LEGEND: The Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay

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The lepton number violating process of neutrinoless double-beta decay could result from the physics beyond the Standard Model needed to generate the neutrino masses. Taking different approaches, the current generation of $^{76}\text{Ge}$ experiments, the MAJORANA DEMONSTRATOR and GERDA, lead the field in both the ultra-low background and energy resolution achieved. The next generation of neutrinoless double-beta decay experiments requires increased mass and further reduction of backgrounds to maximize discovery potential. Building on the successes of the MAJORANA DEMONSTRATOR and GERDA, the LEGEND collaboration has been formed to pursue a tonne-scale $^{76}\text{Ge}$ experiment, with discovery potential at a half-life beyond $10^{28}$ years. The collaboration aims to develop a phased neutrinoless double-beta decay experimental program, starting with a 200 kg measurement using the existing GERDA cryostat at LNGS. These proceedings discuss the plans and physics reach of LEGEND, and the combination of R&D efforts and existing resources being employed to expedite physics results.

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1 Introduction

Two neutrino double-beta decay (\(2\nu\beta\beta\)-decay), \((A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\nu_e\), is allowed in the Standard Model, and observed in isotopes e.g. \(^{76}\text{Ge}\), \(^{130}\text{Te}\), and \(^{136}\text{Xe}\). Neutrinoless double-beta decay (\(0\nu\beta\beta\)-decay), \((A, Z) \rightarrow (A, Z + 2) + 2e^-\), violates lepton number conservation by two units, independently of any model, and if observed, would be a clear signature of New Physics. Such a non-standard process is a key feature of multiple neutrino mass generation models. The experimental signature of \(0\nu\beta\beta\)-decay is a peak at the Q-value of an isotope’s double-beta decay spectrum. Among various isotopes, \(^{76}\text{Ge}\)-based experiments have a high discovery potential.

Specifically in the light neutrino exchange model \([1]\), there is a relationship (through the isotope’s nuclear matrix element and axial vector coupling constant) between the \(0\nu\beta\beta\)-decay half-life, the neutrino mass ordering, and the lightest neutrino mass. In this model, a \(^{76}\text{Ge}\) experiment sensitive to \(T_{1/2} > 10^{28}\) y will be able to probe the entire inverted ordering (IO) scenario, and a significant fraction of the normal ordering (NO) parameter space \([2]\). This half-life is therefore a reasonable target for \(^{76}\text{Ge}\) experiments.

Neutrinoless double-beta decay at a half-life of \(10^{28}\) years would produce a signal of \(\sim 0.5\) counts/t·y, demonstrating the need for ultra-low backgrounds, a large fiducial mass, and a long counting time for an experiment pursuing this goal, as can be seen in Figure 1. To have \(3\sigma\) discovery potential at the bottom of the IO-allowed region with 10 ton·yr of exposure, it would require a tonne-scale detector enriched to 88% \(^{76}\text{Ge}\) with backgrounds less than 0.1 counts/FWHM·t·y.

Currently there are two operating \(^{76}\text{Ge}\) \(0\nu\beta\beta\)-decay experiments: the MAJORANA DEMONSTRATOR \([3]\) and GERDA (the GERmanium Detector Array) \([4]\). Both experiments include germanium crystal detectors enriched to \(\sim 88\%\) in \(^{76}\text{Ge}\) (detectors totalling 29.7 kg for the MAJORANA DEMONSTRATOR, and 37.6 kg for GERDA). Both experiments are also located underground to shield against cosmic ray muon backgrounds: the MAJORANA DEMONSTRATOR in the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA, and GERDA at the Laboratori Nazionali del Gran Sasso (LNGS), located between L’Aquila and Teramo in Italy. To achieve its background goals, the MAJORANA DEMONSTRATOR relied on placing the detectors in 2 vacuum cryostats surrounded by a traditional passive shield, with components made of ultra-clean materials. GERDA took the novel approach of submerging its detectors in liquid argon, which acts as an active shield, as backgrounds are tagged using their resultant scintillation light. Both experiments have lower backgrounds than all \(0\nu\beta\beta\)-decay searches using other isotopes, with GERDA holding the record of \(\sim 3\) counts/(FWHM·t·y) and a sensitivity of \(1.1 \times 10^{26}\) y at the 90% confidence level \([5]\), and have better energy resolution than all \(0\nu\beta\beta\)-decay searches using other isotopes, with the MAJORANA DEMONSTRATOR holding the record of 2.5 keV FWHM at the Q-value of 2039 keV.
2 LEGEND

The LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) collaboration plans to develop a $^{76}\text{Ge}$-based double-beta decay experimental program, building upon the successes of the MAJORANA DEMONSTRATOR and GERDA. LEGEND will proceed in phases towards a neutrinoless double-beta decay discovery potential at a half-life beyond $10^{28}$ years. The best technologies will be selected based on lessons learned in GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups. To expedite physics results, LEGEND will use existing resources as appropriate.

