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Legend-200 and nEXO: A Comparison of Two 0νββ Search Project's Systematic Setups and Muon Veto Efficiency

Jiayi Yang

Department of Physics, University of California, Santa Barbara, Goleta, USA
jiayi_yang@ucsb.edu

Abstract. Neutrinoless double beta decay (0νββ) has been a hot topic in recent neutrino studies. With the existence of neutrino oscillations verified, neutrinos are confirmed to have masses. The next natural questions arise: What is the absolute mass of neutrinos? And where does their mass originate? Searches for neutrinoless double-beta decay (0νββ) aim to tackle these issues, encompassing the determination of neutrinos' absolute mass scale, the clarification of their mass generation mechanism, and the verification of their Majorana nature. This paper will investigate two recent projects searching for 0νββ: LEGEND-200 and nEXO, on how they each approach the problem of accurately probing proposed 0νββ events. Both projects have advanced methods for background suppression, and their structures, designs, and mechanics will be explained in detail in this paper. An emphasis will be placed on vetoing systems for cosmic muons, one of the most common background sources in 0νββ searches, with the comparison between the two projects' designs included. The effectiveness of both muon veto systems will be analyzed using numerical data, with implications for how this reflects the efficiency of different subsystems.

Keywords: Neutrinoless double beta decay, LEGEND-200, nEXO, Muon-veto system

1. Introduction

In the standard model, Double beta decay (2νββ) refers to the process where two neutrons decay into two protons, emitting two anti-neutrinos and two electrons. This process is confirmed by many experiments [1,2]. However, as early as 1939 [3], theorists predicted a analogous process beyond the Standard Model, known as neutrinoless double beta decay (0νββ). This process involves the same fundamental transformation—where two neutrons decay into two protons and two electrons—but with the key distinction that the neutrino pair is annihilated as an internal process. If this process is observed, it would confirm that neutrinos are their own anti-particles. Such particles have a name called majorana particles, first proposed by Ettore Majorana in 1937 [4]. If 0νββ is observed, and neutrinos are indeed majorana particles, that would help theories addressing some important questions. To name a few examples, the absolute mass scale of neutrinos can be calculated; furthermore, the lepton number violation in 0νββ provides a foundational basis for leptogenesis, a theory that seeks to account for the matter-antimatter imbalance.

Despite decades of experimental efforts, 0νββ remains undetected. However, 0νββ searches have achieved remarkable sensitivity, setting lower limits for half-lives for multiple isotopes involved in

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double beta decay. For example, Ge-76 (Gerda) and Xe-136 (KamLAND-Zen) have confirmed half-life limits exceeding years [5,6]. Recent results from AMoRE-I, using Mo-100, set a lower limit of half-life years, constraining ⟨mββ⟩ (effective majorana mass) to meV [6].

Different experiments utilize different isotopes. The LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta decay) project located in Italy made exemplary progress with Ge-76, achieving unprecedented sensitivity [7]. The nEXO (next Enriched Xenon Observatory) project planned in Canada, on the other hand, utilizes Xe-136, has implemented innovative processing techniques like precise event localization. This paper reviews these projects, from theoretical foundations and processing methods, with an emphasis on the muon vetoing system in each, with a comparison included.

2. LEGEND experiment

The LEGEND-200 and future LEGEND-1000 project seeks the possibility of 0νββ from the decay of Ge-76. Such events are extremely rare, with measured lower limits on half lives in order of years [8]. Therefore, to successfully detect it, an extremely precise measurement is required. LEGEND's technical designs to achieve precision, especially in background suppression, will be discussed below. Unless otherwise specified, LEGEND refers to the current LEGEND-200 phase.

The location of LEGEND is chosen to be at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. This lab is deep under mountain rocks, which helps block hadronic cosmic backgrounds. Within the lab, the actual detectors are covered by layers of materials and devices that either reduce external radiation or help veto it. A view of the entire apparatus is attached for better understanding.



