$

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Abstract. This paper presents a review of the search for neutrinoless double beta decay of $^{76}\text{Ge}$ with emphasis on the recent results of the Gerda experiment. It includes an appraisal of fifty years of research on this topic as well as an outlook.

1 Introduction

Fifty years ago Fiorini and collaborators published the first paper on the study of neutrinoless double beta ($0\nu\beta\beta$) decay of the $^{76}\text{Ge}$ isotope, $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^-$ \cite{1}. Physics motivation was the search for lepton number violation (LNV), technical innovation the use of a Ge(Li) crystal acting both as source and high-resolution detector. With a lead-shielded Ge(Li) coaxial detector of 90 g of natural germanium - containing 7.8% of $^{76}\text{Ge}$ - Fiorini et al. observed $\sim 10^{-2}$ counts/(keV·hr) around the transition energy $Q_{\beta\beta} = 2039$ keV, but no $0\nu\beta\beta$ signal, i.e. a sharp peak at $Q_{\beta\beta}$, and inferred after 712 hours of data accumulation a lower half-life limit of $T_{0\nu 1/2} > 3 \cdot 10^{20}$ yr (68% CL). The improvement of the $T_{0\nu 1/2}$ limit in the following decades by 5 orders of magnitude (Fig. 1) is due to a reduction of the background index (BI) - commonly quoted as count rate at $Q_{\beta\beta}$ normalized to energy bin and detector mass $M$ - and an increase of source strength, or exposure $E = M \cdot T$, with $T$ being the run time. The former became possible by better shielding, including the reduction of cosmic

![Figure 1: History of $T_{0\nu 1/2}$ lower limits (68% CL, 90% CL since 1991) and BIs from $^{76}\text{Ge} 0\nu\beta\beta$ studies, see refs. \cite{2,3} and refs. therein. Framed numbers show exposures in mol($^{76}\text{Ge}$)-yr.](image)

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rays by going underground, the latter by progress in the fabrication of larger Ge crystals. Both trends experienced a big boost with the introduction of Ge detectors made from Ge material enriched up to 90% in $^{76}\text{Ge}$ [5].

This article reports mainly on the GERDA experiment which is expected to break the $T_{1/2}^{0\nu} = 10^{26}$ yr frontier in 2018, and on current preparations to reach $T_{1/2}^{0\nu} \geq 10^{27}$ yr sensitivity. These efforts reflect the intensified interest in $0\nu\beta\beta$ decay caused by the discovery that neutrinos have mass, and the theorem that the observation of $0\nu\beta\beta$ decay would establish neutrinos to have a Majorana neutrino mass component, as predicted by various extensions of the Standard Model of particle physics (SM). Among the many models for LNV that of light Majorana neutrino exchange relates $T_{1/2}^{0\nu}$ to an effective Majorana neutrino mass providing access to the absolute neutrino mass scale and its hierarchy [10].

2 Present experiments

The GERDA and MAJORANA collaborations are currently operating a total of 65.3 kg of enriched high purity Ge detectors underground. The main difference of the experiments is the shielding against external radiation, a common feature that they discriminate $0\nu\beta\beta$ decays from background events by their different topology: while the two electrons of a $0\nu\beta\beta$ decay would release their energy within a small detector volume of a few mm$^3$, background events most likely deposit energy in several locations of the detector, on its surface, or in adjacent detectors. Background events can thus be identified by detector-detector anti-coincidences and, in particular, by the analysis of the time profile of the detector signal. For the latter task, both collaborations have independently developed small read-out electrode high purity Ge detectors, p-type Broad Energy (BEGe [11]) or point contact (PPC) detectors [12], which exhibit not only better pulse shape discrimination (PSD) than the traditional coaxial detectors but also superior energy resolution, < 3 keV full width at half maximum (FWHM) at $Q_{\beta\beta}$. To prevent any bias GERDA has adopted, first in the field, the concept of ‘blind analysis’: events within $Q_{\beta\beta} \pm 25$ keV are cached until all analysis procedures and cuts are finalized [13].

