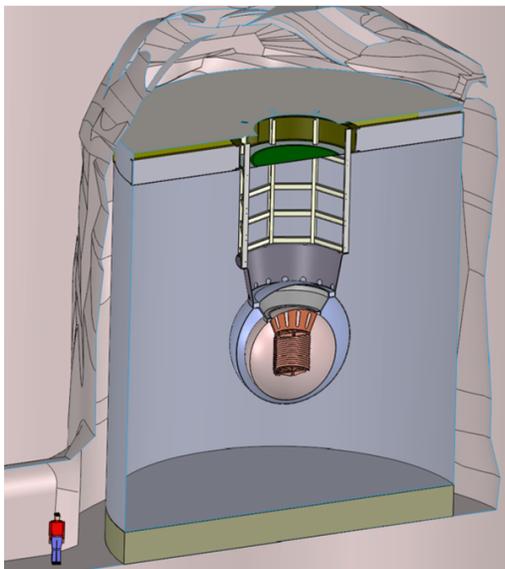


What is nEXO ?

This is a brief introduction to the nEXO experiment, written for the general public. If you are a scientist, particularly a neutrino physicist, you would probably find it more useful to consult our preConceptual Design Report (<http://grattalab3.stanford.edu/neutrino/Publications/1805.11142v2.pdf>) or look at the slides at http://grattalab3.stanford.edu/neutrino/EXO/nEXO_CNNP_Feb2020.pdf.

nEXO is designed to search for neutrinoless double-beta decay. That's quite a mouthful! Double-beta decay is a process whereby a nucleus decays into another one, with two electrons and two antineutrinos also emitted. While this is a rare decay, by virtue of the fact that many particles are emitted together, it is not connected to anything profound; it's only rare. However, a special version of the double-beta decay is the "neutrinoless" version, where the two electrons are emitted alone, not accompanied by the antineutrinos. This is a very special decay that has never been observed and cannot occur according to the laws of physics as we know them. Still, the decay is at the boundary of human knowledge, meaning that a number of theories that may explain strange patterns observed in particle and nuclear physics and cosmology, predict that this decay can occur, while affecting nothing else in our scientific knowledge. These theories predict that neutrinoless double-beta would occur at an unimaginably small rate; indeed experiments carried out until now, have set limits on how rare the decay is, establishing that the half-life of the nuclei involved is longer than 10^{15} times the age of the Universe. This is a million-billion times the age of the Universe! If you want to find out more about why neutrino-less double-beta decay is so important and how it is connected with other concepts in physics, you may find the article http://grattalab3.stanford.edu/neutrino/Publications/Gratta_2010_Phys._World_23_31.pdf useful.



nEXO is designed to extend out knowledge of this rare decay to a level of 10^{28} years, or 10^{19} times the age of the Universe. How do we measure such long half lives? We certainly are not patient enough to wait 10^{28} years! It turns out that, according to the laws of radioactive decay, nuclei in a large collection of them are all identical, and each one of them lives and decays independently from the others –they essentially ignore each other. So, in a collection of -say- a million (10^6) nuclei, each with a million year half life, half the nuclei will have decayed in a million years, and about 1, on average, decays every year. And it is a property of nuclear decays that they can be individually detected, assuming a number of precautions are taken not to be confused by backgrounds. nEXO will be searching for the neutrinoless double-beta decay in the isotope 136 of Xenon (^{136}Xe), using 5,000 kg of it, or about 2×10^{28} nuclei. This very large number of nuclei allows us to translate the potential observation of a few decays in the 10 years of operation of the experiment into a sensitivity to the very large half-lives discussed above. As it is easy to imagine, one of these nuclear decays is pretty insignificant, as only a tiny energy is released

and available for the detection. So, the first step consists in protecting the Xenon from other forms of radioactivity. This is why the experiment will be located in a deep mine (see <https://www.snolab.ca/>); at 2 km depth

How are new theories “invented”?

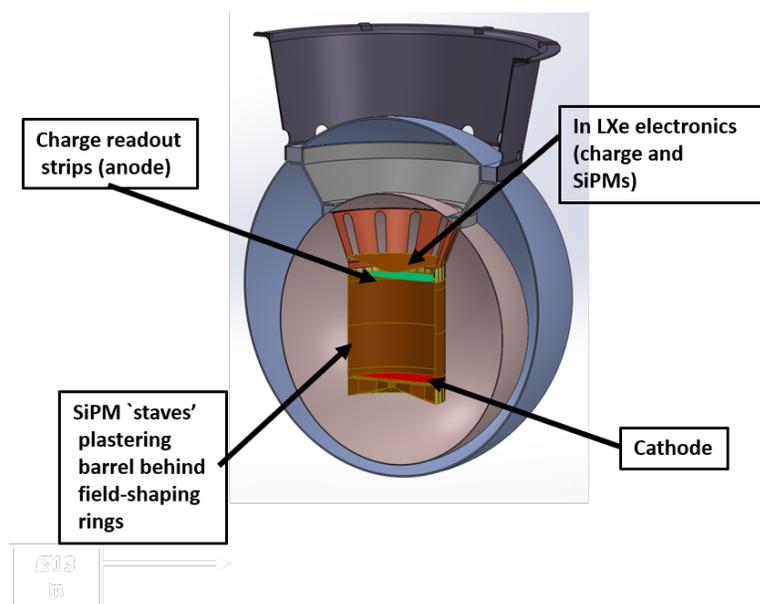
You may wonder how people come up with new theories in physics. You have probably heard that quantum mechanics involves really bizarre and counter-intuitive concepts. So, why don't we “fix” quantum mechanics? This is really hard because we do not get to choose the theory we like. A new theory has to be able, first and foremost, to reproduce all the data we know, and this is really difficult! So quantum mechanics is a wonderful theory that predicts an amazing amount of data and, whether we like it or not, there is no known theory that can replace it. It's like working on a million pieces jigsaw puzzle, having done half of it and asking “maybe we can rearrange everything and it will work better”, not easy! You can watch Richard Feynman discuss the subject at https://www.youtube.com/watch?v=EYPapE-3FRw&ab_channel=seabala

