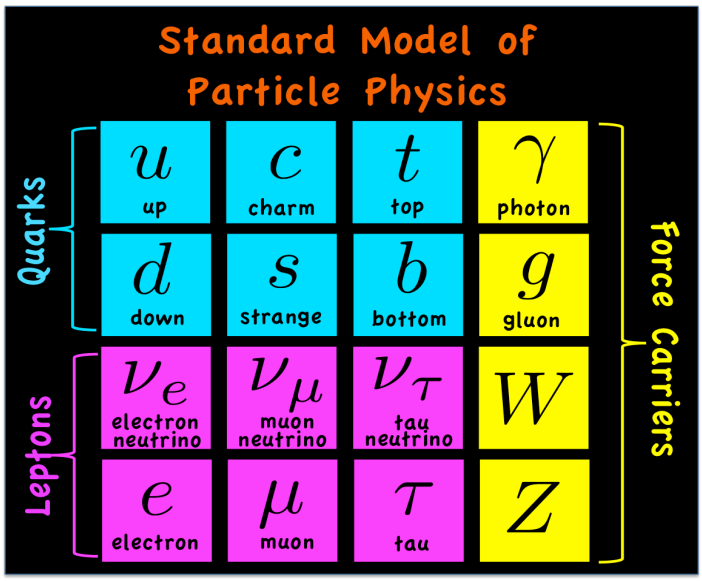
How Does nEXO Work?

by Tessa Johnson

Imagine living in a world where we did not have a periodic table of elements. We would have no way of organizing the elements, their chemical properties, and the way that they interact with each other. Chemists and other scientists would not have the benefit of making educated guesses about reactions and the properties of combined elements, and would have to use much more trial and error when trying to solve problems in the laboratory. We would probably not currently have many of the technologies that we enjoy – modern medicines, semi-conductor electronics, plastics, gasoline, and cleaning products. The periodic table of elements has been an important tool in speedy discoveries that involve chemical interactions.

A similar description exists for particles more fundamental than the elements. The Standard Model of Particle Physics contains all of the known particles at their most fundamental level and a description of how they interact with each other. This list includes the familiar electron and the quarks that make up protons and neutrons inside of the atomic nucleus. Among the particles of the Standard Model are the neutrinos. Neutrinos are the second most abundant particles in the universe, second only to particles of light (photons). There are trillions of neutrinos passing through your body every second, although they very rarely interact with anything! In order to detect and learn more about these elusive particles, physicists have to build underground chambers that can host very massive detectors (more mass to increase the probability of neutrino interaction!) and have to wait for a very long time to build up statistics of neutrino interactions. The current Standard Model assumes that these neutrinos are massless, like particles of light, but many recent experiments have shown that neutrinos oscillate between their three different kinds, which according to Quantum Mechanics implies that neutrinos must have mass. The absolute mass, however, is yet unknown.



Another interesting property of neutrinos is that they are possibly their own anti-particle, like photons. However, a fermion particle (electrons and neutrinos are fermions, photons are not) that is its own anti-particle has never been observed before, and is dubbed a Majorana fermion. If the neutrino were discovered to be a Majorana fermion, it would help physicists who are trying to build models of fundamental physics like the Standard Model to converge on the true theory. How can we tell if the neutrino is its own anti-particle or not?

The most experimentally viable method for the observation of Majorona fermions is through a very rare (so rare that it has never been observed yet!) decay called neutrinoless double beta decay. The observation of this decay would be the undisputed discovery of new physics – the neutrino would have to be its own anti-particle for this decay to occur, and its measured half-life would also indirectly measure the absolute mass of the neutrino.

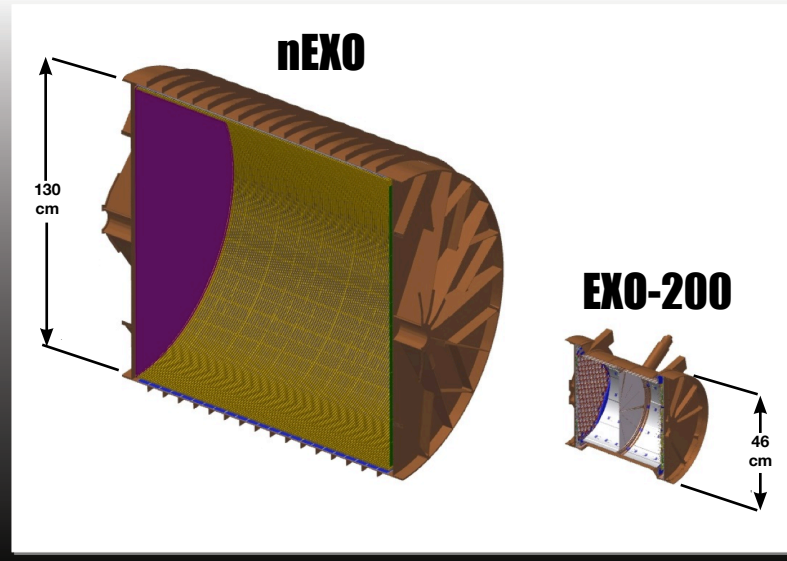
The EXO-200 chamber before it was installed at the experiment site. This type of detector is called a time projection chamber (TPC) that detects both light and charge separately, and uses the two signals to measure the position in three dimensions of each decay.

