Status and Prospects for the EXO-200 and nEXO Experiments

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Abstract. Large ultra-low background liquid xenon detectors have recently emerged as a promising technology that can push the neutrinoless double beta decay search to unprecedented sensitivity. Since it began operation, EXO-200 has completed one of the most sensitive searches for $0\nu\beta\beta$ decay of $^{136}$Xe using its first two years of data. After an unexpected interruption, due to underground incidents at the Waste Isolation Pilot Plant (WIPP), EXO-200 has started its Phase-II running in April 2016 with upgrades to its front-end electronics and Rn suppression system. In this article, we report the performance data of upgraded EXO-200 detector and the projected sensitivity for its Phase-II running. nEXO is a next-generation tonne-scale experiment building on the success of EXO-200. This 5 tonne LXe detector will be capable of probing Majorana neutrino mass in the inverted mass hierarchy region. The status of the nEXO experiment will be discussed in the article.

1. Introduction
Double beta decay is the simultaneous beta decay of two nucleons inside a parent nucleus. There are two possible decay modes. The first decay mode involves the emission of two neutrinos along with two electrons and the final state nucleus ($2\nu\beta\beta$), while the second decay mode has no emitted neutrino in the final state ($0\nu\beta\beta$). The $2\nu\beta\beta$ decay mode is allowed by the Standard Model and has been observed in several isotopes. The $0\nu\beta\beta$ decay mode, on the other hand, is a lepton-number-violating process that can occur only if neutrinos are massive Majorana particles (i.e. their own antiparticles)[1].

In the past decade, the EXO-200 collaboration has pioneered the use of large liquid xenon (LXe) detectors to search for $0\nu\beta\beta$ decay in $^{136}$Xe. LXe detectors have several distinct advantages:

- Xe is used both as the source and detection medium to maximize detector efficiency
- Ionization and scintillation signals are simultaneously collected to improve energy resolution
- Full 3-D reconstruction of all energy depositions in LXe can be used for background rejection
- Monolithic detector structure provides excellent self-shielding against external backgrounds
- Xenon can be continuously purified to achieve superb chemical purity and cleanliness

EXO-200 is a running LXe detector with ~110 kg active volume. In its Phase-I running, it has demonstrated key performance parameters of LXe detector for $0\nu\beta\beta$ search, for example the use of event topological information to discriminate gamma backgrounds. After a two-year hiatus caused by underground incidents unrelated to the experiment, EXO-200 has resumed its Phase-II operation with detector upgrades in 2016.

nEXO is a proposed tonne scale experiment. It builds on the technology demonstrated by EXO-200, and incorporates new advancement in photosensors, charge collection tiles, low temperature electronics, and ultra-low background materials. Sensitivity studies show that nEXO can probe the effective Majorana neutrino mass in the inverted mass hierarchy region.
This article focuses on the detector performance improvements of EXO-200 for its Phase-II running. Other aspects of EXO-200 and nEXO are covered in related articles in this proceeding [2] [3].

2. **EXO-200 Phase-I Results**

2.1 **EXO-200 Detector**

The EXO-200 detector is described in detail in Ref. [4]. The central component of the detector is a LXe time projection chamber (TPC). The chamber is divided into two equal volumes by a photo-etched phosphor bronze cathode plane. Near each end of the chamber are copper platters for housing an array of large-area avalanche photodiodes (LAAPDs) [5] and two wire planes crossed at 60°. When an ionizing radiation event occurs inside the chamber, the electrons produced are drifted towards the wire grids by a main drift field applied between the wires and the cathode plane. The wire plane closer to the cathode plane, called the “V wires,” collects induction signals, while the other wire plane, called the “U wires,” collects charge signals. The wire signals provide two-dimensional position information of the event. The position in the drift direction can be obtained using the known drift speed and the light signal collected by the APDs as time zero.

