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In-situ cosmogenic background for LEGEND

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The Large Enriched Germanium Experiment for Neutrinoless double beta Decay (LEGEND) Collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results. This program will initially operate in an upgrade of the infrastructure used for the GERDA experiment (LEGEND-200), followed by a modular deployment of four detector arrays (LEGEND-1000). LEGEND-200 is currently in commissioning at Laboratori Nazionali del Gran Sasso (LNGS) in the L'Aquila province of Italy. The final design and host site for LEGEND-1000 is an active area of study for the collaboration, and these proceedings will outline some of the factors that are being considered in these decisions.

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1. LEGEND goals and sensitivity

The experimental program for LEGEND is based off of the successes and information garnered by the MAJORANA DEMONSTRATOR and GERDA collaborations, as well as the expertise of many other institutions joining the search for neutrinoless double-beta decay ($0\nu\beta\beta$) in germanium.

	LEGEND-200	LEGEND-1000
Active detector mass (kg)	200	1000
Expected runtime (yrs)	5	10
$T_{1/2}$ sensitivity (yrs)	10^{27}	10^{28}
Effective neutrino mass upper limit (meV)	34-78	9-21
Background index goal (cts/[keV kg yr])	2x10^{-4}	1x10^{-5}

Table 1: A summary of some of the key parameters for LEGEND-200 and LEGEND-1000.

A summary of the goals for both phases of LEGEND can be found in Table 1. The previous $0\nu\beta\beta$ in Ge experiments used total detector masses in the tens of kg range. LEGEND-200 represents a roughly 5 times increase in detector mass compared to previous experiments, and LEGEND-1000 is hence a roughly 25 times increase. This ambitious increase in the scale of operation allows LEGEND to pursue a target half-life sensitivity for $0\nu\beta\beta$ on the order of 10^{28} years in LEGEND-1000. This translates to an upper limit of the effective Majorana neutrino mass of 9-21 meV, depending on the nuclear matrix element model employed for $0\nu\beta\beta$.

As can be seen in Fig. 1, the sensitivity that can be attained for a given amount of exposure relies heavily on the background index achievable in LEGEND. Novel design and analysis techniques will allow LEGEND to meet and potentially exceed its unprecedented background goals.

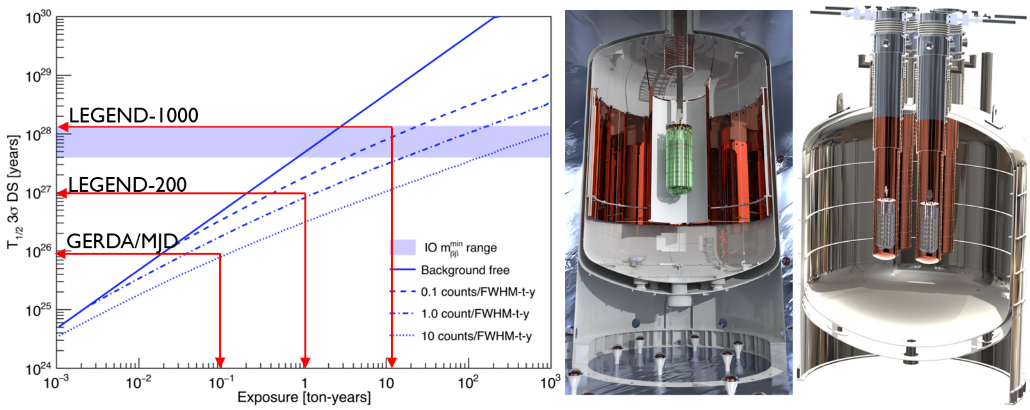

Figure 1: Left: 3σ sensitivity for current and future Ge $0\nu\beta\beta$ experiments. The sharp decrease in discovery potential for higher background indices is illustrated by the blue lines. Right: drawings of the LEGEND-200 and LEGEND-1000 baseline designs. Figures taken from [1].

2. Cosmogenically-induced backgrounds

LEGEND-200 and LEGEND-1000 must be located deep underground, using the earth as a passive shield against cosmic rays. Muons created in cosmic ray showers are highly penetrating, and the survival rate of muons to deep underground sites is highly dependent on the depth of the site. Two sites under consideration, LNGS and SNOLab, have muon flux rates that differ by a factor of about 100[2][3]. The engineering constraints also differ for the two sites. These factors affect which cosmogenic background mitigation strategies are available for each of the sites.

2.1 Prompt signals

Muons ionize the materials along their trajectory. Techniques for detecting and vetoing prompt signals from muons are well understood and highly efficient. LEGEND-200 will employ both an outer water Cherenkov detector and an inner liquid argon scintillation detector to detect the passage of muons through the experimental apparatus. In Gerda, the water Cherenkov detector was shown to detect muons which deposited energy in any of the Ge detectors with very high efficiency[4].