2.1 The GERDA experiment

The Germanium Detector Array (GERDA) experiment [14] is located at the INFN Laboratori Nazionali del Gran Sasso (LNGS) below a rock overburden of $\sim 3500$ m water equivalent. The innovative feature of GERDA is the operation of bare Ge detectors in an ultra-pure cryogenic liquid, liquid argon (LAr), that serves both as cooling and shielding medium. The LAr cryostat is enclosed by a tank filled with ultra-pure water (Fig. 2) as additional shield against external radiation and as medium for a Cherenkov veto system against muons. A clean
Figure 2: The GERDA experimental setup (left) and the Phase II LAr veto system (right) [15].

room on top of cryostat and water tank houses a glove box and lock for assembly and deployment of the Ge detectors.

In Phase I of GERDA (Nov 11 - May 13) the detector array consisted of 15.6 kg of refurbished semi-coaxial Ge detectors from the former HDM [6] and Igex [7] collaborations and of 3.0 kg of BEGe detectors, all enriched to 86% in $^{76}$Ge. The background goal of $BI = 10^{-2} \text{ cts/(keV-kg-yr)}$ was reached. With $\mathcal{E} = 21.6 \text{ kg-yr}$ no $0\nu\beta\beta$ signal was observed and a new 90% CL limit of $T_{1/2} > 2.1 \cdot 10^{25} \text{ yr}$ was set (median sensitivity $2.4 \cdot 10^{25} \text{ yr}$) that excluded the claim of observation by part of the HDM collaboration [8] with 99% probability [13].

Phase II of GERDA started in Dec 2015 with the aim to improve the half-life sensitivity beyond $10^{26} \text{ yr}$. To achieve this at the exposure of $\sim 100 \text{ kg-yr}$ within reasonable time, e.g. 3 years of running, the detector mass has been doubled by augmenting the enriched BEGe detector mass to 20 kg (30 pcs). Simultaneously, the BI had to be reduced by a factor 10 to $10^{-3} \text{ cts/(keV-kg-yr)}$ to stay within the ‘background-free’ regime, i.e. a mean expected background of $< 1$ in the region of interest (ROI), $Q_{\beta\beta} \pm 0.5\text{-FWHM}$. This warrants the sensitivity to scale about linearly with exposure $\mathcal{E}$ while at larger backgrounds it scales as $\sqrt{\mathcal{E}}$ (Fig. 4, left). The background reduction is achieved by various improvements [15]: by the superior PSD performance of the BEGe detectors, by new low-mass cables and detector mounts of improved radio-purity, and by the instrumentation of the LAr surrounding the detector array with light sensitive sensors. The latter allows the detection of LAr scintillation light using photomultiplier tubes (PMTs) and a fiber curtain read out by SiPMs (Fig. 2, right) thus creating an effective LAr veto system against background events.
Figure 3: Top: Phase II energy spectra obtained with the BEGe detectors after indicated cuts. The energy region of the $^{40}$K and $^{42}$K lines is shown enlarged in the inset. The vertical band indicates the blinded region about $Q_{\beta\beta}$. Prominent features are below 500 keV the tail of the $^{39}$Ar $\beta$ spectrum, between 600 - 1600 keV the broad structure from $2\nu\beta\beta$ decays, individual $\gamma$ lines between 400 - 2650 keV, and $\alpha$ structures above 2650 keV, predominantly due to $^{210}$Po. - Bottom: Scatter plot of the PSD parameter $\zeta = (A/E - 1)/\sigma_{A/E}$ vs energy for all Phase II BEGe detectors, and the corresponding energy spectra after indicated cuts (left). Energy spectra in the analysis window with 2 keV binning obtained in Phase I and II after all cuts. The blue lines show a fit of a constant background and a hypothetical $0\nu\beta\beta$ signal corresponding to the 90% CL limit of $T_{1/2}^{0\nu} > 8 \cdot 10^{25}$ yr [9] (right).