With the possibility of such an important discovery, many experimentalists have tried their hand at detecting this phenomenon, but the only accepted outcomes of past experiments have been limits on the half-life. The EXO-200 experiment has searched for neutrinoless double beta decay in the isotope ^{136}Xe with a detector that holds about forty liters of liquid xenon and put a limit on the half-life of the process of > 1.1 x 10^{25} years, or greater than one million billion times the estimated age of the universe. With a known limit on the half-life of such a great magnitude, it would take many years of running the currently built experiments to make any sort of significant discovery. We need a bigger detector!

The nEXO detector will be based around a chamber holding about 5 tons (about 50 times bigger than the EXO-200 detector!) of very cold, liquefied xenon gas, which is about the same volume as a hot tub that would comfortably fit eight people. This xenon will be enriched to about 80% in the isotope ^{136}Xe, which means that there are 54 protons and 82 neutrons in the nucleus. About one in every 130 million atoms in the Earth's atmosphere is ^{136}Xe, which makes it a difficult task to get enough to fill a hot tub sized detector in the liquid phase!

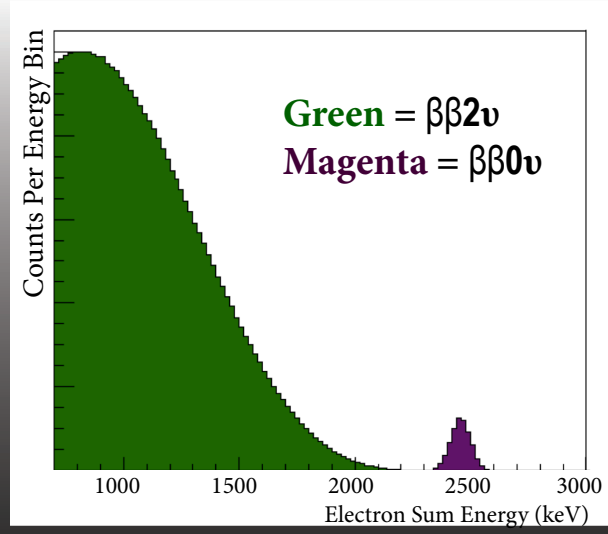
When ^{136}Xe undergoes double beta decay, two high-energy electrons are emitted, and as they travel through the detector they ionize the surrounding xenon. This means that they knock electrons off from other xenon atoms, creating a tiny trail of free electrons. Some of these electrons will recombine with the surrounding xenon emitting light in the process, and some of the electrons will remain free and travel through the xenon under the influence of an electric field established in the detector for this purpose. Separate sets of electronics will be in place to detect the light signal and the charge signal, providing information about the energy of the original double beta decay event.

The total energy emitted in the double beta decay is constant, a characteristic property of the decay called the Q-value. In fact this is exactly the difference between the internal energy of the ^{136}Xe nucleus and the daughter ^{136}Ba nucleus. During the decay, some of the energy is carried off with the neutrinos, which escape our detector, and some is left to the electrons, which we can detect.



nEXO will hold about 50 times more xenon than the EXO-200 detector.

