The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND)

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Abstract. The observation of neutrinoless double-beta decay ($0\nu\beta\beta$) would show that lepton number is violated, reveal that neutrinos are Majorana particles, and provide information on neutrino mass. A discovery-capable experiment covering the inverted ordering region, with effective Majorana neutrino masses of 15 – 50 meV, will require a tonne-scale experiment with excellent energy resolution and extremely low backgrounds, at the level of ~0.1 count /(FWHM·t·yr) in the region of the signal. The current generation ^{76}Ge experiments GERDA and the MAJORANA DEMONSTRATOR, utilizing high purity Germanium detectors with an intrinsic energy resolution of 0.12%, have achieved the lowest backgrounds by over an order of magnitude in the $0\nu\beta\beta$ signal region of all $0\nu\beta\beta$ experiments. Building on this success, the LEGEND collaboration has been formed to pursue a tonne-scale ^{76}Ge experiment. The collaboration aims to develop a phased $0\nu\beta\beta$ experimental program with discovery potential at a half-life approaching or at 10^{28} years, using existing resources as appropriate to expedite physics results.

INTRODUCTION

Neutrinos are the only known fundamental fermions without electric charge. As a consequence they can acquire mass not only through the standard coupling to the Higgs particle but also by additional lepton number violating operators [1]. As further consequences, neutrinos will - in general - be their own anti-particles (Majorana particle) and neutrinoless double beta ($0\nu\beta\beta$) decay may exist [2, 3, 4]: a nucleus (A,Z) decays to (A,Z+2) + $2e^-$. The sum of the electron energies is here equal to the Q value of the decay ($Q_{\beta\beta}$). This is the prime signature for $0\nu\beta\beta$ decay.

OPERATING ^{76}Ge EXPERIMENTS

Currently the GERDA and MAJORANA DEMONSTRATOR experiments are searching for $0\nu\beta\beta$ decay of ^{76}Ge. Both experiments use germanium detectors made out of material with the ^{76}Ge fraction enriched to at least 87%. A major advancement over previous experiments has been GERDA's and MAJORANA's independent development and use of p-type point-contact (PPC) high purity germanium (HPGe) detectors [5]. PPC detectors, with signal time evolution similar to drift detectors, have a number of advantages over conventional coaxial HPGe detectors: simple fabrication and readout, excellent pulse shape discrimination (PSD) between $0\nu\beta\beta$ events and backgrounds, and very low capacitance, providing a low-energy threshold allowing the reduction of potential background from cosmogenic ^{68}Ge. A primary difference between the two experiments is the shielding used against external radiation. However, there are also a number of commonalities including careful attention to backgrounds and the development of ultra-clean fabrication techniques.

The second phase of GERDA started in December 2015 with 37 enriched detectors arranged in 6 strings (total mass 35.6 kg enriched to 87% ^{76}Ge) in a 64 m^3 liquid argon cryostat, with the argon serving as an internal active veto surrounding the detectors. The current background index achieved for the GERDA PPC modified (or thick window)

Broad Energy Germanium (BEGe) detectors is $0.7^{+1.1}_{-0.5} \cdot 10^{-3}$ cts/(keV·kg·yr) with an energy resolution (FWHM) of 3 keV at $Q_{\beta\beta}$ of 2039 keV and a total efficiency of 0.6. This corresponds to a projected background at $Q_{\beta\beta}$ of $2.1^{+3.3}_{-1.5}$ cts/(FWHM·t·yr). Based on a total exposure of 34.4 kg·yr from Phases I and II, GERDA sets a lower-limit on the half-life of $5.3 \cdot 10^{25}$ yr at the 90% confidence level (sensitivity of $4.0 \cdot 10^{25}$ yr) [6]. The Majorana Demonstrator array contains 35 (29.7 kg) PPC detectors enriched to 88% ^{76}Ge enclosed in a compact graded shield with inner layers of ultra-clean electroformed copper and an external active muon veto. The experiment is operating at the Sanford Underground Research Facility (SURF). The full array has been operating since August 2016. An analysis of initial Majorana Demonstrator data with an exposure of 1.39 kg·yr finds a background index of $1.8^{+3.1}_{-1.1} \cdot 10^{-3}$ cts/(keV·kg·yr) with an energy resolution (FWHM) of 2.4 keV at $Q_{\beta\beta}$ and a total efficiency of 0.6. This corresponds to a projected background at $Q_{\beta\beta}$ of $4.3^{+7.5}_{-2.7}$ cts/(FWHM·t·yr) [7]. Both experiments project ultimate sensitivities of discovering a signal with a half life of 10^{26} years.

