nEXO

The nEXO Collaboration

The experimental search for neutrinoless double beta decay ($0\nu\beta\beta$) is a test of the Majorana nature of neutrinos and the violation of lepton number. With some model-based uncertainty, the rate of neutrinoless double beta decay is also proportional to the square of the effective Majorana neutrino mass. Indeed the constraints on neutrino mass from these experiments are among the most stringent in the field. The EXO-200 experiment succeeded in demonstrating many of the advantages of a single-phase enriched LXe TPC in the search for this phenomenon. As a result, the nEXO collaboration is designing a scaled-up version of EXO-200 to a mass of 5,000 kg of xenon enriched in the isotope ^{136}Xe. This new detector will entirely cover Majorana masses in the inverted hierarchy region for certain nuclear models and will provide a natural evolution program for further stages of exploration.

I. EXECUTIVE SUMMARY

The observation of neutrinoless double beta decay would be an unambiguous discovery of new physics. The experimental investigation of neutrinoless double beta decay is currently the most sensitive test for the Majorana nature of neutrinos, where the neutrino is its own antiparticle. The discovery of such a 2-component Majorana Fermion as evidence of the violation of lepton number and would substantially alter our understanding of the natural world. Such an observation would also establish the scale of the neutrino masses, and also possibly mass hierarchy, under the assumption that neutrinoless double beta decay is driven by the exchange of light neutrinos. In the absence of an observation, and under the assumption that neutrinos are Majorana, such experiments provide the most stringent constraints on neutrino masses.

The EXO-200 search for $0\nu\beta\beta$ has successfully demonstrated the power of the LXe TPC approach. EXO-200 was the first "100 kg-scale" detector to come on-line. It has proven that the combination of energy resolution provided by the simultaneous readout of scintillation and ionization along with the event multiplicity and location measurements in an homogeneous tracking detector provide a unique, multi-parameter background identification and suppression. The three tools of energy resolution, multiplicity and location provide important cross-checks that make the analysis robust. These properties, along with a rigorous materials screening program, achieved a background index at the Q-value of of B= 1.5×10^{-3}keV^{-1}kg^{-1}yr^{-1}, the current standard in the field. EXO-200 provided the discovery of the $2\nu\beta\beta$ decay in ^{136}Xe and it precision measurement, the most accurate of these measurements to date.

While EXO-200 ran in low background mode for about 2.5 years fulfilling its initial goals, the accidents at the WIPP repository housing the detector in Feb 2014 forced a shutdown but also provided the opportunity to test the robustness of the detector and its control and monitoring system. Indeed EXO-200 had to first recover the Xe to high pressure cylinders and then warm-up the entire detector system to room temperature entirely from remote, with no human access to the underground location. The successful completion of these tasks with no damage to the detector and no loss of Xe are witnesses to the sound design, that will be further perfected in nEXO.

There are many advantages to using ^{136}Xe as the source of $0\nu\beta\beta$. Xenon is one of the most economical $\beta\beta$ emitters to procure and enrich by ultra-centrifugation. Experiments using Xe as the detection medium have a particularly favorable matrix element and phase-space combination. There are a number of advantages that prove essential in the longer term, adding value to the investment in isotope enrichment and providing a natural evolution of the program under various outcomes of the first 5-year run of a multi-ton detector. A "blank" measurement with natural depleted Xe can follow a possible observation; a tunable-density gas TPC can follow a robust discovery to investigate angular correlations between electrons. Finally, the nEXO collaboration has an active R&D program to investigate the possibility of retrieving and tagging the final state atomic species (Ba) of the double-beta decay of ^{136}Xe. If successful this technique would extend the reach of nEXO with a virtually background-free second phase.

The nEXO detector concept is being designed as a scaled-up version of the EXO-200 detector. As a result of the success of the EXO-200 prototype detector, the nEXO collaboration is designing nEXO as a 5,000 kg, 90% enriched LXe TPC. The detector design closely follows that of EXO-200, with important improvements that are currently under development. Each of the three pillars on which the background identification and suppression rests is expected to improve in nEXO: energy resolution will reach and possibly surpass 1% (σ) thanks to better electronics, Compton identification from multiplicity will improve because of the final charge readout pitch and the different weighting of signal and gamma-background events as function of the distance from the detector walls will become far more powerful because of the larger detector size. In addition the longer term Ba-tagging R&D matches well the need to study transformational new ideas expressed by the McKeown committee in their first report.

