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Search for double beta decay with the EXO-200 TPC and prospects for barium ion tagging in liquid xenon

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Abstract. Neutrino oscillation experiments have shown that neutrinos have very small but non vanishing masses. These experiments are not able to determine neither the absolute mass scale of neutrinos nor whether they are Majorana particles. Neutrino-less double beta decay can only occur if the neutrinos are Majorana particles, a preferred scenario in most possible schemes leading to finite masses. Among several viable candidate isotopes, EXO has chosen Xe-136. The final state (i.e. the barium ion) can be tagged using optical spectroscopy. The efficient detection of the double beta decay daughter nucleus is a key step toward a background free measurement of such a rare process. An intermediate size detector (EXO-200) of 200 kg enriched xenon has been installed underground at WIPP (US). It is an ultra-low background detector with a design sensitivity of 6×10^{25} years for the half-life of neutrino-less double beta decay in Xe-136. A larger, ton-scale experiment is being designed with Ba ion tagging capability. We are presenting the status of the EXO-200 detector and review the R&D activities for a ton-scale EXO detector with barium ion tagging.

1. Introduction

The EXO collaboration aims for the development of a ton-scale, ultra low background TPC filled with xenon enriched in Xe-136 for the detection of neutrino-less double beta decay ($0\nu\beta\beta$) [1]. For the first phase called EXO-200, the collaboration has obtained 200 kg of 80% enriched xenon and has built a cryogenic liquid TPC equipped with both charge and scintillation light readout. Future detection schemes will involve identification of the final state (Ba^+ tagging) which enables complete rejection of the radioactive background (EXO-full).

Considerable efforts have been made to design and build the EXO-200 detector with very low radioactive background. All the materials and components have been screened. The design priority was minimizing the amount of the materials surrounding the TPC. EXO-200 will explore the quasi-degenerate neutrino mass scheme. The two-neutrino double beta decay ($2\nu\beta\beta$) has never been observed in Xe ($T_{1/2} > 10^{22}$ years) [2]. EXO-200 has the sensitivity to measure this channel if current theoretical predictions are accurate. Meanwhile, the collaboration is investigating various techniques for the transport and tagging of the barium ion. The expected performance of EXO-200 is given in table 1 along with the projections for the future phases with Ba^+ tagging.

The collaboration has set up an intensive screening program to determine the residual radioactive contamination of materials considered for the detector construction [5]. The K, U and Th concentrations of more than 350 materials have been measured. A Monte Carlo simulation that includes the geometry of the EXO-200 detector, the measured activities and

Table 1. Projected performance for EXO-200 and following phases. The detection efficiency is mostly dominated by the fiducial cut. For EXO-200 the background is dominated by the contribution of the residual activity. For future phases, the expected background is exclusively from the two-neutrino channel and is a function of the energy resolution. Calculations by [3, 4] used for nuclear matrix elements.

Detector name	Mass [ton]	Efficiency [%]	Run time [year]	$\Delta E(Q)$ [%]	Background [events]	$T_{1/2}$ limit [year]	$m_{\beta\beta}$ limit [meV]
EXO-200	0.2	70	2	1.6	40	6.4×10^{25}	130
EXO-full	1	70	5	1.6	0.5	2.0×10^{27}	24
EXO-full	10	70	10	1.0	0.7	4.1×10^{28}	5.3

event selection algorithms has been developed. It provided the prediction of the background for EXO-200. EXO has studied the energy resolution achievable in liquid xenon using a small test cell equipped with a UV sensitive PMT and a charge readout system [6]. Simultaneous measurements of light and charge provide better energy resolution than any single approach. The energy resolution at the Q value (2458 keV [7]) for the decay of Xe-136 is expected to be $\sigma = 1.6\%$.

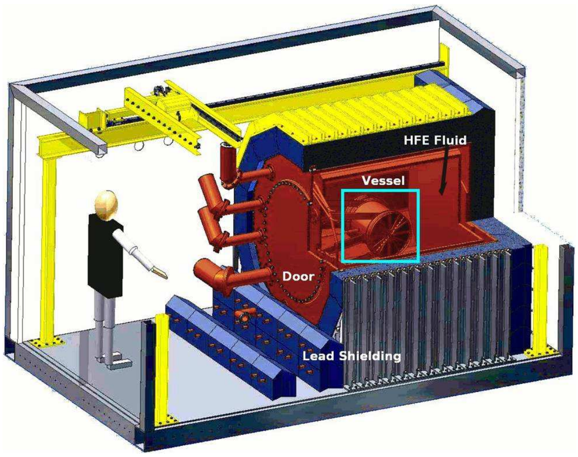

Figure 1. 3-D drawing of the cryostat.

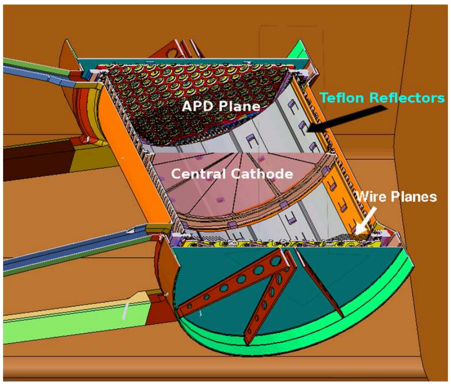

Figure 2. 3-D drawing of the TPC.

