Double beta decay in liquid xenon

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Abstract.

The Enriched Xenon Observatory (EXO) collaboration will search for double beta decay using the $^{136}$Xe isotope [1]. During the initial phase (EXO-200), a 200 kg enriched Xe liquid Time Projection Chamber (TPC) will be deployed in the underground experimental area at the Waste Isolation Pilot Plant (WIPP), Carlsbad, USA. We present the design, construction and installation of the EXO-200 TPC focussing on the specific experimental requirements for the detection of neutrinoless double beta decay: high energy resolution and low radioactive background.

1. Introduction

The double beta decay, a rare nuclear process, is investigated experimentally because it has the potential to reveal new information about the nature and properties of neutrinos [2]. Indeed, this nuclear transition can proceed through multiple channels: with the emission of two electrons and two anti-neutrinos ($2\nu\beta\beta$) as predicted by the standard model of particles, without the release of neutrinos ($0\nu\beta\beta$) or accompanied by the radiation of a third light neutral fermion. The half-life of the neutrinoless decay depends on the effective neutrino mass, a linear combination of the three neutrino masses, and therefore its measurement provides further information about the neutrinos masses which cannot be independently established only from neutrino oscillation experiments [3, 4]. Furthermore, the observation of this exotic decay process would be a direct evidence that the neutrino is a Majorana particle. The spectrum of the energy carried by the two electrons is very different for the various decay channels, in particular for $0\nu\beta\beta$ this is simply a peak at the $Q$ value of the decay. Therefore, events from each channel can be discriminated to a certain extent even when using detectors not sensitive to the topology of particle tracks.

The EXO R&D program aims at the deployment of a very large mass (ton scale), ultra low background TPC filled with xenon enriched in $^{136}$Xe isotope for the detection of $0\nu\beta\beta$. For the first phase, the collaboration has successfully procured 200 kg of 80% enriched xenon that will be employed in a cryogenic liquid TPC providing charge and scintillation light readout. A high pressure gas phase TPC, to be implemented with larger xenon masses, is still under consideration for the next phases because it offers better spatial resolution facilitating efficient event selection based upon the topology of particle tracks. Also, future detection schemes will involve identification of the final state (i.e. $^{136}$Ba$^+$) which allows a drastic reduction of the effective radioactive background.
2. Experimental requirements

For the $^{136}$Xe isotope, the energy released in the double beta decay ($Q = 2458$ keV) is higher than that of most radioactive decays from the U and Th chains. Furthermore, xenon can be purified and enriched efficiently and has been used successfully as a detection medium with TPCs [6]. In the case of $0\nu\beta\beta$ decay, the radioactive background (i.e. events with energies around the $Q$ value that emulate the expected signal) has to be kept under 40 events per year to optimize the EXO-200 detector performance and reach a half-life sensitivity of the order of $5 \times 10^{25}$ years. Also, very strict radioactive background control is necessary to be able to observe the $2\nu\beta\beta$ decay that has a wide energy spectrum. It is therefore extremely important to reduce, or even eliminate, the residual radioactive impurities (from naturally occurring elements, especially K and those from the U and Th chains) found in all the components of the TPC and the surrounding experimental setup [7]. This can be achieved by careful selection of the construction materials and design optimization techniques intended to reduce the mass of the detector’s components, especially those located close to its active volume [8]. Since, ultimately, the allowed double beta decay becomes the dominating background for the $0\nu\beta\beta$ mode, when considering a realistic detector with finite energy resolution, it is obvious that improving the energy resolution is an essential goal independently from the radioactive background control considerations.
3. EXO-200 detector

The EXO-200 TPC has a cylindrical shape, with a diameter of 40 cm and a length of 35 cm, and it is segmented into two zones by a central photo-etched cathode made of phosphor bronze. Both regions are equipped with induction and charge collection wire grids followed by LAAPD (Large-Area Avalanche PhotoDiode) planes, placed parallel to the cathode at the ends of the chamber. Field shaping rings are supported by acrylic pillars and thin Teflon sheets, installed radially, serve as ultraviolet reflectors for the scintillation light. Figure 1 shows a diagram and a 3-D drawing of this assembly. The chamber is made of ultra low radioactivity copper formed from 1.5 mm thick rings welded together employing low contamination methods (e-beam and TIG welding) performed in controlled environments. Each LAAPD plane contains 250 UV (QE > 1 at 174 nm) sensors with an active diameter of 1.6 cm that are operated at about 1500 V for gains in the range 100× to 150×.