II. SEARCHING FOR NEUTRINOLESS DOUBLE BETA DECAY

The experimental discovery of neutrino oscillations, at various energy and length scales, yields compelling evidence for non-zero neutrino masses. Precise data fits are now available for the squared neutrino mass differences and mixing parameters within the three-flavor paradigm. Yet, the current picture does not yet define the mass hierarchy, the existence of non-trivial CP-phases, the overall mass scale, or the possible particle-anti-particle identity of the neutrinos. The investigation of neutrinoless double beta decay is currently the most sensitive test for the Majorana nature of neutrinos. The discovery of 2-component Majorana Fermions in $0\nu\beta\beta$, where the neutrino is its own antiparticle, would serve as evidence of the violation of lepton number and would substantially alter our understanding of the natural world.

Furthermore, in the case that neutrinos are Majorana particles, the investigations of double beta decay provide sensitive tests of the mass scale of the neutrinos. The squared effective Majorana neutrino mass is proportional to the $0\nu\beta\beta$ decay rate, although there is also a model dependent factor arising from theoretically computed nuclear matrix elements. Even with the uncertainty from the knowledge of such nuclear matrix elements, the $0\nu\beta\beta$ decay constraints on the neutrino mass are among the most stringent in the field. Assuming that $0\nu\beta\beta$ decay is driven by the exchange of light neutrinos, the oscillation-derived neutrino data defines three mass scenarios: degenerate, inverse and normal. The current generation of $0\nu\beta\beta$ decay experiments, such as EXO-200, is designed to cover the degenerate case. The initial phase of nEXO will address Majorana neutrinos in the inverted hierarchical scheme that is defined by $\sqrt{\Delta m^2_{atm}}$. This initial phase of nEXO will be a scaled-up version of the well proven technology of EXO-200. A subsequent upgrade to incorporate the identification of the Ba daughter ion of the $0\nu\beta\beta$ decay of ^{136}Xe should reduce the experimental backgrounds and may represent the only conceivable method to reach sensitivities approaching the normal hierarchy mass scheme.

III. THE EXO-200 DETECTOR

The EXO-200 collaboration has developed, built and operated a Time Projection Chamber (TPC)-based ultra-low background tracking detector. The detector is filled with 150 kg of xenon that is enriched to 80% in ^{136}Xe of which about 100 kg are used for high quality analyses. The Xe is used in the liquid phase (LXe) so that the detector can be made as compact as possible. The detector and its radiological shielding and cosmic veto counter are located at the Waste Isolation Pilot Plant near Carlsbad NM, in the USA, at a depth of about 1600 m.w.e. The ability of the detector to track individual radiation deposits allows the precise identification of event locations within the monolithic LXe volume. This allowed the observation of the attenuation of background gammas from their source, in the construction material at the boundaries of the TPC, towards regions of lower background at the center of the LXe mass. The TPC also provides a handle on the multiplicity of the interaction so that a specific event can be characterized as either single-site, which are more characteristic of $\beta\beta$ events, or multiple-site, which are more characteristic of the interactions from background gammas. The simultaneous readout of ionization and scintillation results in an energy resolution of $\frac{\sigma}{E} = 1.53\%$ at the ^{136}Xe double beta decay Q-value. The derived tracking, multiplicity identification, and energy resolution results in a background index around the Q-value of B$= 1.5 \times 10^{-3}$keV^{-1}kg^{-1}yr^{-1}, the lowest in the field.

The first phase EXO-200 has taken low background data from May 2011 until Feb 2014. The data collected provided the first measurement of the $2\nu\beta\beta$-decay of ^{136}Xe [1], and more recently the most precisely measured half life of any double beta emitter, yielding $T^{2\nu\beta\beta}_{1/2} = (2.172 \pm 0.017^{\rm stat} \pm 0.060^{\rm syst}) \times 10^{21}$yr [2]. EXO-200 further published one of the most restrictive bounds on the Majorana neutrino mass [3], which was the first to address the evidence claimed for the observation of the $0\nu\beta\beta$-decay in ^{76}Ge. The result has recently been updated using 2 years of data to: $\langle m_{\beta\beta}\rangle < 190 - 450$ meV using a range of nuclear matrix elements [4]. By now experiments using ^{136}Xe as the source of $0\nu\beta\beta$-decay have surpassed those using ^{76}Ge as the most sensitive tests for the existence of Majorana neutrino masses.