Figure 1. A view of the central apparatus of LEGEND [9]

Starting from the outermost layer, the detectors are first shielded by a large water tank filled with purified water.This water tank's purpose is primarily to identify incoming leptons by Cherenkov light they produce. The tank will contain 590 m^3 of liquid when filled [9]. Therefore, choosing purified water is an economical and efficient choice: it can be produced in large amounts, plus it has a low Cherenkov light threshold of 0.26MeV and can effectively spot minimum-ionizing particles

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[9]. On the inner surfaces of the water tank, photomultiplier tubes (PMTs) are installed, which will detect the Cherenkov light produced.

The cryostat covered by the water tank has High Purity Germanium detectors (HPGe) at its core, while filled with liquid argon. As hinted earlier, this liquid argon (LAr), with its instrumentations, serves as another vetoing system for background radiation. Different from the water tank's primary veto power of external muons, LAr veto capabilities cover a variety of background events. Major background events in the LEGEND experiments include structural materials' components that decay, like K-40, U-238, or Th-232 [10]. Moreover, LAr contains an isotope Ar-42, which decays to K-42, then to Ca-42 (stable), during which it releases beta and gamma background radiations [10]. In addition to these, LAr can also help detect decays of Ge-77 isotope [11], which comes from cosmic muon induced neutrons. This will be gone over in more detail in the comparison chapter.

The central HPGe detectors are the core, as it produces the 2νββ and theoretically proposed 0νββ through the decay of Ge-76. The location of each detector is known, so that the group can localize ionization events. With that, the experimenters can analyze the topology of events, and identify them as single site events(SSE) or multi-site events(MSE). The former occurs within a narrow region in one detector, and the latter occurs across multiple places in one detector [7]. Double beta decays, neutrinoless or not, are SSEs. To separate them out, experimenters cut out MSEs by pulse shape discrimination (PSD) techniques [7]. This technique utilizes the topology data mentioned earlier, and can also cut out events on the surface of detectors [7]. In addition, there are also events that occur across multiple detectors, which can be a combination of previously mentioned events, and they are ruled out with the multiplicity cut in the computation [7]; All these are to isolate out SSEs, containing 2νββ and proposed 0νββ decays.

nEXO experiment

The nEXO project, inherited from EXO-200, attempted to find 0νββ using 5 tons of liquid xenon in the underground lab at Ontario, Canada [12]. A description of their designs will be introduced below, with deeper analysis and comparison with LEGEND being in the next chapter.

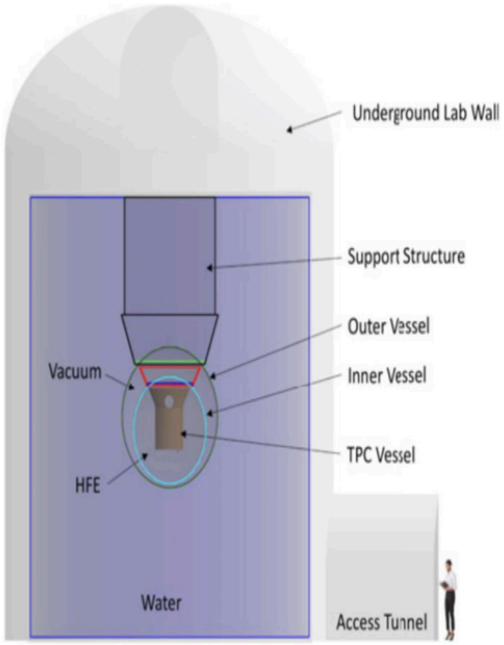

Figure 2. The structural designs of nEXO [12]

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The underground lab is covered with approximately 2 kilometers of rocks, to shield against energetic cosmic radiation [13]. The main device has many layers of background shielding designs just like LEGEND (See Figure 2). The outermost layer is a water tank filled with highly purified water, with photomultiplier tubes (PMTs). Such a water tank can detect the incoming muon, thus vetoing events correlated. Additionally, it can also shield against the radiation from decays of radioactive components in the rock, like Uranium or Thorium [13].