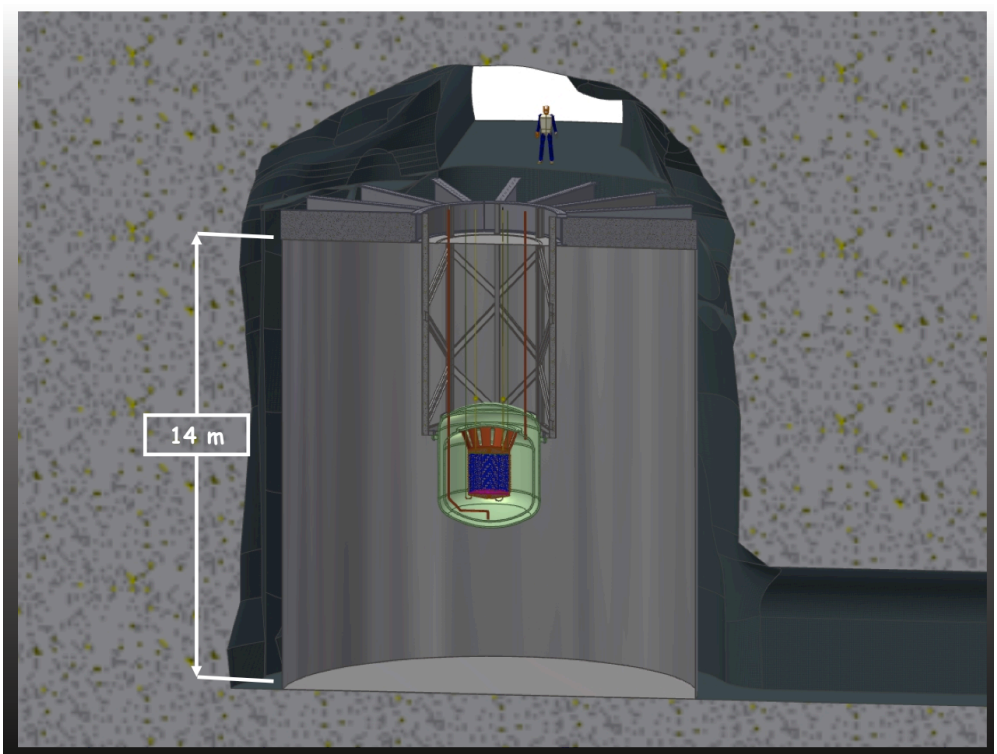
The Law of Conservation of Energy allows us to learn about the properties of the neutrinos by studying the energy of the leftover electrons. If we detect the electron energies from many double beta decay events and plot them on a graph, we will eventually have a spectrum of energies that builds up into a specific spectral shape that ends at the Q-value. Every radioactive isotope has it's own unique spectral shape.



The spectrum for double beta decay that emits two electrons (ββ2ν) is a continuous shape that ends at the Q-value. The spectrum for neutrinoless double beta decay (ββ0ν) is a mono-energetic peak at the Q-value.

If we detect a buildup of events that have an energy at the Q-value, it could mean that all of the decay energy has gone into the electrons and we have detected neutrinoless double beta decay! The neutrino is a Majorana Fermion, we can pick out the correct theory to describe neutrinos, and we can measure the absolute neutrino mass. Many mysteries are solved at once! Unfortunately though, as in most scientific experiments, the measurement process is not that easy. Every experiment has some type of background. Noise from the electronics that detect light and charge blurs the exact energy that is detected. Radioactive particles in the environment spit out gamma radiation that travels to the detector and also ionizes the xenon, at times in a way that is difficult to disentangle from double beta decay. High-energy particles come hurtling through space and plow into the surrounding environment, creating radioactivity as well as large signals in the detector.

It is the experimentalist's job to reduce these backgrounds as much as possible. Charge and light signals are tiny and very sophisticated equipment is required to detect and record them clearly.

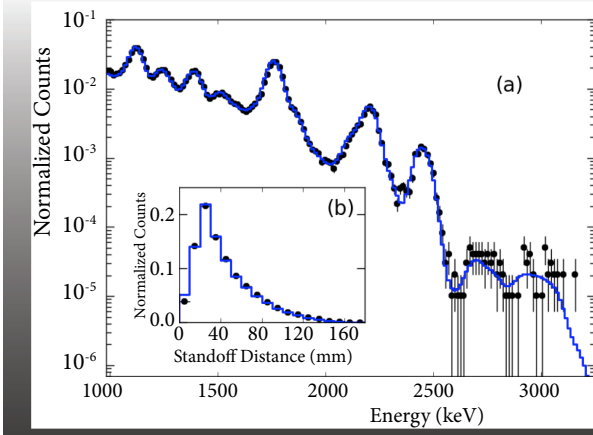


An artists depiction of the nEXO detector (blue) inside of its cryogenic shielding (light green) with 7m of water shielding on all sides in an underground cavern.

