Searching for Double Beta Decay with the Enriched Xenon Observatory

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Abstract. The Enriched Xenon Observatory (EXO) will search for neutrinoless double beta decay in $^{136}$Xe. The first phase of the experiment, EXO-200, uses 200 kg of liquid xenon enriched to 80% in $^{136}$Xe in an ultra-low background time projection chamber (TPC). EXO-200 is in the final stages of assembly at the WIPP site in Carlsbad, NM and will begin taking data in 2009 with two-year sensitivity to the half-life for neutrinoless double beta decay of $6.4 \times 10^{25}$ years. According to nuclear matrix element calculations, this corresponds to an effective Majorana neutrino mass of 0.13 to 0.19 eV. The EXO collaboration is also performing R&D for simultaneous detection of the decay electrons and emerging Ba ion allowing essentially background free detection in a future, ton-scale detector. The status of EXO-200 and of the ion tagging technology in liquid xenon is described.

1. Introduction
Neutrinos have long been a difficult particle to study, yet recent oscillation experiments have answered many questions about neutrinos and their properties. Still, many questions remain unanswered and can be addressed through other similarly challenging techniques. In particular, double beta decay can shed light on the absolute mass scale of the neutrino and the Majorana nature of the neutrino. The Enriched Xenon Observatory (EXO) for double beta decay is a program of experiments, working toward the ton-scale, to look for neutrinoless double beta decay with promising discovery potential.

2. Double Beta Decay
Double beta decay is a second-order standard model process whereby two neutrons in the nucleus of an atom simultaneously decay to protons producing two electrons and two electron anti-neutrinos in the process. This process can occur in particular nuclei where single beta decay is not energetically allowed. These nuclei are also used to look for the neutrinoless double beta decay process ($0\nu\beta\beta$) which is forbidden by the standard model because it requires the violation of lepton number. In addition, neutrinoless double beta decay requires that neutrinos be massive and that they are there own anti-particle classifying them as Majorana particles.

The two-neutrino mode of double beta decay ($2\nu\beta\beta$) has been observed in many isotopes but has not yet been observed in $^{136}$Xe. The probability of decay for the $2\nu\beta\beta$ mode is very small and exceedingly smaller for the $0\nu\beta\beta$ mode making these measurements extremely difficult. The measured lifetime for the $0\nu\beta\beta$ mode is proportional to the inverse of the effective Majorana neutrino mass (a coherent superposition of the electron neutrino projections on the mass...
eigenstates) making the absolute mass scale of the neutrino accessible with such a measurement. The EXO collaboration will search for both the $2\nu\beta\beta$ and $0\nu\beta\beta$ decay modes in $^{136}\text{Xe}$.

The two decay modes can be differentiated by measuring the energy distribution of the electron spectrum produced in the decay. The neutrinoless signal will appear as a peak at the endpoint of the $2\nu\beta\beta$ spectrum. The width of the peak is determined by the energy resolution of the detector making this a critical component of the experiment design while also eliminating possible backgrounds in the region of interest.

3. EXO-200

EXO-200 is the first phase of the EXO experiment, using 200 kg of xenon enriched to 80% in the $^{136}\text{Xe}$ isotope. EXO-200 will use a time projection chamber (TPC) filled with liquid xenon that will serve as the target and detection medium. When the xenon nucleus decays, it will produce both scintillation light and ionization in the detector. These light is collected by a plane of large-area avalanche photo-diodes (LAAPDs) and the charge is collected on a grid of anode wires at each end of the detector. The energy resolution of the detector is greatly improved by collecting both the scintillation and ionization signals in the detector [1][2]. The monolithic detector minimizes surface contamination and the gaseous or liquid volume allows for continuous circulation and purification of the xenon. A high Q-value places the region of interest for $0\nu\beta\beta$ above decay lines, and $^{136}\text{Xe}$ is advantageous with a $Q=2.48$ MeV [3].

$^{136}\text{Xe}$ offers a unique opportunity to tag the daughter barium ion. Identification of the barium ion for each double beta decay event will eliminate all radioactive backgrounds in the $0\nu\beta\beta$ region of interest leaving the $2\nu\beta\beta$ events the only source of background [4]. The barium tagging technique is in the R&D phase and will not be employed in EXO-200.

EXO-200 will look for $0\nu\beta\beta$ in $^{136}\text{Xe}$ with a sensitivity to the half-life of $6.4 \times 10^{25}$ years which is an order of magnitude better than the current limit. In addition, EXO-200 will measure the half-life for the standard $2\nu\beta\beta$. Based on the current best limits for the half-life of the $2\nu\beta\beta$ mode, it is expected that EXO-200 will observe anywhere from 23000 to 1.3 million events in one year.

The TPC was designed to maximize fiducial volume and energy resolution and to minimize radioactive contamination. The limits on radioactivity imply significant constraints on the types and quantities of materials that could be used for the TPC construction [5].