Fig. 3 shows the energy spectra obtained with the BEGe detectors after $\mathcal{E} = 18.2 \text{ kg yr}$ and indicated cuts. In the analysis window between 1930 and 2190 keV, the spectrum is composed of degraded $\alpha$ particles, Compton scattered $\gamma$'s from $^{208}$Tl and $^{214}$Bi decays, and $^{42}$K $\beta$ decays at the detector surface. The power of the LAr veto is illustrated by the $^{40}$K and $^{42}$K lines at 1461 keV and 1525 keV. Following electron capture, the line of the 1461 keV transition in $^{40}$Ar is unaffected by the LAr veto since no energy is deposited in the LAr. On the other hand, the 1525 keV transition follows a $\beta$ decay which deposits up to 2 MeV in the LAr; thus the corresponding line can be suppressed by $\sim 80\%$.

The PSD for BEGe detectors is based on a single parameter determined by the ratio $A/E$ where $A$ is the maximum of the detector current pulse and $E$ the total energy [11]. Fig. 3 also shows a scatter plot of the PSD parameter
\[ \zeta = \frac{(A/E - 1)}{\sigma_{A/E}} \] and its projection on the energy scale. Accepted $\beta\beta$ candidates at $\xi = 0$, mostly $2\nu\beta\beta$ decays, are shown in red; their survival fraction is $(85 \pm 2)\%$. The two K peaks and Compton scattered events located at $\xi < 0$ are easily cut, like the $\alpha$ events at $\xi > 0$.

After all cuts a BI of $1.0^{+0.6}_{-0.4} \times 10^{-3}$ cts/(keV·kg·yr) is deduced confirming a former result from lower exposure [16]. GERDA is thus the first experiment in the field that will stay background-free up to its design exposure. Assuming in the analysis window a flat background and a Gaussian signal at $Q_{\beta\beta}$ (and excluding 10 keV wide intervals around two known $\gamma$ lines), a combined unbinned profile likelihood fit to the Phase I and II spectra after all cuts (Fig. 3, bottom right) yields a half-life limit for $0\nu\beta\beta$ decay of $T_{1/2}^{0\nu} > 8 \times 10^{25}$ yr (90\% CL, mediated sensitivity $5.8 \times 10^{25}$ yr). For light Majorana neutrino exchange this limit converts to an upper limit of the effective Majorana neutrino mass of $0.12 - 0.26$ eV using $g_A = 1.27$ and nuclear matrix elements (NMEs) from $2.8 - 6.1$ [9].

2.2 The Majorana Demonstrator

The Majorana Demonstrator (MJD) [17] is operating at the Sanford Underground Research Facility, South Dakota. Its goal is to prove the design for a 1 ton-scale experiment as to background level and modular design. The MJD contains 35 PPC detectors (29.7 kg) enriched up to 88\% in $^{76}$Ge. The detectors are mounted in two vacuum cryostats within a traditional graded passive Cu/Pb shield with the inner layer consisting of ultraclean electroformed copper. The full detector array is running since August 2016.

With 2.5(1) keV FWHM resolution at $Q_{\beta\beta}$, the MJD has achieved the best energy resolution of any $0\nu\beta\beta$ decay experiment [18], and its sub-keV threshold allowed to perform sensitive tests of physics beyond the SM [19]. The lowest background runs ($\mathcal{E} = 5.24$ kg·yr) yield a BI of $1.6^{+1.2}_{-1.0} \times 10^{-3}$ cts/(keV·kg·yr), being compatible with the projected background level of $3$ cts/(ROI·t·yr) based on the material assay. At $\mathcal{E} = 10$ kg·yr no $0\nu\beta\beta$ signal candidate has been observed which implies a lower limit of $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr (90\% CL) [18].

