

The nEXO detector: design overview

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Abstract. This report presents an overview of the design solutions adopted for the nEXO detector, a large enriched-liquid-xenon time projection chamber to search for the neutrinoless double beta decay (0ν DBD) of ^{136}Xe . The nEXO concept is inherited from EXO-200, the first 100-kg scale DBD experiment to produce physics results, which ran between 2010 and 2018 at the WIPP underground site in New Mexico. Important novel solutions were introduced for nEXO that ease some aspects of the scale-up and, most importantly, allow nEXO to achieve a >100-fold higher sensitivity to 0ν DBD than its predecessor.

1. Introduction

The search for neutrino-less double beta decay (0ν DBD) is one of the declared goals of experimental nuclear physics (see, *e.g.*, [1]). The existence of this exotic decay in which two neutrons inside an even-even nucleus morph into protons emitting two electrons with no final-state neutrinos would at once provide a first instance of lepton number non-conservation and define neutrinos as massive Majorana fermions, *i.e.* their own anti-particles [2]. In particular, 0ν DBD can be viewed as a new mass-generating mechanism [3] and a possible portal through which to explain the dominance of matter in the universe via *leptogenesis* [4].

Searches for this decay have, so far, ended up empty-handed. Experiments performed over the past ten years with three isotopes, including ^{76}Ge and ^{130}Te on addition to ^{136}Xe , have set lower limits for the half life $T_{1/2}^{0\nu}$ of the process well in excess of 10^{25} years (see Tab. 1). Specifically, a best sensitivity and most stringent lower limit of $T_{1/2}^{0\nu} 1.1 \times 10^{26}$ years were reported by the GERDA [5] and KamLAND-Zen collaborations, respectively.

The nEXO collaboration has proposed to search for 0ν DBD of ^{136}Xe using a large time projection chamber (TPC) filled with five tonnes of isotopically-enriched liquid xenon (LXe) operated in single phase [12]. The projected nEXO sensitivity, obtained using radioactivity values of all materials coming from direct measurement either in EXO-200 or radio-assay, is $T_{1/2}^{0\nu} \sim 10^{28}$ years [13], the desirable target half life design sensitivity for the next generation *tonne-scale* experiments. Indeed, this is the sensitivity required to investigate the *inverted neutrino mass ordering*, when 0ν DBD is interpreted via the virtual exchange of light yet massive Majorana neutrinos (a model-dependent assumption!), as illustrated in Fig. 1.

The need for double beta decaying isotope at the tonnes scale is simply explained. The molar mass of all practical DBD candidates ranges between 48 and 150 grams/mole. Using Avogadro's number $N_A = 6 \times 10^{23}$, in order to have 10^{28} atoms, or 16,600 moles, one needs to collect between 0.8 tonnes (^{48}Ca) and 2.5 tonnes (^{150}Nd) of isotope. For a decay life of



Table 1. Current status of experimental searches for 0ν DBD.

$T_{1/2}^{0\nu}$ (10^{25} yr) (sens. / limit)	Isotope	Experiment	Year	Status	Reference
5.6 / >10.7	^{136}Xe	KamLAND-Zen (phases I+II)	2016	completed	[6]
8 / >4	^{136}Xe	KamLAND-Zen 800	2019	running	[7]
11 / >9	^{76}Ge	GERDA (phases I+II)	2018	running	[5]
4.8 / >2.7	^{76}Ge	Majorana Demonstrator	2018	running	[8]
5.0 / >3.5	^{136}Xe	EXO-200 (phases I+II)	2018	completed	[9]
1.5 / >2.3	^{130}Te	CUORE	2019	running	[10]
0.5 / >0.35	^{82}Se	CUPID-0	2019	completed	[11]
	^{130}Te	SNO+		commissioning	

10^{28} years and assuming perfect detection efficiency, one would record and average 10 events in a decade of running.