2. EXO-200 detector

The TPC has a cylindrical shape (40 cm diameter and 35 cm length) and is segmented in two zones by a central photo-etched cathode made of phosphor bronze. Both regions are equipped with induction and charge collection wire grids for ionization measurement and tracking, and with LAAPD (Large-Area Avalanche Photodiode) planes for the collection of scintillation light (peaked at 174 nm). Each LAAPD plane contains 250 UV sensors (with $QE > 1$ at 174 nm) which have an active diameter of 1.6 cm and are operated at a voltage around 1400 V for a gain of 150×. Lateral Teflon sheets serve as ultraviolet reflectors. Figure 2 shows a diagram and a 3-D drawing of the TPC. The chamber is made from ultra-low radioactivity copper by clean welding (i.e. e-beam and TIG welding) of 1.5 mm thick rings, performed in a controlled environment. The TPC is immersed in a refrigeration cryostat filled with 4.2 tons of high purity heat transfer fluid which serves as the inner gamma ray and neutron shield and as a thermal bath that maintains the chamber temperature uniform. The cryostat has a cylindrical shape (1.5 m diameter and 1.5 m length) and it is also made of ultra-low activity copper. A 3-D drawing is shown in figure 1.

The EXO-200 detector is installed at WIPP, in a salt mine at a depth of 665 m. Figure 3 shows pictures of the underground setup. A muon veto composed of plastic scintillator panels (20 units of 65×315 cm^2 and 11 units of 65×375 cm^2) covers the module that hosts the detector. Monte Carlo simulations have been used to optimize the configuration of these panels to obtain a high tagging efficiency (i.e. 99.7% resulting in the reduction of muon related background by a factor of 20×). The cryogenic system has been fully commissioned including the xenon and HFE handling. Data taking using natural xenon has started in November 2010. Operation with enriched xenon is expected for 2011.

Figure 3. EXO-200 underground experimental facility. 180° panoramic view inside the clean room (top) and outside in the drift (bottom).

3. Final state R&D

A ton-scale detector requires further radioactive background reduction that what can be provided by standard material screening techniques. To address this problem EXO envisioned the detection of the final state ^{136}Xe $\rightarrow^{136}$ Ba^{++} as an unique signature to the double beta decay. Precise ion location in the drift volume is important for an efficient final state detection. The reliable ion extraction and transport to the tagging apparatus is essential for a practical device. The Ba^{+} ion can be tagged in a RF trap using resonant light scattering.

3.1. Barium tagging

The double beta decay of xenon produces Ba^{++} ions and, for the liquid phase, charge reduction to Ba^{+} is expected. Laser based Ba^{+} tagging has been accomplished in a RF trap using low pressure helium cooling ($P = 10^{-3}$ torr) [8, 9]. Figure 4 illustrates the excellent resolving power of this method for counting ions.

3.2. Ion collection probe

Several techniques are being investigated for ion collection. A promising avenue is the resonant ionization spectroscopy (RIS) which has been explored for pyrolytic graphite and silicon. In

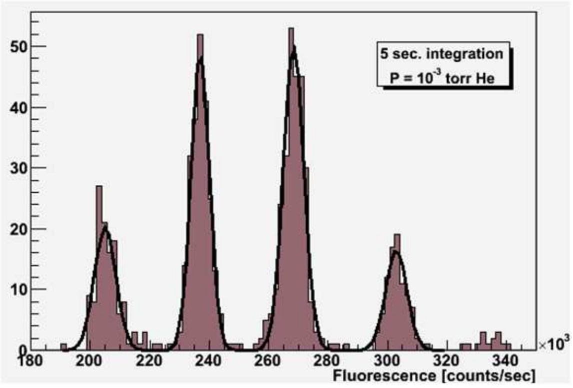

Figure 4. Histogram of the light scattered from barium ions (5 s time slices). The first peak is associated with the background and the following peaks correspond respectively to 1, 2 and 3 ions trapped.

this case, a desorption laser is used in combination with RIS lasers of specific frequency that selectively ionize the barium atom. The 553.5 nm and 389.7 nm lasers are tuned to barium transitions and are able to pump the atom to a highly excited state from which it decays to an ionized state. Figure 5 shows the time of flight spectrum of ions ejected by a desorption laser from a silicon surface with a thin barium layer produced by sputtering. When the RIS lasers are also employed, barium ions greatly dominate the spectrum. An efficiency of 0.1% has been reached and a significant improvement is expected for the next generation setup.

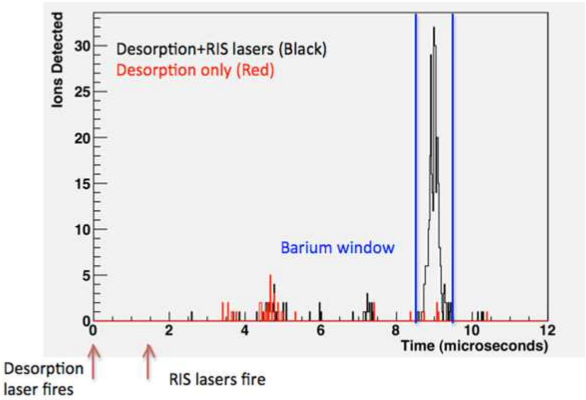

Figure 5. Time of flight spectrum for desorbed ions from a silicon surface with a thin layer of barium. The red curve illustrates the signal when only the desorption laser is employed. When RIS lasers, tuned to barium transitions, are also used then a large number of barium ions is observed as indicated by the black curve.

4. Conclusion

EXO has commissioned the EXO-200 detector and has started data taking. This first step will provide valuable data for future phases and hopefully interesting physics results. Various techniques for barium ion tagging are explored in preparation for the ton-scale detector.

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