PROCEEDINGS OF SCIENCE

The Ton-Scale Search for Neutrinoless Double-Beta Decay in Germanium with LEGEND-1000

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Next-generation neutrinoless double-beta decay searches seek to elucidate 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. 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. The innovation behind the LEGEND-1000 design, its technical readiness, and discovery potential is presented.

42nd International Conference on High Energy physics - ICHEP2024
17-24 July, 2024
Prague, Czech Republic

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PoS(ICHEP2024)193

1. Introduction

Nowadays, the true nature of neutrinos remains unknown as they could be either Dirac or Majorana particles, leading to different scenarios. The golden channel to determine their nature is the neutrinoless double-beta decay ($0\nu\beta\beta$), an ultra-rare process that has yet to be observed. This decay would only occur if neutrinos are Majorana particles, meaning they are their own antiparticles [1]. The LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) project aims at performing a quasi-background-free search for an unambiguous discovery of the ^{76}Ge $0\nu\beta\beta$ decay with a handful of counts at $Q_{\beta\beta}$. Combining the efforts of previous GERDA and Majorana Demonstrator experiments, the LEGEND project will proceed in two stages. The first phase is already in operation at *Laboratori Nazionali del Gran Sasso in Italy* (LNGS) and it is expected to deploy in liquid argon (LAr) up to 200 kg of germanium detectors enriched in ^{76}Ge [2]. With an exposure of 1 t·yr and a background index (BI) of 0.5 cts/(FWHM·t·yr), LEGEND-200 will reach a $0\nu\beta\beta$ half-life sensitivity of 10^{27} yr at 90% CL. The first phase will act as a test bench for the second phase LEGEND-1000 where 1000 kg of enriched germanium detectors will be deployed in underground LAr. With an exposure of 10 t·yr and a background index of 0.025 cts/(FWHM·t·yr), LEGEND-1000 will reach a 3σ half-life discovery sensitivity of 1.3×10^{28} yr [3].

2. Towards LEGEND-1000

The proposed design for LEGEND-1000, foreseen to be installed in Hall C at LNGS following the decommissioning of Borexino, is shown in Fig. 1. The collaboration and its international funding partners aim at finalizing the LEGEND-1000 design and starting its construction in the next years to collect the first data at the start of the next decade.

The core of the experiment will be 336 p-type Inverted Coaxial Point Contact (ICPC) detectors enriched up to 92% in ^{76}Ge with an average mass of 3.0 kg each. These detectors are characterized by larger masses compared to other HPGe detector geometries, which translates into lower background levels due to the reduced surface-to-volume ratio and fewer cables, read-out channels, and supports. Moreover, ICPC detectors are characterized by an outstanding energy resolution of 2.5 keV at $Q_{\beta\beta}$ = 2039 keV, along with excellent pulse shape discrimination (PSD) capabilities for effectively discriminating between background and signal-like events [4].

The primary challenge in LEGEND-1000 is to reach an ultra-low background level of BI = 10^{-5} counts/(keV·kg·yr) at $Q_{\beta\beta}$. This will be accomplished via strict material selection and handling, with stringent radiopurity requirements, starting from ICPC support materials. The detectors will be mounted using rods made from underground-electroformed Cu (EFCu) and plastic insulators. Transparent, scintillating, radiopure poly(ethylene napthalate) (PEN) baseplates will be employed as base holders for HPGe diodes, HV connectors, and front-end boards at the p+ electrode. ICPC diodes will be arranged across approximately 48 string modules, which can be singularly lifted and redeployed separately via single-string locks. All string modules are foreseen to be deployed in 15 m^3 of underground LAr (UGLAr) contained in an EFCu re-entrant tube that isolates this volume from the external 125 m^3 of atmospheric LAr (ATLAr). Each string will be instrumented with its own LAr instrumentation system. The UGLAr will help to reduce the ^{42}K contamination as it lowers it by a factor of 1400. An alternative plan in case no UGLAr was available was developed based on encapsulating HPGe diodes in PEN shields that would stop ^{42}K ion drift to a detector surface where the response to the high-energy β might produce background. The ATLAr cryostat will be hosted in an ultra-pure water tank of 865 m^3 instrumented with PMTs to detect Cherenkov light coming from crossing muons. Additional strategies for reducing the $^{77(m)}$Ge cosmogenic induced background will be required compared to the baseline design. Active background suppression techniques based on delayed coincidences across different subsystems will be adopted. The ATLAr volume will be instrumented with twelve 3-m high, 1-m wide and 10-cm thick Poly-Methyl MethAcrylate (PMMA) neutron moderator panels. The moderator acts both as a slowdown material for crossing neutrons and as a material to enhance the delayed coincidence cut efficiency by identifying neutron captures in argon via de-excitation photons, which are later tagged using a system of light guides placed on both sides of the neutron moderator [5].

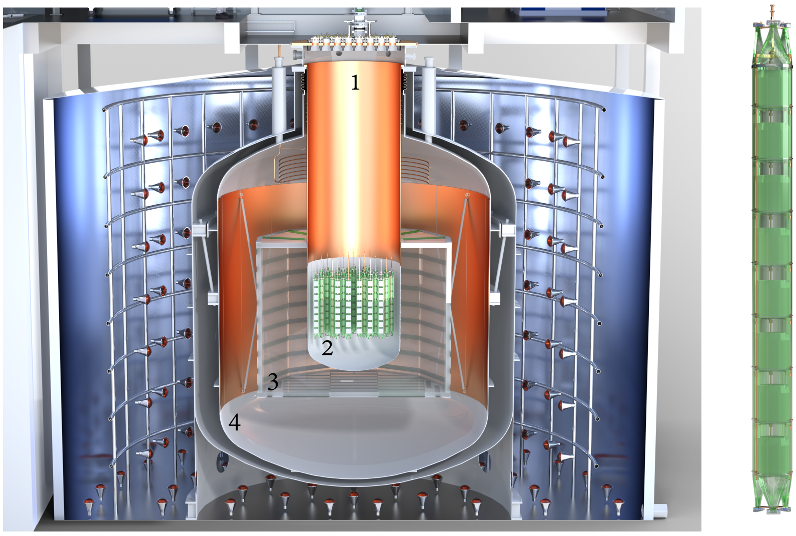

Figure 1: Left: schematic view of the LEGEND-1000 experiment at the LNGS site: (1) re-entrant tube containing UGLAr; (2) string modules for a total of 1000 kg of enriched germanium mass; (3) neutron moderator; (4) ATLAr cryostat hosted in an ultra-pure water tank. Right: string design. Credit to P. Krause

3. Acknowledgements

This work is supported by the U.S. DOE, and the NSF, the LANL, ORNL and LBNL LDRD programs; the European ERC and Horizon programs; the German DFG, BMBF, and MPG; the Italian INFN; the Polish NCN and MNiSW; the Czech MEYS; the Slovak RDA; the Swiss SNF; the UK STFC; the Canadian NSERC and CFI; the LNGS and SURF facilities.

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