The US-led EXO-200 collaboration currently comprises 21 institutions from 7 countries. The EXO-200 experiment was the first “100 kg-class” detector to come on-line, after an approximate decade long absence of new results. The technical soundness of this approach has been demonstrated by the stable data taking period of over 32 months, followed by the unexpected and sudden loss of access to the site, following fire and radiation accidents at WIPP.

Under these very trying circumstances EXO-200 was first emptied of the xenon that was compressed into high pressure cylinders for long term safe storage and then warmed up from 165 K to room temperature. All these operation were performed from remote with not a single access to the site. The detector is currently in a state of “warm shutdown” (at room temperature) and, assuming a restart of underground operations at WIPP in the next several months, will be restarted for about two more years of data taking with upgraded electronics and a radon abatement system. Assuming no damage from over six months of dormant state with no access, shifting ground salt conditions and inconsistent power, the new detector run should provide up to a factor of three improvement in $T_{1/2}$ sensitivity.

IV. THE NEXO DETECTOR

As a result of the success of the EXO-200 prototype detector, the expanded nEXO collaboration has begun the planning of a new, larger experiment that is strongly rooted in the design concept of the EXO-200 approach. The new detector is called nEXO and is envisaged to use 5,000 kg of LXe, isotopically enriched to 90% in ^{136}Xe. Like EXO-200, the detector will operate as a single-phase LXe TPC. The scintillation and ionization will be simultaneously measured so that the position and multiplicity of the event and the energy resolution can all be used in concert to identify and reject the backgrounds, as was demonstrated in EXO-200. A program of material selection similar to the one carried out for EXO-200 will insure that such backgrounds are very modest to start with. The nEXO TPC vessel will be significantly larger that of EXO-200 but will also be built out of low background copper. In order to take maximum advantage of the LXe self-shielding, nEXO is designed with a single drift region, so that there is no cathode in the middle of the detector. The following notable differences between nEXO and EXO-200 are under development and will improve the detector performance:

- Graphite composite cryostat to simplify the construction in a deep underground site while maintaining or surpassing the background levels already reached by EXO-200 (with more conventional copper construction)
- In-LXe readout electronics to improve noise performance, granularity (higher channel count), reliability, electron lifetime and, possibly, background.
- Higher granularity (3 mm instead of 9 mm of EXO-200) charge readout pitch, possibly using strips supported by low background quartz tiles, now under prototyping.
- Novel light sensors (VUV-capable SiPMs) to increase the gain and hence the signal-to-noise ratio in the scintillation channel, reduce the bias voltage required and reduce the mass of the photodetectors. Large arrays of VUV-capable SiPMs are under development.
- Further reduction of the activity of different components by expanding the screening program, and developing new low-background materials.
- Detailed understanding of the performance of HV systems that are operated within LXe.
- Refined design of the cryogenic system for improved reliability, Xe purity and detector live time.

In addition the collaboration is making important progress in the ability of transporting and identifying the Ba-ion produced by the double-beta decay of ^{136}Xe. This technique, if proven viable with efficiency of order 1, will be used in a second phase of the nEXO program. This upgraded nEXO detector would reach Majorana mass sensitivities of $\langle m_{\beta\beta}\rangle < 3 - 8$ meV, covering the inverted hierarchy for all matrix elements and accessing parts of the normal hierarchy phase-space for the most favorable ones. This possible upgrade is unique to the nEXO program.

The collaboration is regularly presenting the nEXO plans to the SNOLab EAC and the EAC has encouraged SNOlab to engage the nEXO collaboration with the goal of locating the detector in the Cryopit where backgrounds from cosmogenically produced neutrons are expected to be nearly negligible. A strong collaboration with SNOlab engineers has developed in the last year. A sketch of the nEXO in the SNOlab Cryopit is shown in Figure 1.

