DEVELOPMENT OF A DIFFUSER BALL TO MONITOR THE WATER-CHERENKOV MUON VETO SYSTEM IN nEXO

SUMMARY: nEXO is a neutrinoless double beta decay search using a single phase liquid xenon time projection chamber shielded by a water-Cherenkov muon veto system (Outer Detector). A laser-driven system with diffuser balls is being developed to calibrate and monitor the performance of this Outer Detector. The status of the monitoring system is presented in this article.

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SAMIN MAJIDI RECEIVED 2ND PLACE IN THE
2025 CAP BEST OVERALL STUDENT POSTER PRESENTATION

Neutrinoless double beta ($0\nu\beta\beta$) decay is a weak interaction that is ideally suited for studying fundamental properties of neutrinos and the limits of the Standard Model. In $0\nu\beta\beta$ decay, two neutrons in a nucleus simultaneously transform into two protons and two electrons without emitting the corresponding electron antineutrinos $(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\mathrm{e}^{-}$. This decay has not been observed yet [1, 2].

Neutrinoless double beta decay is forbidden in the Standard Model as it violates lepton number conservation in weak interactions. A positive observation of $0\nu\beta\beta$ would imply that neutrinos are Majorana particles—that is, they are their own antiparticles [3]. The observation of this decay would further support scenarios in which lepton number violating processes contribute to the generation of the baryon asymmetry of the Universe through leptogenesis [4].

Although the relationship is model-dependent, a measurement of the $0\nu\beta\beta$ decay half-life can provide information on the absolute scale of neutrino masses. The KamLAND-Zen experiment currently sets the limit for double beta decaying isotope, ^{136}Xe, reporting a half-life of $T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ years at 90% confidence level [5]. This corresponds to an upper limit on the effective Majorana neutrino mass in the range of 36–156 meV, based on commonly used nuclear matrix element calculations [5]. The LEGEND experiment has reported a limit of $T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ using ^{76}Ge, translating to an effective Majorana mass of <75–200 meV at 90% confidence level [6].

One of the next-generation experiments searching for $0\nu\beta\beta$ decay with a half-life sensitivity of beyond 10^{28} years is the nEXO experiment [2, 7]. It is being designed using 5 tonnes of liquid xenon enriched to 90% in the isotope ^{136}Xe. Its single-phase liquid xenon (LXe) time projection chamber (TPC), housed inside a vacuum-insulated cryostat which contains a hydrofluoroether cryogenic fluid. The entire assembly is placed at the center of a water-Cherenkov muon veto system, referred to as the Outer Detector [8]. Figure 1 (left) presents an engineering rendering of the nEXO experiment.