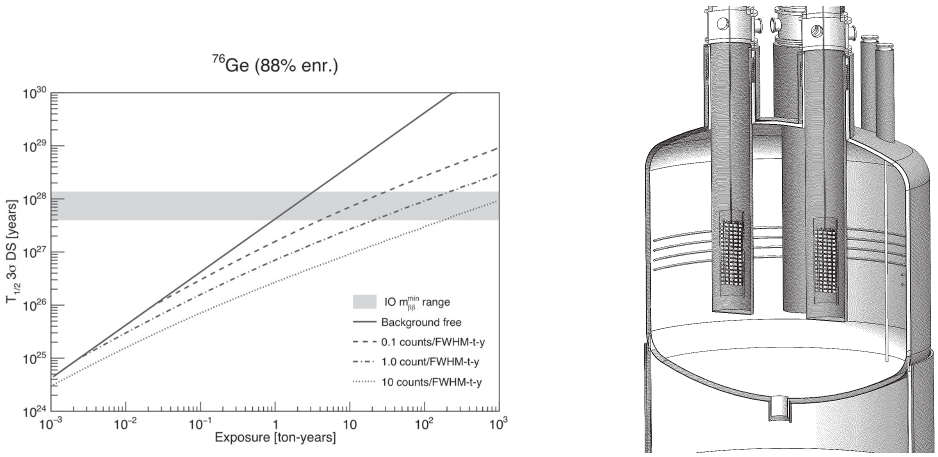
NEXT GENERATION REQUIREMENTS and LEGEND

For $m_{\beta\beta} = 17$ meV, a typical lower bound for the inverted neutrino mass ordering (90% range using parameters from [8]), the 'worst-case' half-life for the most recent ^{76}Ge shell model calculation is about $12 \cdot 10^{27}$ yr. The expected number of decays per t·yr exposure will be 0.5. The current ^{76}Ge experiments have achieved the best energy resolution and correspondingly the lowest backgrounds within an energy window of resolution-FWHM centered at $Q_{\beta\beta}$. The superior resolution coupled with modest improvements in backgrounds makes ^{76}Ge capable of identifying a signal of even a few events at $Q_{\beta\beta}$ and a leading contender to advance to the next generation of tonne-scale $0\nu\beta\beta$ experiments.

The LEGEND collaboration aims to increase the sensitivities for ^{76}Ge in a first phase to 10^{27} yr and in a second phase up to 10^{28} yr both for setting a 90% C.L. half-life limit as well as for "discovery" of $0\nu\beta\beta$ decay defined as a 50% chance for a signal at 3σ significance. Fig. 1(a) shows the sensitivities of a germanium experiment for discovery as a function of the exposure for different background levels. A signal efficiency of 0.6 is taken into account. If the background is "zero", sensitivity scales linearly with the exposure, otherwise only with the square root. For signal detection a low background is most important since the transition from linear to square root dependence occurs at lower exposures, i.e. for a smaller mean background count. Hence the goal is to perform a "background-free" measurement, defined as being < 1 mean expected background count at an experiments design exposure. In LEGEND's first phase up to 200 kg of Ge detectors, LEGEND-200, will be operated in the existing infrastructure of the GERDA experiment at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. For an exposure of 1 t·yr and under conditions approaching background-free measurement (background index of 0.6 cts/(FWHM·t·yr), the envisioned half-life sensitivity can be reached. In the following phases a new facility, LEGEND-1000, holding up to 1000 kg of detectors would be operated with even lower background of less than 0.1 cts/(FWHM·t·yr) and a design exposure above 10 t·yr.

