PROCEEDINGS OF SCIENCE

LEGEND-1000 – a next generation detector for searches of neutrino-less double beta decay

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The LEGEND experiment has been designed to search for neutrino-less double-beta decay in ^{76}Ge. Its discovery would have profound implications for neutrino physics and cosmology providing unambiguous evidence for the Majorana nature of neutrinos, lepton number non-conservation and the absolute neutrino mass scale. The LEGEND-1000 detector represents the ton-scale phase of the LEGEND program, following the current intermediate stage, LEGEND-200, carried out at LNGS in Italy. The LEGEND-1000 will be based on p-type, inverted-coaxial, point-contact germanium detectors enriched in ^{76}Ge up to about 90 %. The detectors will be operated in an active shield based on underground argon. This gas is extracted from an underground source and it is depleted in ^{39}Ar and ^{42}Ar. This approach proved to guarantee the lowest background levels and the best energy resolution at the decay Q value as established by the GERDA and MAJORANA DEMONSTRATOR experiments. The anticipated quasi background-free operation will allow the search for neutrino-less 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 LEGEND Collaboration is successfully seeking funding from US and European agencies. The construction of the detector in Hall C of the underground laboratory of LNGS in Italy should start early 2027 and will take about 8 years. Start of data taking is foreseen for 2031.

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1. Introduction

Double beta ($\beta\beta$) decay is a second order process, which can occur in even-even nuclei, for which the β decay is forbidden due to energy/angular momentum balance. The $\beta\beta$ decay has already been observed for several nuclei, such as ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe and ^{150}Nd. The measured half-lifes for these isotopes are in the range of 10^{18} - 10^{24} yr.

A lepton number violating decay with no neutrinos in the final state ($0\nu\beta\beta$) is considered as well. If observed, it would provide a direct proof that neutrinos are Majorana fermions (it would be the discovery of a new particle). The decay rate will also allow to constrain the absolute neutrino mass scale, and support theories that leptons contributed to the observed matter-antimatter asymmetry in the present Universe. It would be therefore very important contribution to the modern particle physics, nuclear physics and astrophysics.

A particularly interesting isotope that could undergo the $0\nu\beta\beta$ decay is ^{76}Ge ($Q_{\beta\beta}$ = 2039.061± 0.007 keV [1]). The reason is that the detectors made from germanium enriched up to about 90 % in ^{76}Ge can be used to search for the decay. In this case the source is at the same time the detector, which maximizes the detection efficiency. High Purity Germanium (HPGe) detectors have also an excellent energy resolution of about 0.1 %, which next to the background-free operation, is one of the key parameters needed for the discovery of the $0\nu\beta\beta$ decay. Several experiments in the past have used this isotope, and in recent years the two experiments GERDA [2] and MAJORANA DEMONSTRATOR [3] obtained competitive half-life limits for the neutrino-less double beta decay of 1.8×10^{26} yr and 0.8×10^{26} yr at 90 % C.L., respectively

In 2016 the two Collaborations, GERDA and MAJORANA DEMONSTRATOR with participation of new groups, merged and formed the LEGEND collaboration [4]. Its goal is to develop a phased $0\nu\beta\beta$ decay experimental program. LEGEND-200 is its first phase with the aim of reaching the sensitivity of about 10^{27} yr in terms of both, setting a 90 % C.L. limit and achieving a 50 % chance to make a 3σ discovery, thanks to a projected background index of 2×10^{-4} cts/(keV×kg×yr) and an exposure of about 1 t×yr. The second phase, LEGEND-1000, aims for a sensitivity beyond 10^{28} yr by operating 1 tonne of enriched germanium detectors for 10 years (10 t×yr exposure) with a background index of about 10^{-5} cts/(keV×kg×yr).