2. The nEXO detector

The nEXO design is rooted in the successful EXO-200 experiment [14, 15], which has just completed its operations in December 2018. It uses five tonnes of 90%-enriched liquid xenon. EXO-200 was the first kilo-mole DBD experiment to produce results, has set one of best 0ν DBD sensitivities for ^{136}Xe using 80%-enriched xenon [9] and has proven the viability of the single phase liquid xenon time projection chamber (LXe TPC) technique for a 25-fold, multi-tonne experiment, nEXO, shown in Figs. 2,3. The nEXO detector takes advantage of the properties of liquid xenon, including high signal detection efficiency, ii) excellent self-shielding (due to high-Z and high density) against γ -rays, which display their minimum cross-section at the MeV energy of interest for DBD, iii) the ability to purify (initially and over the course of the experiment) the medium from chemical and radioactive impurities, iv) the absence of long-lived radioactive isotopes, v) very good energy resolution when ionization and scintillation signals are combined event-by-event, vi) and excellent single- to multi-site topological background rejection and particle identification capabilities.

The self-shielding and background rejection properties are fully taken-advantage of in the monolithic nEXO design, which uses a single drift volume with anode and cathode at opposite ends of $\sim$ right cylindrical $\sim 1.3 \text{ m} \times 1.3 \text{ m}$ TPC (this is a departure from EXO-200, which used a central cathode and two symmetric drift volumes). This way, radioactive backgrounds, which are predominantly originating from other-than-xenon detector structures, can be suppressed

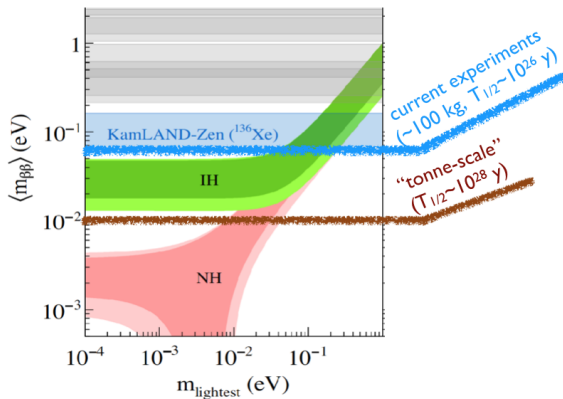


Figure 1. Sensitivity of tonne-scale 0ν DBD tonne-scale experiments to cover the inverted neutrino mass ordering in the model-dependent framework where the decay is attributed to the exchange of light yet massive Majorana neutrinos. The need for $\sim$ tonnes of double beta decaying isotope is an unescapable experimental need for requirement to reach the sought-after sensitivity in a humanly-reasonable timescale.

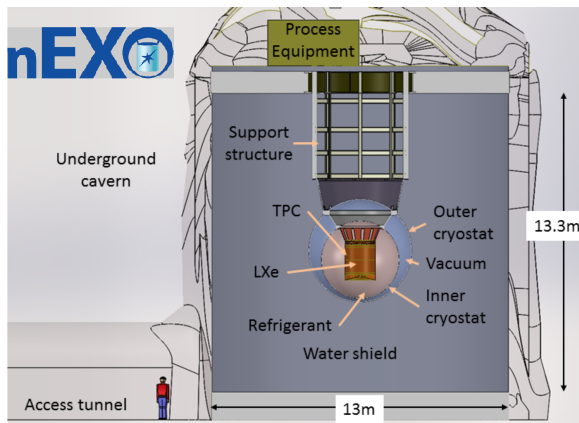


Figure 2. The nEXO detector shown in the SNOLAB Cryopit.