LEGEND builds on the success of the current ^{76}Ge experiments. Both experiments have achieved the lowest background level among current $0\nu\beta\beta$ experiments and remain background-free. The natural next step towards advancing the sensitivity is therefore through the increase of the detector mass while reducing backgrounds from current levels by a factor of ~30. This further background reduction is necessary to remain essentially background-free as the total exposure increases. The combined strength from the GERDA and Majorana Demonstrator concepts and experiences defines the path towards such envisioned background improvement. LEGEND has adopted the GERDA design of a low-Z shielding (water and argon) and an active veto through the detection of argon scintillation light. Muon and γ induced backgrounds are reduced or vetoed. The Majorana Demonstrator has achieved a comparable low background level as GERDA despite not having an internal active veto in the detector region. This is a consequence of careful selection and control of the radiopurity of materials in the vicinity of the target. In addition, the readout electronics and associated cables yield better resolution for the energy and an improved pulse shape parameter used for background rejection. The experience and knowledge from GERDA and Majorana Demonstrator as well as from other LEGEND collaborators with expertise in low-background measurements will be crucial in realizing further background suppression in LEGEND.

LEGEND aims for a number of improvements including larger PPC type Ge detectors with higher mass via an "inverted-coaxial" [9] design, better readout electronics and higher argon scintillation light detection efficiency. Improvements implemented in LEGEND-200 should be applicable for the LEGEND-1000 or will guide its development. The superior energy resolution demonstrated by PPC detectors coupled with improvements in the backgrounds achieved by GERDA and Majorana Demonstrator should position LEGEND-200 and LEGEND-1000 as leading experiments in the field.



(a) (b)

FIGURE 1. (a) Sensitivity for a signal discovery. (b) Sketch of baseline cryostat design for LEGEND-1000.

LEGEND-200

LEGEND-200 plans to operate up to 200 kg of germanium detectors using the existing GERDA infrastructure at LNGS. In order to be "background-free" for an exposure of 1 t·yr a factor of 5 reduction is needed relative to the latest GERDA and Majorana Demonstrator background levels. The existing infrastructure is large enough to house 200 kg of detectors: the neck of the cryostat has a diameter of 800 mm which is wide enough for 19 strings of detectors with a total outer diameter of 500-550 mm. LEGEND-200 will use the existing Majorana Demonstrator and GERDA PPC detectors as well as additional new detectors. The new ones will be of the inverted-coaxial type which offer a similar pulse shape performance but can have much higher mass. Thus the number of channels per kg and the resulting backgrounds from cables and holders will be reduced compared to the current experiments.

The backgrounds for GERDA and Majorana Demonstrator are still under evaluation, but based on a GERDA analysis before cuts, the events near $Q_{\beta\beta}$ are coming in about equal parts from ^{42}K decays, from degraded α events and from ^{214}Bi/^{208}Tl decays. Pulse shape analysis safely removes all α decays and we expect that this will hold true for LEGEND-200. The needed background reduction should be achieved by the following measures:

- The amount of radio-impurities will be reduced. This can be realized by using low-mass Majorana Demonstrator style components.
- An improved design for the scintillation light readout has proven to detect twice as much light and to result in an improvement by a similar factor for ^{214}Bi rejection.
- The electronic noise can be reduced such that the pulse shape discrimination will be more effective.
- The mass per detector will increase by a factor of two or more. Consequently, the number of cables and holder materials per kg will be reduced.
- For ^{42}K the β particle has to pass through an outer dead layer of the germanium where it looses energy such that the fraction of events depositing 2039 keV in the active volume is reduced. An optimized dead layer thickness will further reduce this background. One can also limit the LAr volume contributing to the beta background by encapsulating the detectors in nylon vessels or scintillating plastic material.