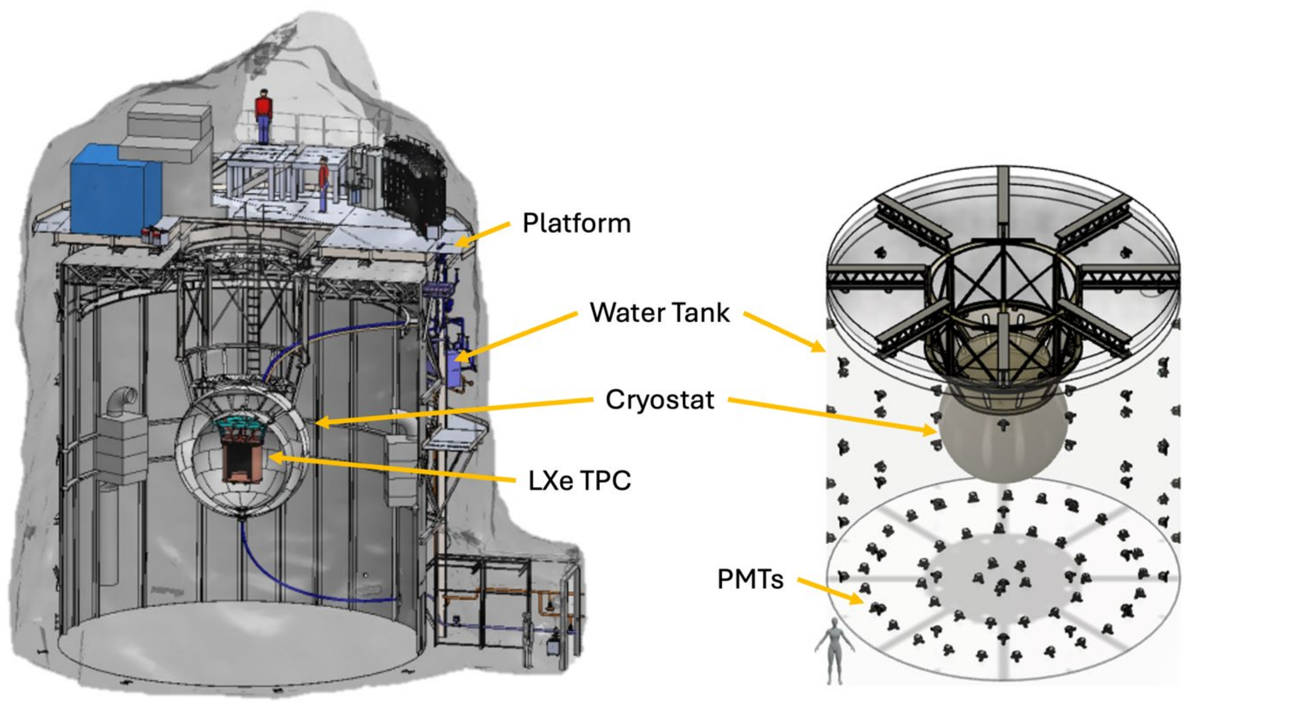


Figure 1. Left: Schematic of the nEXO experiment. The LXe TPC, vacuum-insulated cryostat, and the Outer Detector water tank are shown. Right: Layout of the PMTs in the Outer Detector. PMTs are positioned to optimize the detection of Cherenkov light from charged particles traversing the Outer Detector volume.

THE OUTER DETECTOR

The anticipated location for nEXO is the SNOLAB Cryopit, a cavern in Canada's deep underground laboratory, 2 kilometers below the surface, close to Sudbury, Ontario. This depth provides an effective overburden equivalent to 6000 meters of water, which reduces the flux of cosmic muons, shielding experiments against these muons. At SNOLAB, muons generated by cosmic rays in the upper atmosphere reach the laboratory with a flux of 0.27 μ/m^2/day [9]. Despite this reduction, muons that do penetrate to this depth can produce neutrons through various processes, which may subsequently interact with detector materials and generate background signals.

As muons pass through the Outer Detector, they emit Cherenkov light in a forward-facing cone, with a broad wavelength spectrum that peaks in the ultraviolet and extends into the visible range. In addition to this light, muons interacting with the water produce hundreds of neutrons. These neutrons can capture on ^{136}Xe inside the TPC, producing ^{137}Xe via the reaction: $\mathrm{n} + {}^{136}\mathrm{Xe} \rightarrow {}^{137}\mathrm{Xe}^{*}$. ^{137}Xe has a half-life of 3.82 minutes and decays via beta decay with a Q-value of 4173 keV through the reaction: $^{137}\mathrm{Xe} \rightarrow {}^{137}\mathrm{Cs} + e^{-} + \bar{\nu}_e$. This decay mimics the topology of the signal of interest [8].

The Outer Detector of nEXO [10, 11] is being designed to enable the tagging of these cosmic-ray muons for later analysis and vetoing of muon-induced backgrounds. The Outer Detector will be a cylindrical water tank measuring 12.3 meters in diameter and 12.8 meters in height, filled with 1.5 kilotonnes of ultra-pure water. The water acts as a shield against gamma rays and moderates neutrons originating from the surrounding cavern rock. The Outer Detector will also be instrumented with an array of 125 Hamamatsu R5912 photomultiplier tubes (PMTs) mounted inward facing on the outer walls of the tank [8]. Figure 1 (right) shows the layout of the PMTs in the Outer Detector.