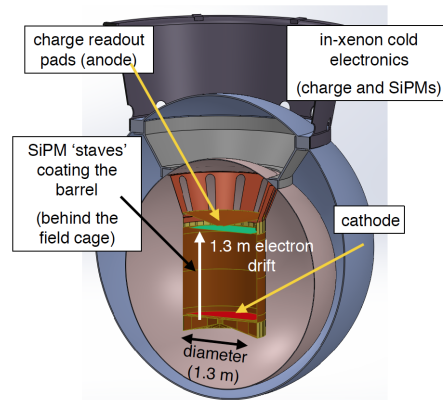


Figure 3. The nEXO inner detector, comprising the TPC and the cryostat.

inside a very large central volume of xenon and, at the same time, measured precisely at the edges of the detector.

The nEXO detector has an optically-open electrode field cage, with VUV-sensitive silicon photomultipliers (SiPMs) to detect the xenon scintillation light covering most of the side surface ($\sim 4 \text{ m}^2$) of a high-purity copper xenon containment vessel. A novel charge readout system of thin, crossed metal strips deposited onto $\sim 10 \times 10 \text{ cm}^2$ fused silica tiles allows for a high modularized design, an advantage at the nEXO scale and level of complexity. The front-end readout for both the ionization and scintillation signals is performed through dedicated in-xenon ASICs. Due to the long drift length in excess of one meter and the need for 1% energy resolution at the 2.5 MeV xenon Q -value, nEXO will minimize the use of plastics in contact with the xenon. This calls for a 10 ms electron drift time, only a factor of two better than what already demonstrated with EXO-200. As a consequence, no PTFE reflector for VUV scintillation light is used. TPC surfaces such as the field shaping rings are made reflective by, *e.g.*, a thin aluminum + MgF_2 coating.

The nEXO cryogenic system is inherited from EXO-200. The liquid xenon volume is cooled down by immersing it inside a large double-walled cryostat filled with a fluorinated organic fluid (Fluorinert HFE-7000 by 3M), which is liquid in the entire range including LXe (165 K) and room temperature. HFE-7000 was also found to be extremely radio-pure. This solution has several advantages: i) it provides a $\sim 60 \text{ cm}$ minimum HFE thickness around the TPC to shield from γ -rays and neutrons from the cryostat and beyond, ii) provides a 30-tonne thermal mass that greatly helps keep the temperature of the LXe stable over time and within a tight band of values, and represents a welcome safety system should cooling power to the detector be lost for any reason.

3. The nEXO R&D

In addition to the experience gained with EXO-200, the design of the nEXO detector is the result of R&D activities carried out since 2013. Main lines of development have involved i) high-efficiency VUV-sensitive SiPMs and detector optics to enhance light collection efficiency, ii) novel tiled charge collection detector, iii) cold, in-xenon electronics and relative interconnections to integrate it with charge and light detectors and carry the signals outside of the TPC, iv) high-voltage delivery to the cathode, v) background control strategies, including materials selection and screening, vi) refined analysis tools on EXO-200 data to fully characterize the projected nEXO detector response.

The overall light collection efficiency for nEXO needs to be $>3\%$. SiPMs for nEXO need to display an photon detection efficiency $>15\%$ with <0.2 probability of correlated pulses within $1\ \mu\text{s}$ of the primary avalanche. Devices meeting and exceeding these specifications have already been identified [16, 17, 18], and development is still ongoing to improve performance and reliability of these devices. Tests of the performance of SiPMs in high electric fields has shown no problem [19], and their VUV reflectivity was characterized to include in refined optical model of the detector [20].

The novel charge tiles were demonstrated to yield similar results to traditional anode wire planes [21]. Recent simulations [22] which use machine learning techniques tested in EXO-200 [9] have shown that the nEXO 0ν DBD sensitivity could be improved by $\sim 20\%$ with respect to that quoted in [13]. These methods will be tested in lab-scale setups in the coming months. Cold in-xenon electronics is being developed for both charge and light, and materials are being radio-assayed to perfection the already mature background model for nEXO.

In conclusion, the five tonne nEXO is currently projected to search for 0ν DBD of ^{136}Xe with an exclusion sensitivity of 9.2×10^{27} years in ten years of running based on a realistic background model and detector responses validated at the hundreds of kg's with EXO-200.

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