Status and improved detector performance of EXO-200

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Abstract. The EXO-200 experiment was created to search for neutrinoless double beta decay \((0\nu\beta\beta)\) using an ultra-low background single-phase time projection chamber. The detector contains 110 kg of active liquid xenon, isotopically enriched in \(^{136}\text{Xe}\), which acts as both the decaying nucleus and the detection medium. The detector has demonstrated excellent energy resolution and background rejection capabilities, and has set a lower limit on the \(0\nu\beta\beta\) decay half-life of \(1.1 \times 10^{25}\) years at 90% C.L. in early 2014. The EXO-200 collaboration has since published several papers on experimental backgrounds and searches for rare or exotic processes. After a two-year data interruption, EXO-200 is now back online with significant hardware improvements, including a radon reduction air system and a front-end electronics upgrade to improve the energy resolution. The improved detector performance since the restart and recent physics results will be presented.

1. Neutrinoless double beta decay
Double beta decay \((2\nu\beta\beta)\) is a second-order process that transforms two neutrons into two protons, emitting two electrons and two anti-neutrinos. Neutrinoless double beta decay \((0\nu\beta\beta)\) is a theoretical process beyond the Standard Model and occurs when an isotope double beta decays but does not emit anti-neutrinos. An observation of \(0\nu\beta\beta\) would suggest that neutrinos are Majorana particles (left-handed neutrinos and right-handed anti-neutrinos are the same) and demonstrate lepton number non-conservation.

2. EXO-200 experiment
Located in the Waste Isolation Pilot Plant (Carlsbad, NM), the EXO-200 experiment searches for \(0\nu\beta\beta\) with 110 kg of active liquid Xe (LXe), isotopically enriched in \(^{136}\text{Xe}\). The centerpiece of the experiment is an ultra-low background time projection chamber (TPC), divided into two segments by a cathode plane. The detector measures both ionization and scintillation signals to reconstruct energies and 3D positions of individual charge clusters from an event. A more detailed description of the detector can be found in [1].

Event topologies provide strong discrimination between \(\gamma\)-like background and \(\beta\)-like signal. The charge depositions are categorized as single-site (SS) or multi-site (MS) based on their multiplicity. From the 3D position reconstruction, we can also calculate the standoff distance, which is defined as the distance between a charge deposit and the closest material that is not LXe, other than the cathode. The majority of \(\beta\)-like events are SS events and are uniformly distributed throughout the detector. On the other hand, the \(\gamma\)-like backgrounds are mostly MS events near the outer edges of the LXe volume.
EXO-200 published the first $2\nu\beta\beta$ observation for $^{136}$Xe in [2] and later improved the measurement with $T_{1/2} = 2.165\pm0.016$ (stat)$\pm0.059$ (syst) $\times 10^{21}$ years [3]. In 2014, EXO-200 set a sensitive lower limit on the $^{136}$Xe $0\nu\beta\beta$ half-life at $1.1 \times 10^{25}$ years with 90% C.L. [4].

3. Recent physics results
EXO-200 had published 8 papers during the two year hiatus in data taking due to a fire in the WIPP facility [4–11], including an investigation of radioactivity-induced backgrounds [10] and a search for $^{136}$Xe $2\nu\beta\beta$ into the first excited state ($0^+_1$) of $^{136}$Ba [11].

3.1. Radioactivity-induced backgrounds
Great care was taken in selecting low-radioactivity materials and constructing the EXO-200 detector in a clean environment to ensure that the detector is ultra-pure. Studies were done to better understand the location and strength of various background sources and a selection of backgrounds investigated is discussed here; for more information and detail on various radioactivity-induced backgrounds, please consult [10].

Neutron capture on $^{136}$Xe can create $^{137}$Xe, which is a $\beta^-$-emitter with a half-life of $229.1 \pm 0.8$ s and a Q-value of $4173 \pm 7$ keV [12]. EXO-200 searched for evidence of $^{137}$Xe production due to cosmic-ray muons passing through the TPC (TPC muon events), which causes a higher neutron flux thus higher expected neutron-capture rate on $^{136}$Xe. The low-background data of EXO-200 run 2 was binned based on the amount of time after each TPC muon event and the results were fitted with both an exponential and a constant function. The $\chi^2$/ndf of the fits indicates a slight preference for the decaying function, which suggests that the $^{137}$Xe in the detector is produced by TPC muon events, although the study is currently too statistically limited to draw a definitive conclusion. Later studies characterized cosmogenically produced backgrounds in more detail [6].

