PROCEEDINGS OF SCIENCE

LEGEND-1000: A Ton-Scale Search for Neutrinoless Double-Beta Decay in ^{76}Ge

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Next-generation neutrinoless double-beta decay searches seek the Majorana nature of neutrinos and the existence of a lepton number violating process. The LEGEND-1000 experiment represents the ton-scale phase of the LEGEND program's search for neutrinoless double-beta decay of ^{76}Ge, following the current intermediate-stage LEGEND-200 experiment at LNGS in Italy. The LEGEND-1000 design is based on a 1000-kg mass of p-type, inverted-coaxial, point-contact germanium detectors operated within a liquid argon active shield. This approach has achieved the lowest background levels and the best energy resolution at the decay Q value as established by the GERDA and MAJORANA DEMONSTRATOR experiments. The LEGEND-1000 experiment's technical design, energy resolution, material selection, and background suppression techniques combine to project a quasi-background-free search for neutrinoless double-beta decay in ^{76}Ge at a half-life beyond 10^{28} yr and a discovery sensitivity spanning the inverted-ordering neutrino mass scale.

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1. Introduction

LEGEND-1000, the ton-scale Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay is an experimental search designed to seek the Majorana nature of neutrinos and the existence of a lepton number violating process. The first phase of the strategic, staged approach pursued by the LEGEND Collaboration is the intermediate-stage LEGEND-200 experiment currently operating at LNGS. LEGEND-1000 is designed to probe $0\nu\beta\beta$ decay with 1000 kg of Ge detectors enriched to >90% in the ^{76}Ge isotope for a 3σ (99.7% CL) discovery sensitivity in the ^{76}Ge half-life beyond 10^{28} years, corresponding to a $m_{\beta\beta}$ upper limit in the range of 9–21 meV in 10 yr of live time to span the inverted-ordering neutrino mass scale [1].

Germanium is a leading material for $0\nu\beta\beta$ decay searches for several reasons: Ge detectors have achieved a superb energy resolution of 0.1% FWHM at $Q_{\beta\beta}$; discrimination of backgrounds via a multivariate event topology analysis; they have achieved the lowest background of any $0\nu\beta\beta$ decay experiment per FWHM at $Q_{\beta\beta}$ with no contamination from two-neutrino double-beta decays; and the background is flat, well understood, and does not require modeling. Therefore, $0\nu\beta\beta$ decay events would create a lone, sharp peak above a flat background in the energy spectrum visible to the eye.

2. LEGEND-1000 Conceptual Design

The LEGEND-1000 technical design is centered around the demonstrated low-background and excellent energy performance of p-type, point-contact, high-purity Ge semiconductor detectors, enriched in ^{76}Ge used by the Majorana Demonstrator [2] and Gerda [3] experiments, and operated in liquid argon (LAr) instrumentation system to detect background-induced scintillation light as done in Gerda and LEGEND-200. The newer p-type, inverted-coaxial, point-contact (ICPC) detectors used exclusively in LEGEND-1000 maintain the excellent energy and event reconstruction performance yet are 2–4 times larger, which allows the overall number of detectors to be reduced, also reducing the number of cables, read-out channels, and detector support materials.

The LEGEND-1000 design is based on instrumenting 336 individual ICPC detectors with an average mass of 3.0 kg for a total detector mass of 1000 kg (Fig. 1). The detectors are mounted using copper rods made from underground-electroformed Cu and plastic insulators. Below each detector is a scintillating PEN (poly(ethylene napthalate)) baseplate supporting a wire-bonded signal cable and front-end application-specific integrated circuit (ASIC) board to collect charges at the detector's p^+ electrode. The Ge detectors are nominally distributed among 42 independently operating strings containing 24-kg of Ge detector mass to allow deployment and commissioning of the array in stages, which also allows early data while later-stage detectors are being produced. The detector strings are immersed in radiopure, underground-sourced LAr (UGLAr) that is instrumented for single-photo-electron detection of the 128 nm scintillation light emitted from energy depositions in the Ar by backgrounds. The use of underground-sourced Ar [4] greatly reduces the presence of the cosmogenic ^{42}Ar, which decays to the ^{42}K isotope that subsequently decays with a Q value of 3525 keV. The scintillation light from LAr is readout by a curtain of wavelength-shifting (WLS) polystyrene fibers surrounding each Ge detector string (see Fig. 1). The TPB (tetraphenyl butadiene) coated fibers are coupled to arrays of Si photomultiplier (SiPM) readout.

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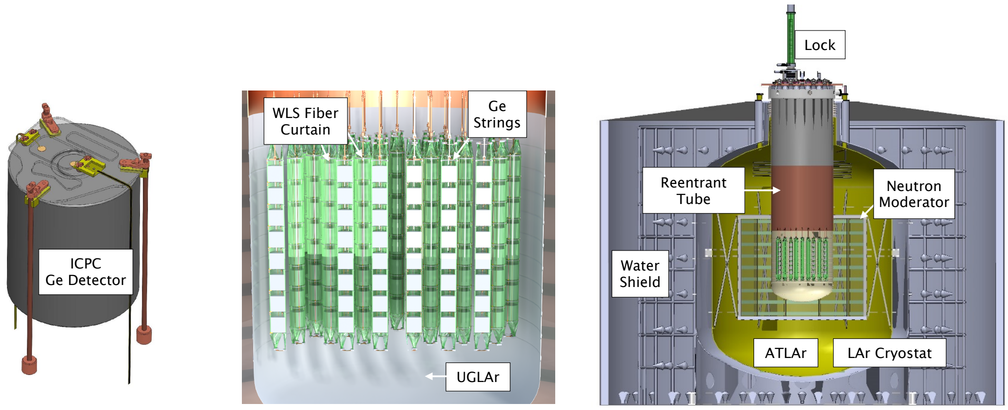

Figure 1: Left: An individual ICPC Ge detector holder that forms the strings in the array. Middle: A close-up of the detector array showing the strings of Ge detectors and LAr scintillation instrumentation. Right: The LEGEND-1000 detector array within a reentrant tube inside of a vacuum-insulated LAr cryostat and water tank.