The veto system will tag muons via their Cherenkov light emission, which will be detected by the PMTs. In offline analysis, we will examine correlations between muon events and signals in the inner detector. Once a muon is tagged, a window of approximately 10 ms of data from the TPC will be selected and the system will search for prompt gamma signals from neutron capture de-excitation. If an increase in gamma activity is observed, the corresponding data will be associated with the muon event. The data will subsequently be vetoed for an extended period, corresponding to several half-lives of ^{137}Xe. Approximately 99% of ^{137}Xe decays will occur within a 25-minute veto window.

THE OUTER DETECTOR MONITORING AND CALIBRATION SYSTEM

A system is being developed to calibrate the muon veto and to monitor its performance throughout the lifetime of the experiment. The optical properties of the water and the performance of the PMTs must be monitored and the timing properties of the PMTs readout system need to be calibrated. This system consists of a fiber and a diffuser ball. Laser light pulses are injected into the fiber connected to the diffuser ball which emits isotropically and enables continuous monitoring of the PMTs responses. Laser sources with wavelengths between 360 and 390 nm are optimal for our system, as this range corresponds to the peak quantum efficiency of the PMTs [12]. In a current test setup, a 450 nm laser is being used due to availability in the lab.

The diffuser ball consists of a Teflon plug and a Teflon sphere. The Teflon plug is slightly more transmissive than the sphere, causing initial light diffusion at the plug, followed by a second diffusion stage in the sphere. The Teflon plug and sphere are housed inside a pressure housing made of a titanium flange and borosilicate hemispherical glass window. A photosensor will be placed inside the pressure housing, next to the Teflon sphere, to monitor the light output of the diffuser ball. All of the internal surfaces will be coated with a low-reflective coating material to prevent introducing reflective elements into the emission profile. Figure 2 shows the first prototype of the diffuser ball without the anti-reflective coating and without photosensor. The concept of the diffuser ball and its design is based on the design developed for the P-ONE and IceCube experiments [13, 14].

Simulations with varying numbers and configurations of diffuser balls inside the water tank indicate that the optimal number for monitoring the Outer Detector is five. The results also show that the placement of the diffuser balls does not affect the system's performance, provided they are distributed

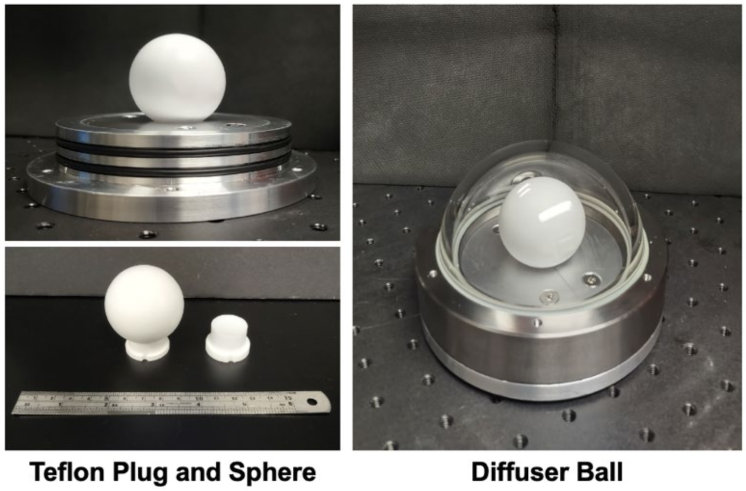
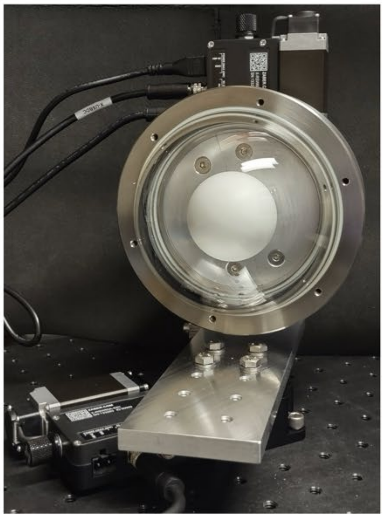


Figure 2. First prototype of the diffuser ball for the Outer Detector monitoring system. Bottom left: the Teflon plug and the Teflon sphere. Top left: the latter mounted in the flange. Right: the entire assembly.

homogeneously throughout the tank. In this case, all PMTs receive the required light intensity for proper calibration. A requirement of at least 10 photons reaching each PMT has been chosen as the design requirement for the calibration system [12].