3 The next generation of experiments

Already in 2005 the GERDA and Majorana collaborations recognized that the ton-scale experiment which is needed to cover the inverted mass hierarchy would call for a world-wide effort. Hence they signed a MoU on open exchange of knowledge and technologies and declared their intentions to merge for a ton-scale experiment combining the best features of both experiments. The recently formed LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay) collaboration is the result of these joint efforts including new members. It proposes a staged approach [20]: the operation of up to 200 kg
of detectors in the existing GERDA infrastructure at LNGS, and in a next step the use of 1000 kg of detectors in a new installation at a location to be still determined. Fig. 4 shows the envisaged $T_{1/2}^{0\nu}$ limit setting sensitivities.

Figure 4: Left: $T_{1/2}^{0\nu}$ sensitivities (90% CL) of GERDA Phase II and LEGEND-200/1000 vs exposure; the horizontal band indicates the lower bound of the inverted neutrino mass ordering (IO) [21]. Right: Tentative baseline design of a cryostat for LEGEND-1000 [20].

For LEGEND-200 the GERDA lock and cryostat piping will be modified to accommodate up to 200 kg of detectors. The major challenge will be the reduction of background to 0.6 cts/(FWHM·t·yr), i.e. by a factor 5 compared to GERDA; this is needed to stay 'background-free' up to the design exposure of 1 t·yr where the sensitivity of $10^{27}$ yr is reached. Envisaged improvements include: (i) the use of PPC detectors of larger mass, 1.5–2 kg, which becomes possible with the novel inverted coaxial PPC detector type [22]; one of these devices will substitute 2–3 BEGe detectors, keeping the excellent PSD properties while reducing the number of detector holders, cables and electronic channels by the same factor; (ii) better LAr scintillation light collection with a denser fiber curtain for increased $^{214}$Bi rejection; (iii) a new design of the electronic readout chain for better noise reduction such that PSD will become more effective; and (iv) the overall reduction of radio-impurities close to the detector array by using low-mass MAJORANA DEMONSTRATOR style components. Preparations for LEGEND-200 are in progress: the PSD power of prototype inverted coaxial detectors has been verified [23], the purchase of Ge material enriched in $^{76}$Ge has started, and the cryostat piping has been redesigned.

The LEGEND-1000 goal to stay ‘background-free’ for $10^{28}$ yr sensitivity up to the exposure of 10 t·yr requires a BI of less than 0.1 cts/(FWHM·t·yr), a factor of 30 lower than achieved in GERDA. Several options for reaching this goal are under study, and the experience gained with LEGEND-200 will help thereby. An initial baseline design (Fig. 4 right) shows the main cryostat volume separated by thin copper walls from 4 smaller volumes of ~3 m$^3$ each.
Each volume carries on top a shutter and lock, like in Gerda, such that 4 payloads with up to 250 kg detectors can be deployed separately. The 3 m$^3$ volumes might be filled with depleted LAr eliminating the background due to $^{42}\text{Ar}/^{42}\text{K}$ β decays. An important R&D effort will be the minimization of all construction materials which do not scintillate and hence cannot be used to veto background events.

4 Conclusion

The GERDA Phase II upgrade has achieved the desired background goal of $10^{-3}$ cts/(keV·kg·yr). GERDA will thus run ‘background-free’ up to its design exposure of 100 kg·yr reaching in 2018 a $T_{1/2}^{\nu\bar{\nu}}$ sensitivity beyond $10^{26}$ yr. The MAJORANA DEMONSTRATOR is expected to exhibit a similar performance. $^{76}\text{Ge}$ experiments have shown the best energy resolution and the lowest background in the ROI of any isotope for $0\nu\beta\beta$ searches [24]. This is motivation for future experiments with 200 kg of $^{76}\text{Ge}$ and more. The newly formed LEGEND collaboration plans a ton-scale $^{76}\text{Ge}$ experiment for probing half-lifes $T_{1/2}^{\nu\bar{\nu}}$ up to $10^{28}$ yr. Preparations for the first stage, LEGEND-200, are in progress.

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