2. LEGEND-200

LEGEND-200 is based on the GERDA infrastructure (cryostat, cryogenic infrastructure, water tank etc.) therefore, it could be prepared relatively fast. First physics run begun in March 2023 and lasted until February 2024. 142.5 kg of Germanium detectors of different types were deployed into the cryostat: 14.7 kg of semicoaxial (Coax), 19 kg of Broad Energy Germanium (BEGe) detectors (both came from GERDA), 22.1 kg of p-type point-contact (PPC) detectors (from MAJORANA DEMONSTRATOR) and 86.7 kg of inverted-coaxial (IC) detectors. The IC detectors have been already developed within the LEGEND Collaboration. A total exposure of 85.5 kg×yr has been collected, of which 61 kg×yr was used for the analysis. The achieved background index for the BEGe and IC detectors was 5×10^{-4} cts/(keV×kg×yr) and 13×10^{-4} cts/(keV×kg×yr) for the Coax detectors. This allowed us to establish a limit for the half-life of 0.5×10^{26} yr. Combining the

LEGEND-200 data with the GERDA and MAJORANA DEMONSTRATOR data one gets $T_{1/2} \geq 1.9\times10^{26}$ yr (90 % C.L.) [5]. The LEGEND-200 detector continues to take data.

3. LEGEND-1000

LEGEND-1000 will be built in Hall C of the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. The schematic view of the experimental setup is shown in Fig. 1. The detector array consisting of 1000 kg of IC detectors enriched to more than 90 % in ^{76}Ge will be deployed in the so-called underground argon (UAr), which is depleted in ^{39}Ar and ^{42}Ar by a factor of at least 1400. UAr is needed to suppress the background component coming from ^{42}K, a ^{42}Ar daughter. This is the same argon as the DarkSide experiment (searches for direct interactions of cold dark matter particles in liquid argon) uses. About 20 tonnes of UAr will be contained in the 1.9 m diameter re-entrant tube made from a thin copper foil. The tube separates UAr from the atmospheric argon (AAr, 200 tonnes), which will be filled into the vacuum insulated cryostat. Both argon volumes will be instrumented and will serve as passive and active shields. The cryostat will be installed in a tank filled with ultra pure water providing passive shielding and a muon veto.

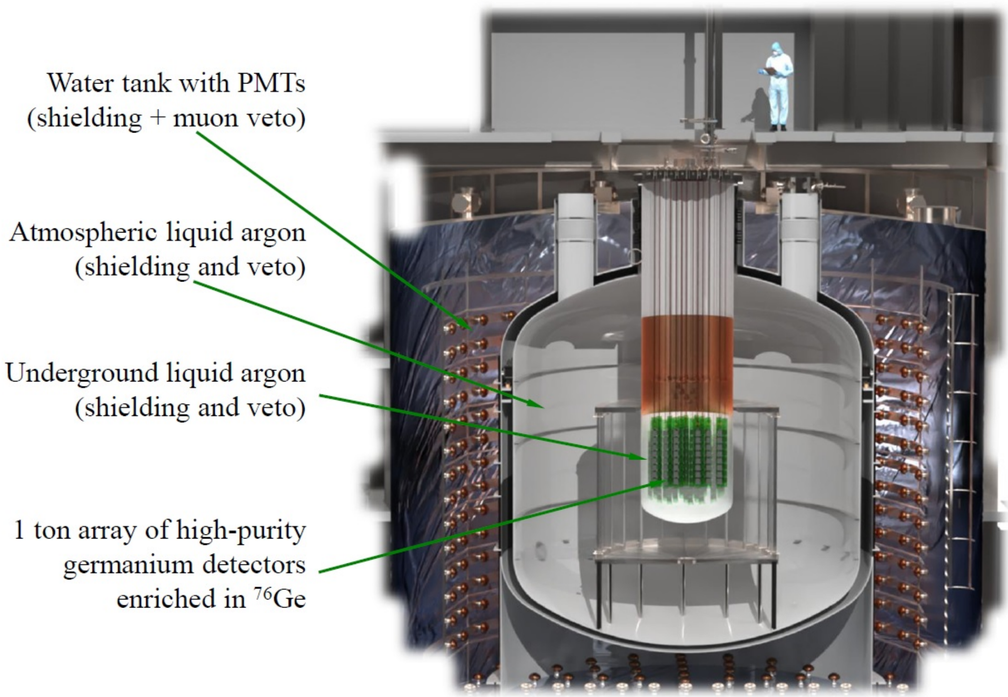

Figure 1: Schematic view of the LEGEND-1000 setup with the germanium detector array deployed in the re-entrant tube filled with underground argon. The re-entrant tube is installed in a stainless steel vacuum insulated cryostat full of atmospheric argon. The external tank hosts the cryostat and it is filled with ultra pure water. It serves as an passive shield and, being instrumented with PMTs, also as an active muon veto.