2.2 **EXO-200 Phase-I Results**

EXO-200 began low-background data taking in June 2011. The detector successfully operated for two and half years before underground fire and radiological accidents at WIPP unrelated to the experiment temporarily halted the underground access and the detector operations. Using the first two years of data, the collaboration published a 0νββ decay search result with total $^{136}$Xe exposure of 100.0 kg·yr [6]. The global fit of the low-background spectra predicts a background rate of $1.7 \times 10^{-3}$ kg$^{-1}$yr$^{-1}$keV$^{-1}$ in the region of interest (ROI) near the endpoint. Using a profile likelihood study, we extract a value of $T_{1/2}^{0νββ} > 1.1 \times 10^{25}$ yr for $^{136}$Xe at 90% C.L. This value is lower than the experimental sensitivity of $1.9 \times 10^{25}$ yr due to upward fluctuation of the background. Both the radioactivity-induced and cosmogenic backgrounds to the 0νββ decay search are studied in detail in Ref. [7] and [8].

In addition to the 0νββ decay search, EXO-200 has published a precision measurement of 2νββ decay of $^{136}$Xe, $T_{1/2}^{2νββ} = 2.165 \pm 0.016$ (stat) $\pm 0.059$ (sys) $\times 10^{21}$ yrs [9]. This has been the most precisely measured 2νββ decay half-life of any isotope, demonstrating the power of LXe TPC as a precision measurement instrument. The ultra-low background achieved in EXO-200 detector has allowed us to perform sensitive searches to Standard Model physics channels such as the $^{134}$Xe 2νββ decay, and $^{136}$Xe decays to 0$^+$ excited states of $^{136}$Ba [10] as well as physics channels beyond the Standard Model, including the searches for Majorons [11] and Lorentz violation processes [12]. Using the Rn decay chain, we successfully measured ion fraction and mobility of alpha and beta decay products in liquid xenon [13]. The measurement of beta decay daughter ion fraction is relevant to the development of a “Ba tagging” technique for the nEXO experiment [14].

3. **EXO-200 Phase-II Operation**

3.1 **Recovery from Underground Incidents**

In Feb. 2014, an underground fire followed by radiation release at WIPP halted underground access to EXO-200. All enriched xenon was safely recovered into storage bottles a few days later and the cryostat was warmed up slowly to room temperature over a period of two months. Although most of the operations had to be done remotely, the Xe recovery and detector warm-up went flawlessly, demonstrating the robustness of the control system as well as the readiness and capability of the operation team in dealing with unexpected emergencies.

In early 2015, EXO-200 regained regular access to the experimental area underground. The recovery and restart of EXO-200 went smoothly. Stringent radio assay tests showed no contamination due to the radiation release both inside and outside the cleanrooms. After reestablishing system control, the operation team verified that the detector survived the pressure swings during Xe recovery and power
outages. Major equipment damaged during the underground incidents, including UPSes and refrigerators, were replaced in the second half of 2015. The cryostat was cooled down in December 2015 and the TPC was filled with enriched xenon in January 2016. The detector reached excellent xenon purity and ultra-low internal Rn level shortly after the restart.

Two major detector upgrades were carried out between February and April 2016. First, the front-end readout system was upgraded to reduce coherent noise in the scintillation channels and lower the threshold for the V wire channels. Second, a Rn-suppressed air system was commissioned to purge the air gap between the cryostat and lead shielding. Details of the upgrades are discussed in the sections below.

3.2 EXO-200 Electronics Upgrades

Analysis of EXO-200 Phase-I data reveals that the detector energy resolution and analysis threshold were limited by coherence noise in the light readout channels. Elimination of this noise can substantially improve the detector performance. After thorough studies of noise data and bench testing, the electronics group identified APD preamp regulator noise and ground currents as the main sources of coherent noise and performed prototype board testing at WIPP in early 2014. The full-scale production boards were produced at SLAC in 2015.