We are developing a setup to test and characterize the diffuser ball, in particular to verify the isotropy of the emission profile. The diffuser ball assembly with glass window and flange is mounted on a two-axis rotary stage that can rotate the diffuser ball in 4π. A picture of the diffuser ball assembly mounted on the rotary stage is shown on the left in Figure 3. A PMT will measure the light intensity at each angle. The characterization setup will be housed inside a dark box. Laser light will be injected into the ball via a fiber optic patch cable connected to a fiber port at the back of the ball.

The development of a diffuser ball for calibrating and monitoring the Outer Detector of nEXO has been the focus of my work. The project began with proposing the idea of using laser-driven diffuser balls, followed by simulations to evaluate the concept for our detector and to determine optimal system parameters—such as laser wavelength, the number of diffuser balls, and their placement. The next stage involved designing the mechanical structure of the diffuser ball and building the first prototypes. Currently, the focus is on developing a setup to test and characterize the light emission profile of the diffuser ball. In the future, we plan to make necessary improvements to the prototype, including the integration of a photosensor to monitor the light intensity of the diffuser ball *in situ*.



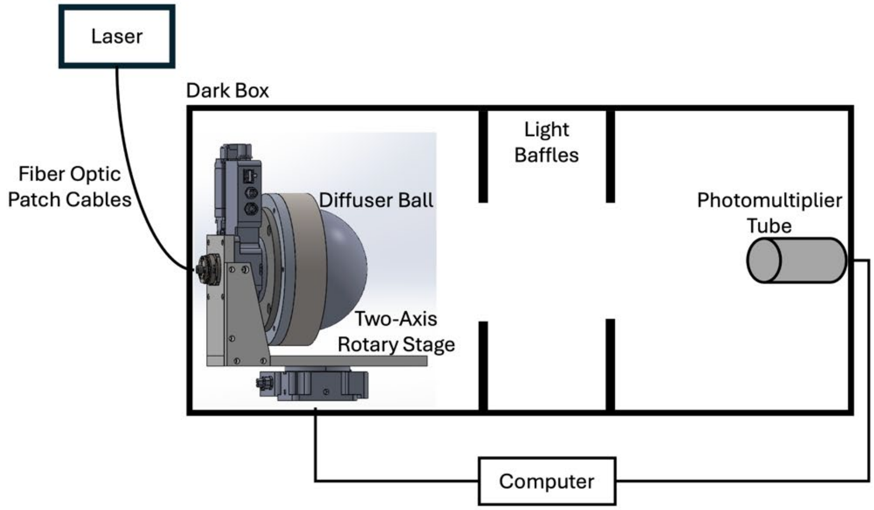


Figure 3. Test setup for measuring the emission profile of the diffuser ball. Left: Photograph of the Teflon sphere inside its pressure housing with optical hemisphere mounted on two-axis rotary stage. Right: Sketch of the characterization setup consisting of a dark box, housing the stage and the PMT. A laser beam is delivered to the diffuser ball via a fiber optic patch cable connected to a fiber port at the back of the stage. The computer controls the motors and records the PMT output.

ACKNOWLEDGMENTS

The author gratefully acknowledges the valuable feedback provided by project supervisors Thomas Brunner and Erica Caden, as well as the nEXO Outer Detector group. Appreciation is also extended to Irina Nitu, Iskender Isikbay, and Peter Liimatainen for their important contributions. Special thanks to the engineering team at SNOLAB for their support and technical assistance.

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