The center cryostat has an inner and outer vessel, both concentric spheres, as shown in Fig 2. A vacuum is maintained between the inner and outer vessels to provide thermal insulation for the materials inside the inner vessel, isolating them from the water tank. Between the inner vessel and Time Projection Chamber (TPC), nEXO deploys around 33 tons of HFE-7000 [14], which thermally bathes the TPC and shields radiation [12].

Liquid Xenon filled the time projection chamber, immersing other devices within it. The field cage within TPC is the primary device of detection. When a 2νββ or 0νββ occurs from a Xenon decay, the two electrons produced will travel through liquid Xenon, dissipating their energy, and creating clouds of free electrons [13]. An electric field of 400 V/cm between the top anode and bottom then drifts these clouds towards the anode. They will move in a straight line as the field is uniform. As they reach the top they will be collected by tiles arranged as strips in arrays [13]. This allows researchers to determine two of the spatial coordinates of the electrons' paths. The remaining coordinate is determined from the light signal produced by the electron pair. They not only produce charge clouds but also light flashes in Xenon. Silicon photomultipliers (SiPMs), arranged in a barrel shape, detects the light's intensity pattern and exact arrival time [12]. Since charge clouds arrive slower, the time difference between the light and charge clouds can be used to determine how long clouds travel, thus how far they come from [13]. This gives the third coordinate.

3. Detailed explanation & comparison of the muon veto systems

A more detailed explanation of LEGEND and nEXO's muon veto system, and a comparison between the two's designs will be discussed in this chapter.

In LEGEND, The PMTs distribution has a higher density across the floor and the pillbox (the region directly below the center cryostat), totaling up to 66 PMTs [15]. This is done primarily because muons going through the center will land more on the floor than the walls [16]. In fact, the PMTs in the pillbox region, despite being only 20 percent of all muon-veto PMTs, detect around 70.8 percent of the total coincident muon events with the liquid argon veto system [16]. LEGEND does not use this alone to tag cosmic muons. Another complement comes from the LAr system.

The key effect of LAr is to distinguish events by scintillation light. As mentioned before, LEGEND identifies desired double beta decay events by finding SSEs. This gives rise to one question: 2νββ and 0νββ are not the only possible processes that leave a SSE signature. For instance, a background photon might also deposit energy at a narrow range within a detector, leaving a SSE event. To address this, LAr provides a veto system based on scintillation light. When relevant background radiation within the experiment's energy range shows up in LAr, they will produce a combination of singlet and triplet excimer states [17]. The ratio R of singlet to triplet, is used to define the term $\mathrm{ETC} = \frac{1}{1+\frac{1}{R}}$ [18]. Since R depends on the linear energy transfer (LET) $\frac{dE}{dx}$, and different particles have different LETs, R and hence ETC can be used as signatures of different particles' events in LAr [18]. Along with other properties like time difference between different events in a decay chain, LAr is able to identify types of relevant particles generating the light in it

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through a pulse shape analysis of the light [18]. This includes the cosmic muons' induced events, like creation and the subsequent decay of Ge-77.

Monte-Carlo simulations of the LEGEND team have put this dual veto system combining both PMTs and LAr into test. The combined efficiency of detection, in testing of LEGEND-1000, reaches 94%, for muons likely producing cosmogenic background in relevant energy range [19].

For nEXO, it is reported that the primary cosmogenic background comes from the Xe-137 produced by cosmic muons [20]. Researchers require more than 95% muon tagging efficiency, for ones that tend to produce cosmogenic backgrounds. Based on their calculations, this is defined as muons arriving within 3.35 meters of the TPC center. These muons will account for more than 99% of the total cosmogenic Xe-137 production [20]. In the simulation, different components of the water tank inner surface are assigned a reflective index based on their physical properties(refer to figure 5.1 in [20]). The main changing variable is the reflective coating for the wall and floor. The cumulative reflectivity of the walls and floor ranges from 40% to 98%, depending on the extent of 99% reflective coating coverage. Specifically, the lower end (40%) corresponds to scenarios with no coating—where only the stainless steel surface is exposed—while the upper end (98%) applies to near-complete coverage [20]. PMTs' distribution is also varied for optimal output. The result is that, with 80 % reflective coating, and a floor-biased PMT distribution, the system can achieve around 97.5 % tagging efficiency "for all muons passing through the water tank" [20]. Floor bias refers to the design of placing 45 out of 125 total PMTs over floor, and merely 16 over the ceiling. Wall's PMT distribution is also slightly skewed towards the bottom, with the lower third and upper two thirds containing the same amount of 32 PMTs [20].