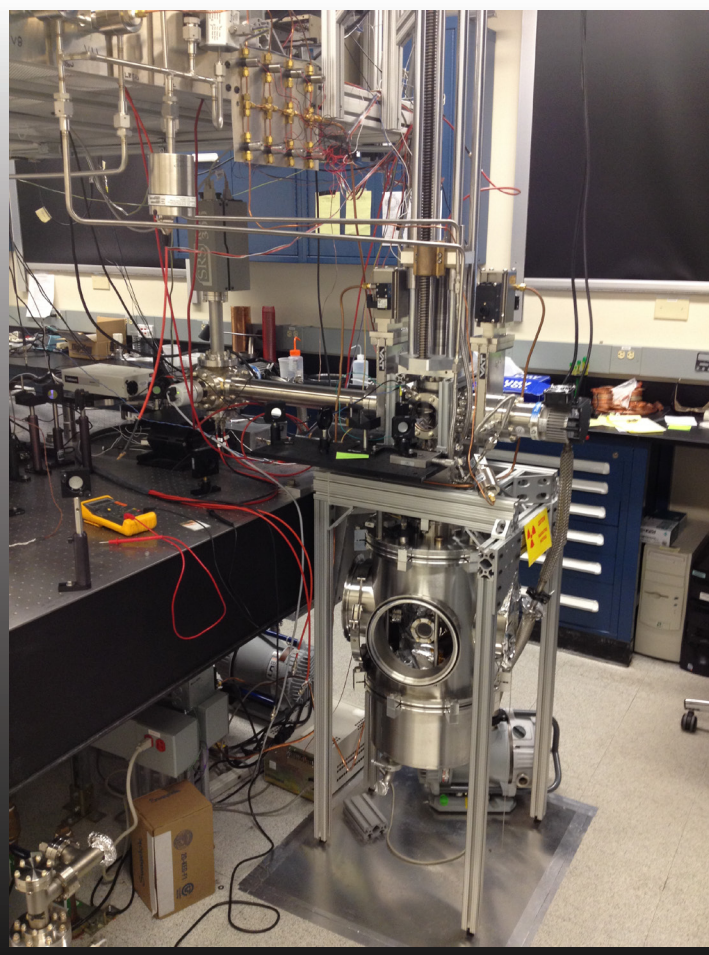
In order to reduce radioactive background from the surrounding environment, each material chosen for the detector must be carefully screened for radioactivity, with materials closest to the xenon at activities less than 1 billion times lower than an average pile of dirt. In order to shield from the radioactivity of the external environment, nEXO will be surrounded by a bath of cryogenic and shielding fluid that slows and stops gammas rays on their way to the detector, as well as keeps the xenon cold enough to remain liquid.

The whole cryogenic system will be submerged in a large water tank, big enough to shield from gammas emitted from the surrounding rock. In order to reduce the number of energetic cosmogenic particles knocking around the atoms in or near the detector, the whole experiment will be put about 2 kilometers underground and the earth itself will act as a giant shield.

Try as we might, no one has ever been able to construct a completely background free experiment. There will always be some imposter signals acting like double beta decay and building up at energies near the Q-value. A number of data analysis techniques are used to try to distinguish true signals from background. The most important technique is to simulate all conceivable radioactivity from components of the surrounding environment and to fit it to the data. The physicists working on nEXO are also designing elaborate calibration techniques to subject the detector to various characteristic signals. Matching simulations of these calibration sources to the data will improve our understanding of the physics occurring inside of the detector and validate the process of background identification and suppression.



EXO-200 uses external radioactive sources to perform calibration of the detector. The simulation (blue) fits well to the data (black points), showing that the model used to simulate radioactivity approximates the function of the detector well.



The nEXO collaboration is also developing techniques for barium tagging. This picture shows an apparatus for extracting barium ions from liquid xenon.

A unique aspect of nEXO that is currently under development is the prospect of barium tagging. Many institutions around the world involved in nEXO are working on finding an optimal system that will reach into the nEXO detector after a beta decay-like event, grab the daughter ^{136}Ba atom, and detect this single atom as ^{136}Ba. This technique has never been executed before and would reduce all gamma backgrounds from the experiment, greatly increasing nEXO's sensitivity!

When nEXO will be ready to deploy, it will be the largest collection of ^{136}Xe atoms on earth, and will be more sensitive to neutrinoless double beta decay than any other experiment. Simulations of future detector designs have shown that nEXO will have the sensitivity to detect neutrinoless double beta decay with a half-life of higher than 10^{28} years, which would be greater than 500 times the currently measured limit! The deployment of this detector will be a great feat by many collaborating scientists in building a large, low background experiment – and of course in furthering our knowledge of the properties of the elusive neutrino.