![Figure 1: EXO-200 TPC Diagram](image1)

3.1. EXO-200 cryostat

The TPC is hosted in a refrigeration based cryostat that uses 4.2 tons of high purity heat transfer fluid. Due to safety constraints, liquid nitrogen cooling techniques cannot be employed at the WIPP underground facility and therefore a refrigeration based solution has been selected. Multiple heat transfer fluids have been evaluated and 3M's HFE-7000 was chosen primarily because it has the lowest residual radioactive contamination of all the candidates [8]. This fluid has a dual role, it serves as the inner gamma ray and neutron shield as well as the thermal bath that maintains the xenon temperature uniform. The cryostat has a cylindrical shape, with a diameter of 1.5 m and a length of 1.5 m, and it is made of ultra low activity copper. A 3-D drawing is shown in figure 2. This cryogenic scheme has been fully commissioned at Stanford University including the xenon and HFE handling systems.

3.2. Underground installation

The WIPP underground experimental area is located in a salt mine at a depth of 300 m. The EXO project has been allocated a vast dedicated tunnel that is provided with the necessary utility services. The collaboration installed a series of clean room modules supported by adjustable pillars in which the EXO-200 detector and its support infrastructure are enclosed, protected from mine dust and salt. Figure 3 shows a few pictures of the EXO experimental area before and after the placement of the clean room modules as well as during the installation of the cryostat and its outer lead shield. A muon veto composed of plastic scintillator panels (20 units with dimensions 65 × 315 cm² and 11 units with dimensions 65 × 375 cm²) covers the module that hosts the detector. Monte Carlo simulations have been used to optimize the configuration of these panels and the best solution, illustrated in figure 4, provides a tagging efficiency of 99.7% resulting in the reduction of muon related background by a factor of 20×.

![Figure 3: WIPP underground experimental area](image2)
4. Radioactive background survey

The EXO collaboration conducted a large campaign to determine the residual radioactive contamination of many materials and components considered for the construction of the EXO-200 detector and its support infrastructure [8]. The potassium, thorium and uranium concentrations of more than 350 materials have been measured and a database containing the results for 225 interesting candidates has been made available to the experimental community developing detectors with similar low background requirements. Various methods have been employed for this survey: standard mass spectrometry (MS), glow discharge MS (GD-MS), inductively coupled plasma MS (ICP-MS), neutron activation analysis (NAA), alpha and gamma counting. To reach optimal sensitivity, each method imposes particular constraints on sample preparation, but generally those are complementary. For example, direct gamma counting offers the best sensitivity to cost ratio for large mass samples whereas ICP-MS performs the best for small mass samples that are chemically compatible with acid based preconcentration methods. A complete Monte Carlo simulation that includes the detailed geometry of the EXO-200 detector, the measured activities of the selected materials and event selection algorithms has been developed and allowed us to predict the background induced by residual contamination.

5. EXO-200 expected performance

The EXO-200 detector is expected to have a very low background induced by the residual radioactive contaminants, i.e. around 40 events per year in the energy range of interest for $0\nu\beta\beta$ decay. To reach such purity, it is necessary to do a careful selection of materials in parallel with a custom detector design. Also, all the manufacturing, handling and installation phases have to be done in clean environments to insure that additional radioactive contamination is not injected during these manipulations. An energy resolution of $\sigma = 1.6\%$ at 2.5 MeV is projected when combining both charge and scintillation light measurements. Therefore, considering reasonable parameters (200 kg of enriched xenon, 70% efficiency and 2 years run time), the expected sensitivity of EXO-200 is $T_{1/2}^{0\nu\beta\beta} = 6.4 \times 10^{25}$ which translates, in terms of effective neutrino mass to $\langle m_\nu \rangle = 133$ meV when the nuclear matrix elements are calculated with QRPA [9] (alternatively $\langle m_\nu \rangle = 186$ meV for calculations done with NSM [10]). Also, drawing advantages from the EXO-200 low radioactive background effort, the $2\nu\beta\beta$ decay mode of the $^{136}$Xe isotope could be observed for the first time (current limit is at $T_{1/2}^{2\nu\beta\beta} > 1.2 \times 10^{24}$).