The reentrant tube housing the Ge detector array is surrounded by conventional atmospheric-sourced LAr (ATLAr), doped with Xe, to provide additional shielding and scintillation light detection. Neutron moderator panels sit within the ATLAr volume and include WLS light guides and SiPM arrays for photodetection. The LAr is maintained at cryogenic temperatures within a vacuum-insulated cryostat. Outside of the cryostat sits a water tank instrumented with photomultiplier tubes to provide additional active shielding. Above the cryostat and tank sits a lock system that allows the deployment (or removal) of a complete Ge detector string and fiber shrouds (see Fig. 1). The LEGEND-1000 reference design accommodates siting in LNGS Hall C or the SNOLAB Cryopit.

3. Event Topology and Background Sources

The $0\nu\beta\beta$ decay events are inherently single-site, mono-energetic events occurring within the bulk of a single Ge detector, whereas many background events have larger spatial distributions or contained within the surface of the detectors. LEGEND-1000 will use a multivariate analysis to identify and discriminate against backgrounds based on several observables. *Pulse Shape Discrimination* provides information on the interaction-site multiplicity, the interaction-site location, and the presence of any delayed or slow charge collection, allowing the prompt, single-site signature from bulk $0\nu\beta\beta$ decay energy depositions to be easily distinguished from backgrounds. *Anti Coincidence* relies in the granular nature of the Ge detector array and its immersion within an active LAr scintillating volume to offer strong discrimination between $0\nu\beta\beta$ decay signal events, which are isolated to a single Ge detector, and background-generating events in multiple coincident detectors or the active shield systems. *Delayed Coincidences* with $0\nu\beta\beta$ decay candidates (either as the prompt or delayed event) can thus help discriminate between a lone $0\nu\beta\beta$ decay signal and backgrounds with a time structure. This technique can be used to tag Bi-Po coincidences from Rn-chain progeny, and tag μ-induced cosmogenics like $^{77(\mathrm{m})}$Ge. The latter is important at the depth of LNGS; tagging delayed coincidences utilizing the full instrumentation of LEGEND-1000 is expected to contribute $< 5\%$

of the total background goal at the depth of LNGS (μ-induced backgrounds would be negligible at the depth of SNOLAB).

The expected background rate is found through an iterative and comprehensive Monte Carlo simulation campaign, relying on the extensive radiopurity assays of selected materials, and the proven multivariate analysis methods that extract the topology of the collected events [1]. The background model is being continuously refined based on the latest evolution of the conceptual design to include updated detector layout and spacing, recent material radiopurity assay data, and finer detail of internal components. The total projected background index in the LEGEND-1000 experiment is $< 10^{-5}$ cts/(keV kg yr).

4. Summary and Outlook

The LEGEND-1000 design is optimized for a quasi-background-free $0\nu\beta\beta$ search with a low-risk path to meeting its background goal of 10^{-5} cts/(keV kg yr). Its low backgrounds, excellent resolution, and event topology discrimination allow for an unambiguous discovery of $0\nu\beta\beta$ decay with a half-life discovery sensitivity of 1.3×10^{28} years. The collaboration and its international funding partners are planning a path forward to finalize the LEGEND-1000 design, begin construction, and achieve first data by the end of the decade, as shown in Fig. 2.

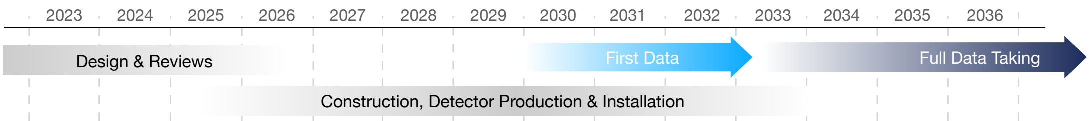

Figure 2: The technically driven, notional schedule of the LEGEND-1000 experiment

5. Acknowledgements

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References

[1] LEGEND collaboration, *The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay: LEGEND-1000 Preconceptual Design Report*, 2107.11462.

[2] Majorana collaboration, *Final Result of the* Majorana Demonstrator*'s Search for Neutrinoless Double-β Decay in ^{76}Ge*, *Phys. Rev. Lett.* **130** (2023) 062501 [2207.07638].

[3] Gerda collaboration, *Final Results of GERDA on the Search for Neutrinoless Double-β Decay*, *Phys. Rev. Lett.* **125** (2020) 252502 [2009.06079].

[4] DarkSide collaboration, *Results From the First Use of Low Radioactivity Argon in a Dark Matter Search*, *Phys. Rev. D* **93** (2016) 081101 [1510.00702].