On site choice, both projects agree on choosing a deep underground lab for optimal muon rejection, reported by LEGEND to be more than six orders of magnitude [9] decrease in muon influx.

On systems used, LEGEND utilizes both PMT and LAr systems for vetoing, while nEXO primarily uses the PMT system. Noteworthily, LEGEND used only 66 PMTs while nEXO plans to deploy 125 PMTs. While exhibiting minor structural variations—such as differences in roof design —both water tanks approximate a cylindrical shape. The radius and height are 5 and 8.3 meters for LEGEND [21], and 6.17 and 12.8 meters for nEXO [20]. Thus, the rough inner surface ratio is about 0.57. Whereas the PMT ratio is about 0.53, which is close to each other. Their PMT models also have the same size of 8 inches [21,20], with similar quantum efficiencies [22,23]. Therefore their PMT systems' performances should be similar.

The key reason why nEXO does not need an additional veto system like LEGEND comes from the fact that nEXO has more topological information of events. Namely, nEXo's LXe detectors can reconstruct energy deposition's time and spatial locations. These provide strong veto power so that a complimentary veto system is not needed. For example, when a muon enters, it will first travel through a water tank, leaving a track from light detected by PMTs. Then, if it deposits energy, say by creating some Xe-137, the delayed decay events of Xe-137's spatial positions, time, and energy released will all be recorded. Researchers can then see that these events sum to a total energy matching what is expected from cosmic muons' induced Xe-137, having a time difference comparable to half-lives of Xe-137, and spatially close to the previous muon track in the water tank. With this information, events from cosmic muons are highly identifiable.

In LEGEND, muons can also create secondary particles like Ge-77 that have a delayed decay. PMTs alone can tag a muon entering, but cannot link them to delayed events. However, even if the HPGe detectors can be used to estimate the z-coordinate from pulse rise time at contacts [24], the other two spatial coordinates cannot be determined. Without this topological information, LEGEND

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needs the LAr system for more veto power. Through the LAr scientillation light analysis gone over previously, LEGEND can link these events with a cosmic muon passing through earlier, thus vetoing. Note that LAr also cannot provide exact spatial coordinates of events, but a rough energy distribution, from information like whether lower or upper SiPMs receive more light input. Thus, the veto primarily relies on a coincidence cut [25], which is triggered when both germanium (Ge) events and scintillation light are detected within a specific time window.

4. Conclusion

This paper has gone through the designs of LEGEND (primarily LEGEND-200) and nEXO projects. The structural designs of both projects are explained layer by layer, from the outermost shield to inner core detectors. Combined with images and data quotes, the working principle of various parts of the machine is discussed in depth. An emphasis is placed on the muon veto system of both projects, while both use PMTs in water tank, LEGEND utilizes LAr systems for additional tagging capability around HPGe detectors, and nEXO exploits the precise topology collection of its LXe detectors' design.

With its sophisticated designs, LEGEND-200 is able to reach extremely high resolution. Even if they have not found 0νββ, they set a highly-credible lower limit on its half-life. A combined analysis of data from LEGEND-200, GERDA, and MAJORANA Demonstrator yielded a 90% confidence level (C.L.) exclusion sensitivity of years for the 0νββ half-life from Ge-76, with an observed lower limit of half life exceeding years.

nEXO, though still in R&D phase, with its advanced liquid xenon time projection chamber design, has projected to achieve exceptional performance. According to one of their publications, the collaboration anticipates a 90% C.L. exclusion sensitivity of years for the 0νββ half-life of Xe-136, with a 3σ discovery potential at years after ten years of data taking and a design energy resolution of ≤1 % at 2458 keV.

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