Status of the Large Enriched Germanium Experiment for Neutrinoless ββ Decay - LEGEND

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(For LEGEND Collaboration)

Introduction

Definitive evidence for non-zero neutrino masses from oscillation experiments has been available for nearly two decades. However, the incorporation of neutrino masses into the Standard Model (SM) of particle physics remains an open issue. Because it is electrically neutral, the neutrino is the only known fundamental fermion that could be its own anti-particle, and obtain its mass through a Majorana mass term. The motivation to test the Majorana nature of the neutrino has never been higher. At present, the only feasible method for testing a pure-Majorana SM neutrino without requiring new fields or symmetries is to search for neutrinoless double-beta (0νββ) decay.

GERDA and MAJORANA

The GERDA and Majorana Demonstrator experiments are searching for 0νββ decay of ^{76}Ge. A primary difference between the two experiments is the use of shielding against external radiation. The current background level achieved for the GERDA PPC modified Broad Energy Germanium (BEGe) detectors is $1.0^{+0.6}_{-0.4}\times10^{-3}$ counts/(keV-kg-yr) with an energy resolution (FWHM) of 3keV at $Q_{\beta\beta}$ of 2039 keV. This corresponds to a projected background at $Q_{\beta\beta}$ of $3.0^{+1.8}_{-1.2}$ counts/(FWHM-ton-yr). Based on a total exposure of 34.4 kg-yr from Phase–I&II. GERDA sets a lower-limit half-life of 5.3×10^{25} years at 90% confidence level [1]. The Majorana Demonstrator array contains 29.7kg PPC detectors enriched up to 88% ^{76}Ge enclosed in a compact graded shield with inner layers of ultra-clean electroformed copper. They achieved background level at $Q_{\beta\beta}$ of $4.3^{+7.5}_{-2.7}$ counts/(FWHM-ton-yr). Both experiments project ultimate sensitivities better than 10^{26} years.

Next Generation Requirements

For $m_{\beta\beta}$ = 17 meV, a typical lower bound for the inverted neutrino mass ordering at 90% range using parameters from [2], the 'worst-case' half-life for the most recent ^{76}Ge shell model calculation is about 12×10^{27}yr. The expected number of decays per tone-yr exposure will be 0.5. The ^{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 the 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 tone scale 0νββ experiments.

LEGEND Collaboration

This collaboration is the combination of GERDA + Majorana + some other new groups around the globe. The LEGEND collaboration aims to improve the ^{76}Ge half-life discovery level to 10^{27}yr (3σ) in its first phase with further improvement to 10^{28}yr in its second phase. Here discovery level is defined as a 50% chance to observe a signal at 3sigma significance. Fig. 1 shows the sensitivities of a Ge experiment for discovery as a function of the exposure for different background levels. A signal efficiency of 0.6 is taken into account.

To set the best limit, low background is critical to maintain the linear dependence on exposure. In LEGENDs first phase up to 200kg of Ge detectors will be operated in the existing infrastructure of the GERDA experiment at the Laboratori Nazionali del Gran Sasso (LNGS) laboratory in Italy. For an exposure of 1 tone-yr and under conditions approaching background-free measurement (background index of 0.6 counts/(FWHM-ton-yr), the envisioned half-life sensitivity can be reached. In the following phases a new facility holding up to 1000kg of detectors would be operated with even lower background of less than 0.1 counts/(FWHM-ton-yr) and a design exposure above 10ton-yr.

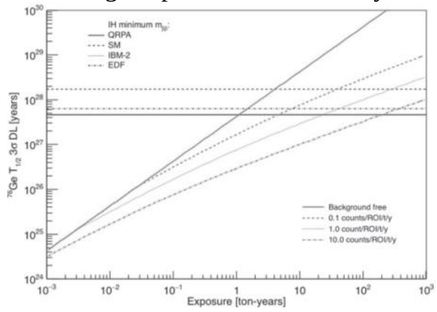

Fig. 1 Sensitivity plot of LEGEND for a signal discovery.

Fig. 2 Photograph of LEGEND-200 and sketch of baseline cryostat design for LEGEND-1000.

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 modest factor of ~30. This further background reduction is necessary to remain essentially background-free as the total exposure increases. LEGEND has adopted the GERDA design of a low-Z shielding and an active veto through the detection of argon scintillation light. In addition, the readout electronics yields better resolution for the energy and the pulse shape parameter for background rejection. The experience and expertise 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 will require a number of improvements starting from a new PPC type Ge detector with higher mass and an "inverted-coax" [3] construction, improved readout electronics and higher argon scintillation light detection efficiency. Engineering questions such as the feed through also have to be answered.

LEGEND-200 plans to operate up to 200 kg of Ge detectors using the GERDA infrastructure at LNGS. In order to be "background-free" for an exposure of 1tone-yr a factor of 5 reduction is needed relative to the latest GERDA and Majorana Demonstrator background levels. The events near $Q_{\beta\beta}$ are coming 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.

For the next phase of the experiment, LEGEND-1000, the exposure of 10ton-yr is reached by operating 1000kg of detectors for 10years. This requires new infrastructure and a more ambitious background goal to remain in the background-free regime. These considerations lead to the design shown in Fig. 2. An alternative design being considered is for example to use a scintillating plastic as a construction material since it has good mechanical properties. External backgrounds from neutrons and γs can be shielded by liquid argon and water. Time correlation between muon, neutron captures and background event can reduce the background drastically. The cosmic-ray flux can be reduced by a factor of 100 relative to that of LEGEND-200 at LNGS (1400m rock overburden) at deep underground laboratories like SNOLAB (2000m rock overburden) in Canada and CJPL (2400m rock overburden) in China.

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 (FWHM-ton-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 exploit half-lives up to 10^{28}yr using 1000kg of enriched germanium detectors. Under favorable funding scenarios, LEGEND-200 could start operations by 2021.

References

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[3] R. Cooper et al., Nucl. Instru. Meth. **A665**, 25 (2011).