From February to April 2016, upgrades to the EXO-200 front-end readout system were carried out. First, new front-end readout boards for APD channels were installed. These new boards used a new preamp design less sensitive to the regulator noise. Second, new ground adapter boards were installed to minimize ground currents between the APD channels. Third, the shaping times for V wire channels were optimized to lower the induction signal reconstruction threshold. As shown in Figure 1, the coherent sum noise of the APD channels has been reduced by a factor 2.5 after the electronics upgrade. Only 20% of extra coherent noise remains for Phase-II data. The excess noise mostly lies in the high-frequency region outside of the sensitive frequency band of the preamp, therefore having minimal contribution to the effective noise after signal reconstruction.

Elimination of the APD coherent noise had an immediate impact on the detector energy resolution. Figure 2 shows the time dependence of the energy resolution of single-site (SS) events (i.e. events making only one energy deposition in the LXe detector) for EXO-200 data taking period from September 2011 to June 2016. During Phase-I data taking, the resolution of the $^{208}$Tl peak (2.61 MeV) exhibits a large time variation between 1.5% and 2.1%, due to variation in the coherent noise. The resolutions can be improved by the application of a sophisticated denoising algorithm [15]. Even after denoising, a small time variation of the energy resolution remains. Applying time averaging, an effective energy resolution of 1.58% was achieved at the $0
\nu\beta\beta$ decay Q value (2.46MeV) for the Phase-I data. After the electronics upgrades, the energy resolution at the Q value improved to 1.38% without the application of the denoising algorithm. In fact, application of the denoising algorithm does not change the resolution, indicating that coherent noise is no longer a limiting factor of the resolution.

To optimize the detector performance, the cathode bias voltage of the detector was increased from -8 kV to -12 kV, changing the main drift field from ~380V/cm to ~576V/cm. The detector has
operated stably at this bias voltage since June 2016. The energy resolution at the Q-value improves to 1.28% at this higher drift field. Further improvements in detector energy resolution are possible with improvements in analysis techniques such as better signal reconstruction and detector non-uniformity corrections. Elimination of the APD coherent noise has also lowered the scintillation reconstruction threshold, enabling us to probe physics channels at lower energies in phase-II data.

3.3 Deradonator Installation and Performance

It is known that Radon in the air primarily consists of $^{222}$Rn from $^{238}$U decay chain. Due to its long lifetime and gaseous nature, it will travel long distances and permeate into any gaps before it decays. The high-energy gammas produced in its subsequent decay chain, in particular 2448 keV line from $^{214}$Bi, can pose a background problem for double beta decay experiments. The average radon level in the clean room air at WIPP is measured to be ~ 7 Bq/m$^3$ with a Rad7 radon detector. Analysis of the Phase-I data hints that part of $\nu\beta\beta$ decay background can be attributed to Rn in the airgap between the lead shielding and outer copper cryostat. The exact amount of the Rn in the airgap is difficult to pin down due to degeneracies in background models.

To eliminate this external Rn background, a Rn suppression system was constructed. The deradonator, capable of continuous air flow rate of up to 0.85 m$^3$/min, uses charcoal-based vacuum swing adsorption filters for Rn suppression. Clean air taken from cleanroom air handling unit is forced through an activated charcoal column to filter out Rn at atmospheric pressure. Before the charcoal filter reaches saturation, it is regenerated by purging the charcoal column with a small flow of Rn free air under near vacuum pressure. The large pressure dependence of Rn adsorption rate on charcoal ensures its effective regeneration. A dual column design allows continuous operation of the system. While one column acts as the filter, the other column undergoes regeneration using a small amount of Rn free air from the output of the running filter column. The coconut-based charcoal used for the filter is known for its good radon adsorption properties and low $^{222}$Rn emanation rate. Before filling the columns, the charcoal was washed thoroughly with water then dried to eliminate dust particles.