In its first phase, LEGEND-200, the existing GERDA infrastructure at LNGS will be modified, and up to 200 kg of detectors will be deployed in the cryostat. This initial phase permits early science with a world-leading experiment, helping to maintain skilled workers on the timeline leading up to LEGEND-1000. LEGEND-200 has a background goal of less than 0.6 counts/(FWHM·t·y). This required reduction in background has already been demonstrated as feasible in the MAJORANA DEMONSTRATOR, GERDA, and dedicated test stands. Achieving this background rate will allow LEGEND-200 to reach a sensitivity greater than $10^{27}$ y after accumulating 1 ton·y of exposure. The corresponding discovery potential is shown in Figure 1. LEGEND-200 physics data collection is expected to begin in 2021.

Subsequent stages will occur in new infrastructure, with 1000 kg of detectors deployed in stages up to the complete LEGEND-1000. The background goal for LEGEND-1000 is less than 0.1 counts/(FWHM·t·y). This background reduction is necessary for LEGEND-1000 to achieve a $0\nu\beta\beta$-decay discovery potential at a half-life greater than $10^{28}$ years on a reasonable timescale (see Figure 1). The required depth to keep cosmogenic activation backgrounds (e.g. $^{77m}\text{Ge}$) within the background budget is currently under investigation (e.g. [6]), and will be a contributing factor in the choice of site. The timeline of LEGEND-1000 is connected to the U.S. Department of Energy down-select process for the next generation neutrinoless double-beta decay experiment.

3 Background reduction plans

Multiple techniques are planned to achieve the background reduction required for LEGEND-200, and the further reduction required for LEGEND-1000. This section discusses a selection of these techniques.

3.1 Electroformed copper

Amongst the ultra-clean materials employed by the MAJORANA DEMONSTRATOR is electroformed copper. Its uranium and thorium decay chain backgrounds each average
Reduction of backgrounds is crucial to achieve good discovery potential. Majorana and GERDA technologies combined with new R&D to accomplish this.

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Figure 1: Neutrinoless double-beta decay half-life $3\sigma$ discovery potential as a function of exposure and background rate for detectors enriched to 88% in $^{76}$Ge. The bottom of the inverted ordering mass region ($m_{\beta\beta} = 17$ meV) is shown for unquenched axial vector coupling and nuclear matrix elements ranging from 3.5 to 5.5. The discovery potentials for the projected combined total exposures of the Majorana Demonstrator and GERDA are shown, along with the exposures of 1 ton·y of LEGEND-200 at a background rate of 0.6 counts/FWHM·t·y, and 10 ton·y of LEGEND-1000 at a background rate of 0.1 counts/FWHM·t·y.

$\leq 0.1 \mu$Bq/kg, which are lower than the majority of the commercial OFHC copper used in the Majorana Demonstrator by at least an order of magnitude [7]. It is employed in the parts closest to the detectors (e.g. detector mounts, inner copper shield) where using ultra-clean materials is most crucial to achieving low backgrounds.

The electroformed copper used in the Majorana Demonstrator was produced underground at Pacific Northwest National Laboratory and SURF, and parts were machined and stored underground as well. This reduces the potential for cosmogenic
activation to produce $^{60}$Co, whose decay can produce photons above the 2039 keV Q-value [5], a potential source of background.

**MAJORANA** electroforming practices should improve on GERDA radiopurity for LEGEND-200. Copper electroforming for LEGEND-200 is underway in the facilities on the 4850’ level at SURF. Production of 37 kg of electroformed copper should be complete by the fall of 2019.

### 3.2 Liquid argon veto

The active liquid argon (LAr) veto employed by GERDA tags external backgrounds depositing energy in the LAr that subsequently scintillates [9]. The LAr scintillation light is read out by photomultiplier tubes above and below the detector array, and a shroud of wavelength-shifting optical fibres surrounding the array read out by silicon photomultipliers. An upgrade this year increased the fibre curtain density and added a fibre shroud surrounding the central column of detectors, to improve light collection efficiency.