LEGEND-1000

For the next phase of the experiment, LEGEND-1000, the exposure of 10 t·yr is reached by operating 1000 kg of detectors for 10 years. This requires new infrastructure and a more ambitious background goal to remain in the background-free regime. Several options are still under consideration for LEGEND-1000, but an initial baseline design has been established with bare germanium detectors operating in liquid argon. Because the enrichment and detector production will be spread over several years, it is planned to install the detectors in several batches of ~250 kg each. The data taking of the already installed detectors should continue largely undisturbed. These considerations lead to the preliminary design shown in Fig. 1(b). The main cryostat volume is separated by thin copper walls from four smaller volumes of about 3 m^3 each. Each volume will house a subset of the detectors and is closed on top by a shutter. There will be a lock above each of the shutters such that the germanium detector array can be assembled in nitrogen atmosphere in a glove box together with the argon veto. An important design criterion will be the minimization of 'dead' material, i.e. material like copper or PTFE which contributes to the background and does not scintillate. One alternative design being considered is to use a scintillating plastic, such as polyethylene naphthalate (PEN) as a construction material since it has good mechanical properties[10].

Compared to LEGEND-200 the background needs to be reduced by another factor of 6. Intrinsic contaminations of the U/Th decay chains have never been observed in a HPGe detector [11]. External backgrounds from neutrons and γs can be shielded by liquid argon and water. The most worrisome backgrounds are summarized below:

- *U/Th contamination in close components:* The aim is to increase mass per detector by about a factor of two, which will also reduce the fractional number of cables and supports. The Majorana Demonstrator levels in U/Th for cables and detector support are sufficiently low and together with the LAr veto these backgrounds should be acceptable.
- *^{42}K from ^{42}Ar:* ^{42}Ar is produced in the air by cosmogenic activation similar to the production of ^{39}Ar [12]. LEGEND is considering the use of argon from underground sources based on its potential reduction of backgrounds and possible availability. DarkSide has found that the ^{39}Ar concentration from an underground source is reduced by a factor of 1400 ± 200 [13] with comparable reductions expected for ^{42}Ar.
- *Detector surface contaminations:* During detector fabrication surface contaminations like ^{210}Po ($T_{1/2}$ =138 d), ^{210}Pb ($T_{1/2}$ =22.3 yr) or ^{226}Ra ($T_{1/2}$ =1602 yr) can be introduced. These backgrounds are effectively identified by PSD for the current measurements. However a R&D program is planned to further reduce the surface contamination for example by reducing the time detectors are handled in air.
- *Muon induced background:* While the prompt muon background is easily removed, isotopes like ^{77m}Ge produced by spallation neutrons are a potential background source. Time correlation between muon, neutron capture and background event can reduce this background. The cosmic-ray flux can be reduced by a factor of 100 relative to that of LEGEND-200 at LNGS (1400 m rock overburden) at deep underground laboratories like SNOLAB (2000 m rock overburden) in Canada and CJPL (2400 m rock overburden) in China. Based on current analysis of results from GERDA and Majorana Demonstrator, LNGS and SURF remain potential sites for LEGEND-1000.

Summary

The Majorana Demonstrator and GERDA experiments searching for neutrinoless double beta decay of ^{76}Ge using PPC HPGe detectors with intrinsic energy resolution of 0.12% have the lowest background levels in terms of FWHM·t·yr in the field. These are important prerequisites for a future signal discovery. The recently formed LEGEND collaboration will build on these successes and proposes to probe half-lives approaching 10^{28} yr using 1000 kg of enriched germanium detectors. In an early phase, 200 kg will be operated in the existing infrastructure at LNGS with a sensitivity of 10^{27}yr. Under favorable funding scenarios LEGEND-200 could start measurements by 2021.

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