The deradonator was first assembled and tested at UMass Amherst before it was shipped to WIPP. Installation and commissioning of the deradonator at WIPP took place in late 2013 and early 2014. The system commissioning however was interrupted by WIPP accidents in 2014. During the EXO-
200 restart in 2015-2016, the deradonator was recommissioned successfully. Preliminary electrostatic counter measurements show that the Rn level in the airgap has been reduced by a factor of ~10, sufficient to suppress the background for $0\nu\beta\beta$ decay searches. Tests have also shown that the high airflow has no effect on the frontend electronics noise level.

![Graph showing comparison of $0\nu\beta\beta$ half-lives between $^{76}\text{Ge}$ and $^{136}\text{Xe}$ for different matrix element calculations (GCM, NSM, IBM-2, QRPA, and SkymeQRPA). Effective Majorana mass in eV is shown on each matrix calculation line.](image)

Figure 3. Comparison of $0\nu\beta\beta$ half-lives between $^{76}\text{Ge}$ and $^{136}\text{Xe}$ for different matrix element calculations (GCM, NSM, IBM-2, QRPA, and SkymeQRPA). Effective Majorana mass in eV is shown on each matrix calculation line. The claimed discovery in $^{76}\text{Ge}$, represented by a grey band, is shown together with the most recent GERDA [16] result and sensitivity. Both EXO-200 and KamLAND-Zen results and sensitivities are also shown. The dotted blue line shows projected combined Phase-I and Phase-II sensitivity for EXO-200.

### 3.4 EXO-200 Phase-II sensitivity

EXO-200 low background data taking began on April 29, 2016 and is expected to continue until 2018. Sensitivity studies indicate that with the detector upgrades and analysis improvements, EXO-200 can reach a $0\nu\beta\beta$ decay half-life sensitivity of $5.7 \times 10^{25}$ yr, using combined Phase-I and Phase-II data as shown in Figure 3. Although EXO-200 is unlikely to surpass the recent $^{136}\text{Xe}$ $0\nu\beta\beta$ decay limit set by KamLAND-Zen [17], the EXO-200 result will provide an important check for the KamLAND-Zen result with different systematic uncertainties and demonstrate the capabilities of LXe TPC for future tonne-scale detectors.

### 4. The nEXO experiment

The success of EXO-200 demonstrates that LXe TPC technology is well suited for a large-scale double beta decay experiment. nEXO is a proposed ~ 5-tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach $0\nu\beta\beta$ half-life sensitivity of $\sim 10^{28}$ yrs.

A substantial R&D program is underway to validate the nEXO detector design concepts and technologies. The high voltage group is studying high voltage breakdown issues related to large liquid xenon detectors and developing breakdown protection schemes. The photosensor group is working with industry to maximize the performance of VUV sensitive silicon photo-multipliers (SiPMs). The electronics group is performing design studies of cold frontend readouts for both charge and light signals. The TPC group is active in pushing the technology boundary of ultra-low background TPC.
designs. Furthermore, substantial progress in radio-assay and detector simulation groups has assisted the detector design optimization and provided accurate predictions of $0\nu\beta\beta$ sensitivity. The current projected sensitivity for the nEXO experiment is shown in Figure 4, and discussed in detail in Ref. [3]. After a 1-2 year of R&D phase, nEXO will be ready to move towards detector conceptual design.

As an upgrade option for nEXO, technologies that can tag the $\beta\beta$ daughter barium nuclei efficiently in situ are under development. Such a Ba-tagging technique, if realized, can make a background-free experiment possible [14]. Since Ba-tagging is still in early R&D, it will not be incorporated in the initial phase of nEXO.

![Figure 4. Projected sensitivities to the Majorana neutrino mass for the EXO-200 and nEXO experiments. The left and right plots show the allowed sum of neutrino mass for the normal and inverted hierarchy respectively. The dotted and solid lines correspond to $1\sigma$ and $3\sigma$ uncertainty levels of neutrino oscillation parameters.](image)

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