the rock overburden protects the experiment from cosmic radiation that is too energetic to be stopped by artificially made shields. The nEXO detector in the underground cavern is shown schematically on the previous page. The scale of the detector is shown by the human silhouette to the left; it's a very large detector, and building it 2 km underground is a bit like building a ship in a bottle, just way harder!

The next step in reducing radioactive backgrounds consists in building the detector like an onion, with layers that are progressively lower in natural radioactivity, as they get closer to the "inner sanctum", the Xenon located in the center. Each layer shields the radioactivity produced by the outer layers. For example, the

rock of the mine contains lots of Uranium and Thorium, both radioactive elements that exist in the Earth's crust at a rather large 1 part-per-million level; these are primarily shielded by the water in a large tank. Lots of water is required, because there is plenty of radioactivity to shield. The water itself contains some (way less) radioactive contaminants, and those are shielded by a special fluid contained by the brown sphere. The Xenon is kept in liquid form inside a very thin cylindrical copper vessel, inside the sphere. Why "thin copper"? Because copper is the highest purity metal available and it has to be thin because, as pure as it may be, it is not perfect and we cannot afford having too much of it near the much purer Xenon. The levels of radioactive contamination in the materials close to the Xenon are quite extraordinary, as illustrated by the comparison with a banana in the table above.

Object	Decays/second
A 150 g banana	14
The 5-tonne nEXO detector	1.4×10^{-8}



Since only the isotope ^{136}Xe can potentially undergo neutrinoless double-beta decay, to optimize the experiment we use Xenon that is enriched to 90% in that isotope. In this way, the detector is smaller and several aspects of it are simplified. This step is achieved by ultracentrifugation, starting from the 9% concentration of ^{136}Xe in natural Xenon. Ultracentrifugation is the same technology used to produce Uranium enriched in the isotope 235 for nuclear power plants and nuclear weapons and obtaining 5,000 kg of ^{136}Xe in this way is quite an enterprise!

In order to liquefy the Xenon, the central part of the detector is cooled to 165 K (this is -108 C, or -163 F, depending on your culture). Indeed, the spherical shells also shown in the figure here to the left are a cryostat and the volume between

them is evacuated, to provide thermal insulation. The liquid Xenon, filling the cylindrical copper vessel, is not only the source of the potential decays, but also the medium in which the decays would be detected. To achieve this, a large voltage difference (about 50,000 volts) is established between the bottom of the cylinder (red in the figure) and the top (green). The liquid Xenon is a good dielectric so that, even with this large voltage, there is no current flowing between the electrodes. When a double-beta decay occurs, the two electrons leave the decay site with substantial kinetic energy and slow down by dissipating their energy ionizing more atoms of Xenon along the way. Hence clouds of free electrons are produced and these are "drifted" towards the positive anode, under the influence of the large voltage. This arrangement is called a "Time Projection Chamber" and properly instrumenting the anode allows one to measure the energy of the original electrons and the location where they were produced. In fact, the geometrical structure of the decay is also recorded; this is important because the residual background is mainly due to gamma-rays and not electrons, and the gammas deposit energy in patterns that are largely different from those of the electrons produced by the double-beta decay. Since the ionization electrons drift in straight lines towards the anode, the point where they land is a direct projection of two of the coordinates of the decay position. The third coordinate requires more work. Along with ionization, the original electrons produce a flash of light in the liquid Xenon.

Special photodetectors plaster the inside of the Time Projection Chamber and record the amount of light produced and the exact time at which it was produced. Since the ionization electrons drift relatively slowly, the difference in time between the flash of light and the arrival of the ionization at the anode provides the third coordinate of the decay. Some combination of the amount of light detected and of the charge collected at the anode is used to reconstruct the total kinetic energy of the original electrons from the decay. The readout of light and ionization signals is obtained with ultra-sensitive electronics, with custom-made chips (ASICs, Application Specific Integrated Circuits) designed for the experiment to operate at cryogenic temperature and very pure in terms of radioactive elements. Amplified and digitized numbers are continuously transmitted outside of the Time Projection Chamber, to conventional computers at room temperature.

A substantial amount of support infrastructure is required to run nEXO, from ultra-high vacuum, to cryogenics (we will operate a large liquid nitrogen plant underground), to sophisticated mechanics and electronics. Components for the experiment are fabricated in many places around the world, because, in many cases, they are unique and are procured from wherever they are available. A consortium of over 150 scientists and technologists from 31 institutions and eight countries, shown below, are contributing to the design and construction of nEXO. Everybody in the consortium will analyze the data, that is expected to flow over a period of ten years.