The xenon vessel, which contains the TPC, is only 1.5 mm thick because of radioactivity requirements. The read-out cables are flex-circuits made of copper on kapton. The field-shaping rings are copper while the anode grid wires and cathode are all phosphor-bronze. The cathode is located in the center of the cylindrical TPC which is 40 cm in length and diameter. The plane of anode grid wires and APD plane of 234 LAAPDs (see [6] for more information on the APDs) are located at each end of the detector. Teflon is used inside the cylindrical volume as a reflective surface to increase light collection.

The TPC is kept at a temperature of 170 K to keep the xenon liquid at a pressure of 1.5 atmospheres. The xenon vessel is kept cold while in thermal contact with a cryogenic fluid made by 3M called HFE-7000. The HFE is contained in a copper cryostat that is cooled by three heat exchangers, each of which is connected to a cryogenic refrigerator. The cryostat containing the HFE is kept cold by a volume of insulating vacuum. This outer cryostat is shielded by a 25 cm thick Pb wall. The entire experimental set-up is contained within a class-100 clean room. Additionally, the clean room is surrounded by a muon veto detector.

EXO-200 is installed at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico at a depth of 655 m and ~ 1600 mwe. The assembly of the TPC was completed at Stanford University, and the TPC was shipped to WIPP in October this year and is ready for installation. Cryogenic commissioning of the xenon, HFE, and control systems has just been completed at WIPP. Once the TPC is installed, the experiment will perform an engineering run with natural...
Figure 1. The TPC inserted in the xenon vessel with the attached cryostat door. The legs contain the readout flex-circuits and are the conduits for xenon circulation.

xenon soon followed by physics data-taking with the enriched xenon.

4. Barium Ion Tagging in Liquid Xenon
The $0\nu\beta\beta$ decay process produces a daughter Ba$^{++}$ ion which is expected to quickly convert to Ba$^+$ in a liquid xenon environment. The barium ion produced can be optically identified because of its specific shelving signature. By optically pumping the two transitions with red and blue lasers, a fluorescence rate of $\sim 10^8$ Hz can be measured in vacuum.

The barium ion tagging scheme would be to build a probe that could electrically attract the barium ion out of the liquid xenon and would then be transported to a quadrupole linear ion trap where the ion will be optically pumped and the fluorescence identified by a CCD camera. The ion trap has been built and has successfully shown identification of single Ba ions while a buffer gas is present in the trap [7].

Currently there are two types of probes being developed for the barium tagging in liquid xenon. One probe uses a cryogenic capacitive sensor on a tip to freeze a layer of xenon on the tip after first attracting the ion to the probe tip with a bias voltage [8]. The layer of xenon ice on the tip is well-controlled by the capacitance sensor on the tip. Research is underway to install this probe on the top of linear ion trap to measure efficiency of the probe and trap system. A second technique using resonant ion spectroscopy is being developed.

In order to test the efficiency of the entire tagging system, it is important to have a reliable single-ion barium source. One method is to use $^{137}$Cs, which will single beta decay to $^{137}$Ba$^+$ and an electron with a half-life of 30 years. $^{137}$Cs comes in the form of CsCl salt and needs to be chemically isolated. This process has been successfully completed in vacuum and is proceeding in the gaseous and liquid xenon environments.

5. Future Plans
EXO-200 will begin data-taking in 2010 and will provide the first results of the half-life for $2\nu\beta\beta$ decay in $^{136}$Xe and set competitive limits on the half-life of the $0\nu\beta\beta$ decay mode. The understanding of the liquid xenon TPC and radioactive background measurements will provide essential knowledge for design work for a future ton-scale EXO experiment. The predicted sensitivities for the the EXO-200 and ton-scale EXO experiments are shown in Table 1. It is assumed that the ton-scale EXO will use the Ba tagging technique. A limit on the effective
Table 1. The predicted EXO sensitivities to the $0\nu\beta\beta$ decay based on nominal experimental parameters and recent nuclear matrix element calculations.

| Case       | Mass (ton) | Eff (%) | Run Time (yr) | $\sigma_{E}/E$ (%) | Radioactive BG (events) | $T_{1/2}^{0\nu}$ (yr) $^{90\%}$ CL | Majorana Mass (meV) | QRPA$^{[9]}$ | NSM$^{[10]}$ |
|------------|------------|---------|---------------|--------------------|------------------------|-------------------------------------|---------------------|--------------|--------------|
| EXO-200    | 0.2        | 70      | 2             | 1.6                | 40                     | $6.4 \times 10^{25}$                  | 133                 | 186          |
| Conservative | 1          | 70      | 5             | 1.6                | 0.5 (1) $^{2\nu/3\nu}$ | $2 \times 10^{27}$                     | 24                  | 33           |
| Aggressive | 10         | 70      | 10            | 1                  | 0.7 (1) $^{2\nu/3\nu}$ | $4.1 \times 10^{28}$                  | 5.3                 | 7.3          |

neutrino mass at the tens to few meV scale will exclude the inverted hierarchy for the Majorana neutrino.

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