Figure 4. Muon veto panel formation.
6. Energy resolution study

A decisive requirement for $0\nu\beta\beta$ detectors is very good energy resolution because the ratio of signal to $2\nu\beta\beta$ induced background depends strongly on the aforementioned quantity:

$$\frac{S}{B} = \frac{m_e}{7Q\sigma^6} \frac{T^{2\nu\beta\beta}_{1/2}}{T^{4\nu\beta\beta}_{1/2}},$$

where $m_e$ is the mass of the electron, $\sigma$ the energy resolution of the detector and $T_{1/2}$ the half-life of the respective decay modes. Therefore, the energy resolution achievable in liquid xenon has been studied using a small cell equipped with a UV sensitive PMT and a charge readout system [11]. The active volume had a cylindrical shape, with a diameter of 20 mm and a height of 6 mm, and a very thin $^{207}$Bi source was attached to the cathode grid. The measurements clearly indicate that ionization and scintillation signals in liquid xenon are anti-correlated as illustrated in figure 5. The cell has been operated at multiple drift voltages and the results point out that this effect is due to the dependence of the scintillation yield on the amount of charge recombination. Therefore, simultaneous measurements of light and charge provide better energy resolution than any single approach as it is shown in figure 6 ($\sigma_{\text{min}}$ is the minor elliptical axis of the 2-D peak as it can be seen in figure 5). From this study, when considering a small volume, the scaled energy resolution expected at the $Q$ value for the $^{136}$Xe decay is 1.4%. Careful considerations have been applied during EXO-200 design to insure optimal scintillation and charge collection schemes to provide similar energy resolution performance for a much larger detection volume.

7. Detection of the final state

The double beta decay of xenon produces $^{136}$Ba$^{++}$ ions and their detection can be used as a very powerful tool to discriminate against radioactive background. Techniques using resonant light scattering from ions trapped in a RF cage have been applied successfully to Ba$^+$ ions. Therefore, final state detection can be reduced to ion charge conversion and extraction from the detection medium followed by laser based spectroscopy. For the liquid phase, charge reduction occurs naturally because xenon has a larger ionization potential than barium and, for the gas
phase, various additives can be employed with xenon. Ion extraction is a rather complex process especially for very large detectors and further R&D work is planned by the collaboration [12].

![Figure 7](image.png)

**Figure 7.** Histogram of the light scattered from barium ions.

Laser based Ba$^+$ tagging has been successfully accomplished in a RF cage using low pressure He ($P = 10^{-3}$ torr) cooling and reliable single ion transport has been demonstrated [13, 14]. Figure 7 shows the spectrum of fluorescence light for 5 s time slices, the first peak is associated with the background and the following peaks correspond respectively to 1, 2 and 3 ions (the area of each peak is proportional to the respective survival time). It illustrates the excellent resolving power of this method for counting ions, which is complemented by the capability of uniquely identifying Ba$^+$ ions (493.41 nm and 649.69 nm lasers are both required for resonant light scattering, the readout is performed in the blue frequency range and the red laser is used as a switch). In-situ solutions for liquid and gas phases are explored by the collaboration because they offer the advantage of dispensing with the extraction process.

8. Conclusion
The EXO-200 detector will be commissioned for underground operation during 2009. The collaboration has successfully conducted a R&D program to produce 200 kg of enriched xenon and designed a liquid phase TPC optimized for double beta decay search. Very low radioactive background and high energy resolution are expected. In the future, the detection scheme may be extended to include final state tagging to improve background rejection.

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