Internal $^{222}$Rn backgrounds in the TPC result from the $^{214}$Bi decay, which produces a $\gamma$ with 2448 keV. This decay is tracked by monitoring the counts of 5.5 MeV $\alpha$s, which are tagged with their distinct light-to-charge ratio in the TPC. About 17% of the $^{214}$Bi decay in the active xenon and 83% on the cathode, and these are tagged using the $^{214}$Bi-$^{214}$Po decay coincidences. The measured $^{222}$Rn decay rate is constant in the TPC suggesting that there is a supply of $^{222}$Rn. The most likely source of $^{222}$Rn are the polyimide readout cables, which are capable of contributing up to 270 $^{222}$Rn atoms in the LXe. A far-source $^{238}$U-like backgrounds outside of the TPC had also been observed in earlier $0\nu\beta\beta$ searches [13]. Originally, the source was thought to be the $^{222}$Rn content in the air gap between the lead wall and cryostat. However, the measurement of $^{222}$Rn in the clean-room air obtained by a commercial Rad7 device is inconsistent with the estimated activity of $^{222}$Rn from the far-source $^{238}$U-like background, suggesting that the air gap is not a predominant contribution of said background. Nevertheless, the $^{222}$Rn content in the air gap can be decreased by the deployment the radon-abatement system (deradonator), the performance efficiency of which will be discussed later.

3.2. Decay to excited states search
A $^{136}$Xe nucleus can $\beta\beta$ decay into the first excited state of $^{136}$Ba, followed by the emission of two de-excitation $\gamma$s at 760.5 keV and 818.5 keV. This process is allowed by the Standard Model and its analog has been observed in two other isotopes. Measurement of this decay’s half-life will provide additional constraints for the nuclear matrix elements calculation and test exotic theories of alternate $\beta\beta$ decay mechanisms. A 2D fit is performed over the SS and MS data using probability density functions in energy and excited state discriminator variable, which improves the sensitivity of the search. A boosted decision tree machine learning algorithm is employed in this study to create the discriminator variable as the second dimension, as opposed to the standoff distance variable in the main analysis. The list of variables used to generate the
discriminator includes multiplicity, energy, the sum energy of the de-excitation photons, standoff distance, and the individual de-excitation photon energy; the ranking and the detailed analysis of this study can be found in [11]. The choice of the discriminator variable was made before the final fit in order to make sure that the results are unbiased.

With the machine learning algorithm, EXO-200 obtained a sensitivity for the half-life of the decay from $0^+ \to 0^+_1$ to be $1.7 \times 10^{24}$ years with 90% CL and reported a lower limit for the half-life of $6.9 \times 10^{23}$ years at 90% CL.

4. Recent upgrades and current detector performance
Recent upgrades for EXO-200 include the deradonator for the air gap between the copper cryostat and the lead shield wall, and the front-end electronics.

The deradonator filters air in the air gap using two stainless steel columns filled with charcoal. While air from the air gap is drawn into one column, the other column undergoes desorption under vacuum, providing the capability to purge 30 cfm of air with reduced radon content constantly. Preliminary measurement shows that the radon level of the air gap has been reduced by more than a factor of 10 since the deradonator installation.

The front-end electronics upgrade includes installation of new avalanche photodiode (APD) boards, filter boxes, and ground adapter boards. The detector has been able to maintain stability after increasing the cathode high voltage to -12kV, which enables an increase in drift field strength. After the upgrade, the coherent sum noise of the APD channels is reduced by a factor of 2.5, and the signal is increased by about 5%.

By reducing the APD coherent noise with new electronics and increasing the drift field strength, energy resolution in the region of interest has been improved from an average of 1.5% to 1.2%. Current source calibration data shows shape agreement with MC simulations. Purity in the detector has increased to about 3.5 ms, which is well above the criteria for golden low-background physics data taking. Combining 3 additional years of run time in phase 2 and data from phase 1, the $0\nu\beta\beta$ sensitivity outlook for EXO-200 is currently at $5.7 \times 10^{25}$ years. With meticulous material selection, component radioassay, and various handles on backgrounds, EXO-200 will be able to continue lowering the $0\nu\beta\beta$ half-life limit in the upcoming run.

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