There are many advantages to using ^{136}Xe as the source $0\nu\beta\beta$. It should be pointed out that the noble gas xenon is one of the most economical $\beta\beta$ emitters to enrich by ultra-centrifugation. Since the cost of the natural xenon is small compared to that of enrichment, this advantage is, to a large extent, independent from the fluctuations of the price of the feed-stock. As a result of this, and the lack of the need for crystal growing suggests that the scalability of the xenon-based approach is excellent. In addition, the ^{136}Xe isotope offers a particularly favorable matrix element and phase-space combination. Experiments using Xe as the detection medium offer the possibility of running with a natural isotope mix to verify the particle physics nature of any putative signal at the Q-value, or to later re-configure the enriched Xe stockpile in a lower density gas TPC, using a drastically different technique to confirm a discovery

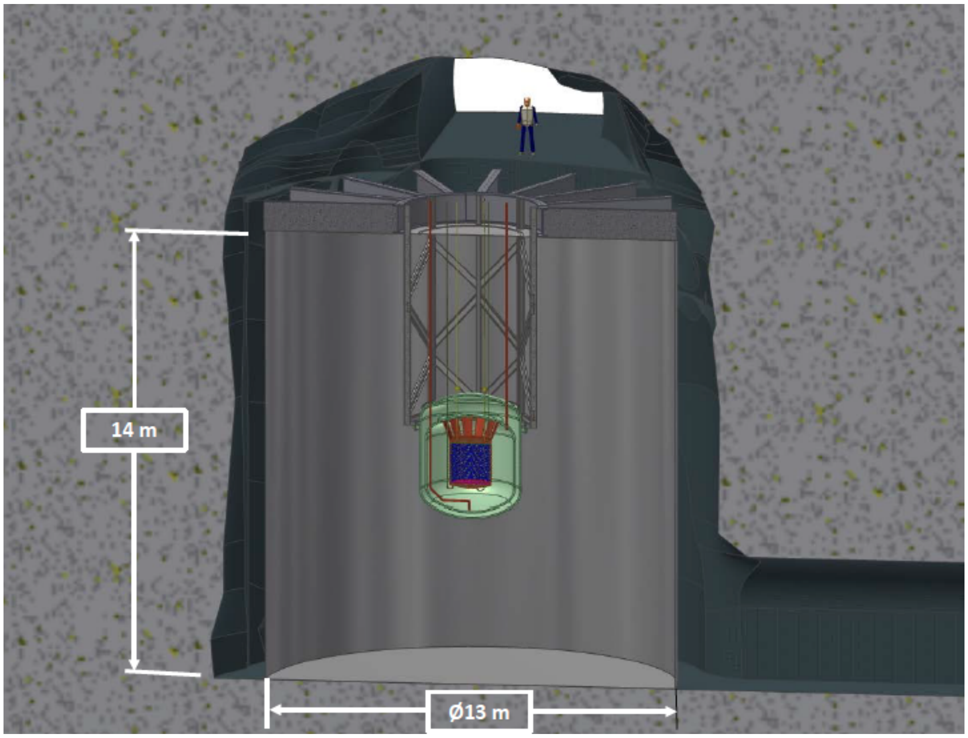

FIG. 1: Artist's concept of the nEXO detector in SNOLab's. In this model the TPC is housed in a large graphite composite cryostat which in turn is submerged in a water shield equipped with photomultiplier tubes to double as a cosmic ray veto detector.

and beginning the quest to understand the nature of the neutrino-less double-beta decay. The flow chart of the first phase of nEXO and the possible upgrades or further runs to react to the realities of data is shown in Figure 3.

The nEXO sensitivity estimate is developed taking full advantage of the EXO-200 experience. The background eventually measured with the EXO-200 low background data was modeled well before the completion of the detector using a model that properly accounted of the measured activity of all components. The result of such modeling was found to be in very good agreement with the background measured from data. A similar procedures has been applied to nEXO, using the preliminary model for the new detector. The sensitivity to the neutrino-less decay was further extracted from a simultaneous fit to the energy spectrum, the even multiplicity that discriminated against Compton-producing gammas and the position of the even in the very large detector that discriminated between the uniform signal and the gamma background that primarily enter the detector from the outside. This complex fit optimally uses all information and statistics available and was carefully studied for EXO-200 data. A simpler (but of course less powerful) method defining regions of interest for the decay gives consistent results. The estimated sensitivity of the first phase of nEXO is $T_{1/2} > 6.6 \times 10^{27}$ yrs (90% CL) for 5 years of data. The derived neutrino mass constraints of 7-18 meV (the range reflecting the matrix element variability) cover the inverted mass hierarchy for the GCM matrix element calculation.