LEGEND-200 will use a similar design, though different geometries of fibres between detector columns are currently being studied to optimize light collection when many more detectors are present in the existing GERDA cryostat. In addition, light yield and attenuation can be improved with better LAr purity, as well as doping with Xe, which is currently under investigation. Using more radiopure fibres and digitizing the signals in the LAr are also currently under investigation.

The $^{42}$Ar in natural liquid argon is important to consider in the detector design. $^{42}$Ar decays to a $^{42}$K ion, which drifts to the charged detectors, and undergoes $\beta$-decay to $^{42}$Ca with $Q_\beta = 3.5$ MeV, providing a source of background to the $0\nu\beta\beta$-decay search. In GERDA and the future LEGEND-200, the drift of $^{42}$K ions is limited by nylon shrouds around the detector columns. In GERDA and LEGEND-200, coincident $\gamma$ $^{42}$K-decays are tagged well by the LAr veto, and pure $\beta$-decays on the detector surface are cut with $\sim 99\%$ efficiency by pulse shape analysis.

For LEGEND-1000, a design that would remove this background completely makes use of underground argon free of $^{42}$Ar. In this configuration, the detectors are separated into four copper-walled volumes containing underground argon, submerged in a large natural argon volume. This design would require 21 tons ($15$ m$^3$) of underground argon, which is similar to the volume of underground argon planned to be used by the Darkside-20k experiment [10].

### 3.3 Front-End electronics

The first stage of the **MAJORANA** readout is the Low-Mass Front-End (LMFE) [11], located as close as possible to each detector’s p+ contact. Each LMFE contains an MX-11 JFET, and the feedback resistor and capacitor of the resistive feedback charge
sensitive preamplifier. The feedback loop runs 2.15 m out through the shielding to the warm preamplifier, and back to the LMFE. Locating the first stage of the amplification close to the detector contributes to the low noise and excellent energy resolution of the Majorana Demonstrator.

Situating the LMFE close to the detectors requires that it have low backgrounds, through using clean materials and keeping its mass to a minimum. To this end, the LMFE features Ti/Au 200/4000 Å thick sputtered traces on a 200 µm thick amorphous silica substrate, with the feedback capacitance provided by the capacitance between traces, and a 4000 Å sputtered amorphous germanium feedback resistor. As a result, the LMFE is the most radiopure front-end ever built.

The LMFE is therefore in the baseline design for LEGEND-200, where it should result in reduced backgrounds and noise. Research and development activities into its performance in liquid argon and its use with longer cables are currently underway. For LEGEND-1000, research and development into an ASIC preamplifier that can be placed near the detector is currently underway.

3.4 Larger \textsuperscript{enr}Ge detectors

The BEGe-type detectors used by GERDA average 0.66 kg per detector unit, and the PPC-type detectors used in the Majorana Demonstrator average 0.85 kg per detector unit. Both of these detector types have excellent energy resolution, and superb pulse-shape sensitivity to reject multi-site and surface background events. However, larger detectors for LEGEND would require fewer cables and preamplifier front-ends per active kilogram of detector material, which would lower the backgrounds due to these components. A new detector geometry, the Inverted-Coaxial Point Contact (ICPC) detector [12], allows detectors as large as a normal coaxial detector, but with similar performance to the BEGes and PPCs employed by GERDA and the Majorana Demonstrator [13]. The baseline mass for these detectors is 1.5-2.0 kg, with natural germanium detectors near 3 kg also being studied. Five enriched ICPC detectors, each around 1.9 kg, have been produced and deployed in a recent GERDA upgrade, supporting the selection of this detector design for LEGEND-200.

4 Conclusions

The next generation of neutrinoless double-beta decay experiments requires reduced backgrounds and additional mass. \textsuperscript{76}Ge detector arrays have demonstrated the lowest backgrounds and best energy resolution of all the next generation experiment technologies. The LEGEND collaboration plans to take the best of Majorana and GERDA, and perform additional R&D to build a detector with 0\nu\beta\beta-decay discovery potential at a half-life beyond \(10^{28}\) years. LEGEND will proceed in a phased approach,
starting with the 200 kg LEGEND-200, for which the background reduction goal is realistic and consistent with the most conservative assay and simulation results. Research and development work directed towards LEGEND-200 and LEGEND-1000 is ongoing.

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