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Preparations for the experiment are advancing very well. Some funding has already been received from European (Italy, Germany, Switzerland, Poland) and US agencies. Several grant

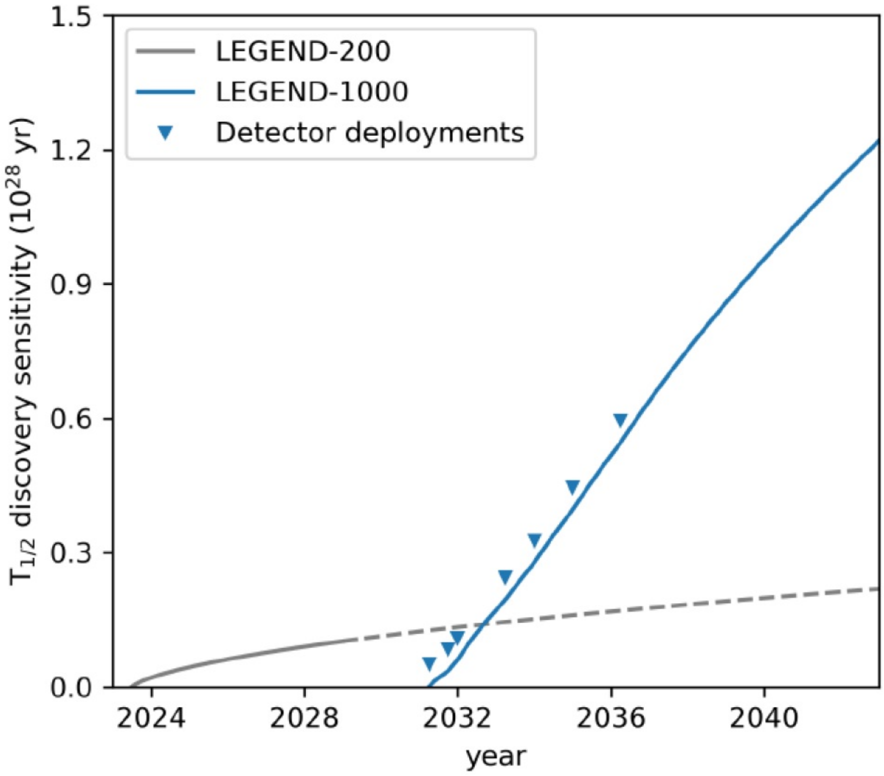

Figure 2: Projected LEGEND-1000 sensitivity as a function of the enriched germanium mass, which will systematically increase due to subsequent detector deployments. For comparison sensitivity of LEGEND-200 is shown as well.

applications are under preparation or evaluation. A milestone, in this context, will be the Critical Design-1 (CD-1) review, which is planned by US Department of Energy (DOE) for the end of 2025. In 2027 the procurement of enriched germanium should start (with expected capacity of about 200 kg/yr) and the production of the detectors will follow. In parallel, the construction of the cryostat, cryogenic infrastructure, and other auxiliaries will proceed. Filling of the detector with argon is scheduled for the end of 2030, commissioning for 2031 and hopefully the start of data taking.

In the LEGEND-1000 budget the dominant component (~75 %) is the enriched germanium (including production of the detectors). It is planned and included in the design of the experiment that the detectors will be commissioned in several individual deployments improving systematically the sensitivity, as shown in Fig. 2. This increases the robustness of the project against the risk of funding delays. Extensions beyond 1000 kg are also feasible.

After 10 yr of data taking with 1 tonne of ^{76}Ge and the anticipated background index of 10^{-5} cts/(keV×kg×yr) LEGEND-1000 should be able to reach the design discovery sensitivity beyond 10^{28} yr to fully explore the neutrino inverted order hierarchy down to the effective neutrino mass in the range 9 - 24 meV.

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