For LEGEND-1000 at SNOLab, engineering constraints may prevent deployment of the water Cherenkov detection system, though the water would remain as a passive shield. A simulation campaign using the Geant4 particle simulation toolkit estimated the impact of removing this system, and determined that the cosmogenic background from prompt signals would be <1% of the total background budget using the liquid argon scintillation system alone, rendering this background negligible. A plastic veto panel deployed on top of the cryostat would detect roughly two out of three muons, increasing efficiency further.

2.2 Delayed signals

Neutrons produced in-situ during muon showers can capture on detector or shielding materials, creating long-lived radioactive impurities. Most notable of these are the isotopes ^{77}Ge and ^{77m}Ge. These isotopes are problematic because they are produced inside the detectors, and the end-point for the beta decay is above the Q-value of $0\nu BB$. Suppressing this source of background is a complex process, with multiple possible approaches.

At SNOLab depth, techniques employed in current-generation experiments are expected to be sufficient to suppress the delayed cosmogenic background to <5% of the background budget for LEGEND-1000. At LNGS depth, a number of novel techniques are being explored. A delayed coincidence (DC) cut as in Ref. [5] for the shorter-lived ^{77m}Ge isotope would add an estimated factor of 15 suppression (Table 2), at the cost of introducing roughly 10% dead-time to the experiment in the baseline design. Relaxed engineering constraints and lower estimates of construction cost and time at LNGS may help offset this increase in dead-time. The DC cut could be applied at SNOLab as well, resulting in a background contribution of about 0.6% with almost no additional dead-time.

Passive neutron shielding with neutron absorbers in LAr have proven to be effective in simulations as well [6]. However, well-known neutron absorbers such as boron and gadolinium could introduce large amounts of radiogenic background. Polyethylene naphthalate (PEN), a polymer with chemical formula $(C_{14}H_{10}O_4)_n$, is an attractive material for shielding due to its excellent physical properties including scintillation and its ability to be produced with very high radiopurity. A simulations campaign estimated the cosmogenically-induced ^{77}Ge production rate with 10 cm thick PEN shields installed close around the Ge detectors, and also with the shields placed roughly 1m from the detectors (the far away design in Fig. 2). The production rate of this isotope decreased by a factor of 2 in the latter simulation, but increased by a factor of 2 in the former. While the PEN

Source	Location	BI before DC [cts/(keV kg yr)]	BI after DC [cts/(keV kg yr)]
^{77}Ge	SNOLAB	3.2×10^{-8}	N/A
^{77}Ge	SURF	5.0×10^{-7}	N/A
^{77}Ge	LNGS	3.0×10^{-6}	N/A
^{77m}Ge	SNOLAB	3.9×10^{-7}	2.6×10^{-8}
^{77m}Ge	SURF	6.0×10^{-6}	4.0×10^{-7}
^{77m}Ge	LNGS	3.6×10^{-5}	2.4×10^{-6}

Table 2: Background index estimates for the isotopes primarily responsible for delayed cosmogenic signals, with and without the DC cut described in the text.

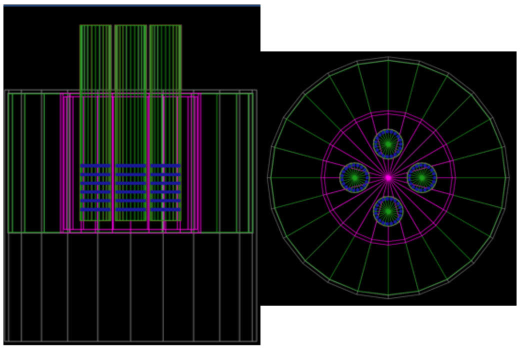

Figure 2: The Geant4 simulation geometry used for these results, with a far-away PEN shield added (magenta). LAr volumes are shown in green, and Ge detectors are blue.

moderated the neutrons created in the showers, it was not efficient at absorbing the neutrons. The lower-energy neutrons introduced near the detectors have a higher capture cross-section on ^{76}Ge. By placing the PEN shields farther away from the detectors, most of the moderated neutrons will be captured on the liquid argon shielding material instead. This highlights the need for detailed design and optimization studies if a neutron shield is deployed without added absorbers.

A number of other suppression techniques are under investigation using simulations. Also in consideration are alternative solid shielding materials, the introduction of neutron absorbing dopants into the liquid argon, using event topology information to identify showering muons, and identifying neutron capture events in the shielding materials. More novel techniques will continue to be studied, with the goal of reducing the cosmogenically-induced background at LNGS depth to <10% of the total LEGEND-1000 background budget.

References

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