[1] N. Ackerman *et al.* (The EXO Collaboration), Phys. Rev. Lett. **107**, 212501 (2011).
[2] J. B. Albert *et al.* (The EXO Collaboration), Phys. Rev. C **89**, 015502 (2014).
[3] M. Auger *et al.* (The EXO Collaboration) Phys. Rev. Lett. **109**, 032505 (2012).
[4] J. B. Alber *et al.* (The EXO Collaboration) Nature **510**, 229-234 (2014).
[5] T. R. Rodriguez and G. Martinez-Pinedo Phys. Rev. Lett. **105**, 252503 (2010).

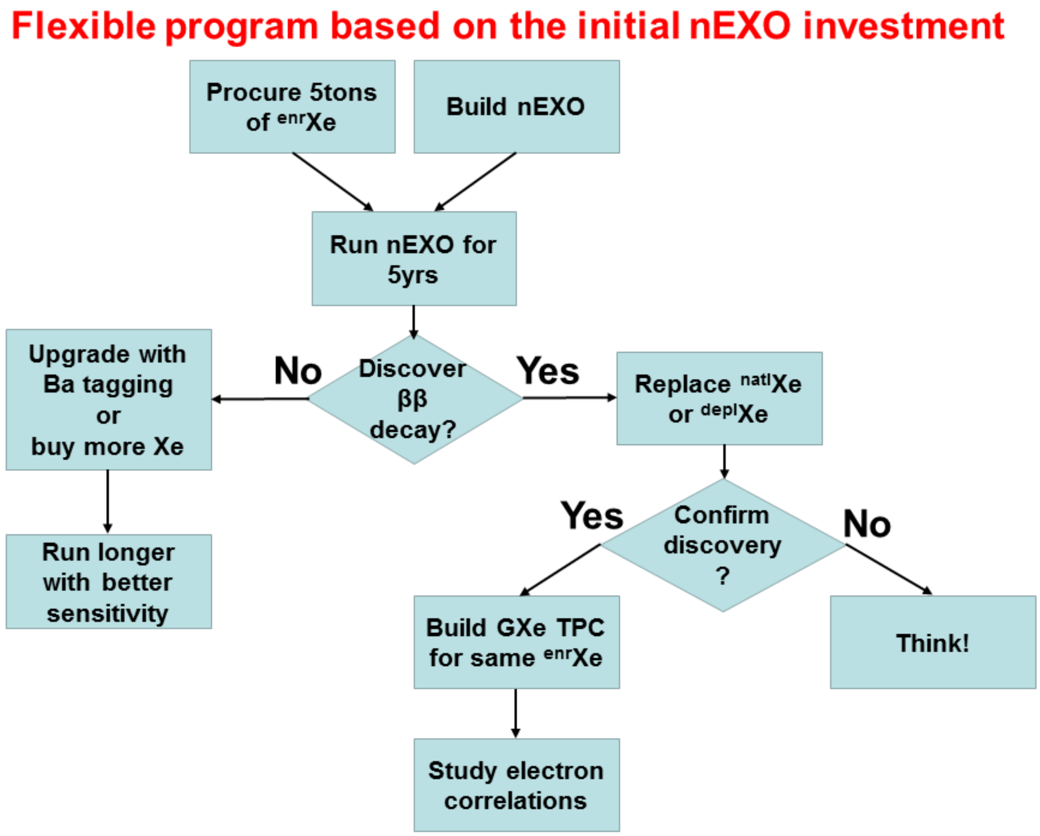

FIG. 2: A flow chart describing many of the possible routs that a xenon-based double beta decay program can take in the search for neutrinoless double beta decay.

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FIG. 3: The nEXO collaboration.