Search for neutrino-less double beta decay with EXO

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Abstract. Neutrino oscillation experiments have shown that neutrinos have very small but non vanishing masses. These experiments however are not able to determine neither the absolute mass scale of neutrinos nor whether they are two-component Majorana particles, i.e. their own antiparticles. 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 to search for this decay. Its main advantage is that the final state, i.e. the barium ion, can be tagged using optical spectroscopy. The detection of the double beta decay daughter nucleus can be the key to a background free measurement of such a rare process. An intermediate size detector (EXO-200) of 200 kg enriched xenon (80% Xe-136) is about to take data at the WIPP underground site in New Mexico. A ton-scale experiment is being designed with Ba ion tagging capability. EXO-full will detect, in addition to the two electrons, the coincident appearance of a barium ion. This improved event signature is expected to provide total elimination of the background from radioactive impurities.

1. Introduction

The double beta decay has the potential to reveal new information about the nature and properties of neutrinos [1]. This rare nuclear transition can proceed through multiple channels: with the emission of two electrons and two anti-neutrinos ($2\nu\beta\beta$, allowed in the standard model), without the release of neutrinos ($0\nu\beta\beta$) or accompanied by the radiation of a light neutral fermion. The half-life of the neutrino-less decay $0\nu\beta\beta$ depends on the effective neutrino mass, a linear combination of the three neutrino masses, and therefore its measurement provides additional information about the neutrinos masses which cannot be established from neutrino oscillation experiments [2, 3]. The observation of this exotic process would indicate 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. 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 even when using detectors which are not sensitive to the topology of electron tracks.

The EXO R&D program aims for the development of a ton-scale, ultra low background TPC filled with xenon enriched in Xe-136 [4]. The collaboration has procured 200 kg of 80% enriched xenon that will be employed in a cryogenic liquid TPC equipped with both charge and scintillation light readout for a first phase called EXO-200. A high-pressure gaseous TPC is still under consideration for the next phase because it offers better spatial resolution facilitating efficient event selection using the topology of electron tracks. Future detection schemes will involve identification of the final state (i.e. Ba^+ tagging) which enables complete rejection of the radioactive background.

The EXO-200 project will test the feasibility of the liquid option. Considerable efforts have been made to design and build a detector with very low radioactive background. All the materials and components used for EXO-200 have been screened. The design priority was minimizing the amount of the materials surrounding the TPC. EXO-200 does not include final state tagging as this technique is still under development. EXO-200 will also provide interesting physics results. It will explore the quasi-degenerate neutrino mass scheme. The two-neutrino double beta decay has never been observed in xenon, the best limit gives $T_{1/2} > 10^{22}$ years [5]. EXO-200 should be able to measure this channel if current theoretical predictions, which anticipate half-live values not far away from the experimental limit, are accurate. Meanwhile, the collaboration is intensively investigating various techniques for the transport and tagging of the barium ion.

The expected performance of EXO-200 prototype is given in table 1 along with the projections for the future phases for which final state tagging is expected to provide complete radioactive background rejection.

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 [6, 7] 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

2. EXO-200 preparation

The reduction of the background due to the residual radioactivity (especially from K-40 and the isotopes of the U and Th chains) is necessary for the observation of the double beta decay. Ultimately, the allowed channel becomes a background for the $0\nu\beta\beta$ and therefore improving the energy resolution of the detector is an important goal.

2.1. Radioactive background survey

The collaboration set up an intensive measurement campaign to determine the residual radioactive contamination of many materials and components considered for the detector construction [8]. The K, U and Th concentrations of more than 350 materials have been measured. A database containing the results for 225 interesting candidates has been made available to the 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. 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 Monte Carlo simulation that includes the geometry of the EXO-200 detector, the measured activities and event selection algorithms has been developed. It enabled us to predict the background induced by the residual contamination.

2.2. Energy resolution study

The collaboration 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 [9]. The measurements with a thin Bi-207 source indicate that ionization and scintillation signals in liquid xenon are anti-correlated as illustrated in figure 1. 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 2 (σ_{min} is the minor axis of the 2-D peak seen in figure 1). The energy resolution at the Q value (2458 keV [10]) for the decay of Xe-136 is expected to be 1.6%. Careful considerations have been applied during EXO-200 design to insure optimal scintillation and charge collection readout.

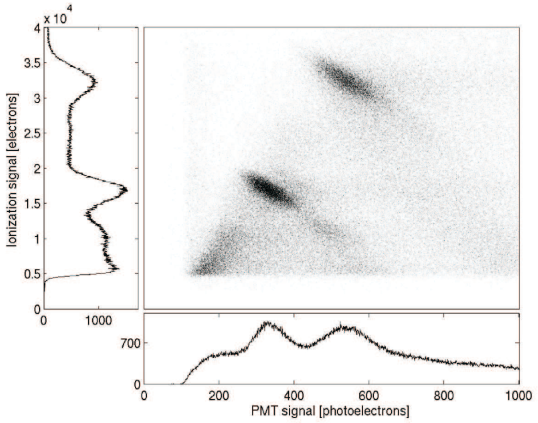

Figure 1. Two-dimensional scintillation and ionization spectrum (4 kV/cm drift field).

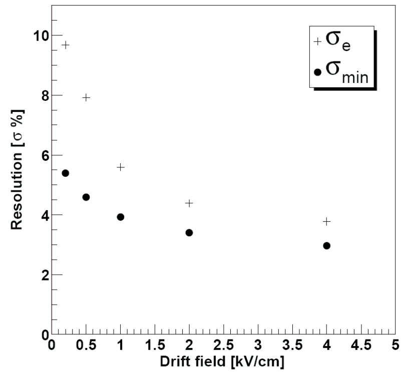

Figure 2. Energy resolution for the ionization channel alone compared to the minimal value obtained from a fit to the two-dimensional spectrum (570 keV peak).

3. EXO-200 detector

3.1. EXO-200 chamber

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 3 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.

3.2. EXO-200 cryostat

The TPC is immersed in a refrigeration cryostat filled with 4.2 tons of high purity heat transfer fluid. Many candidates have been evaluated and HFE-7000 was chosen primarily because it has the lowest residual radioactive contamination of all [8]. This fluid serves as the inner gamma ray and neutron shield and as a thermal bath that maintains the chamber temperature uniform.

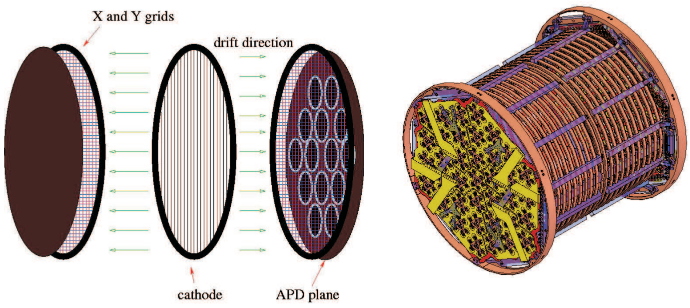

Figure 3. TPC diagram and 3-D drawing.

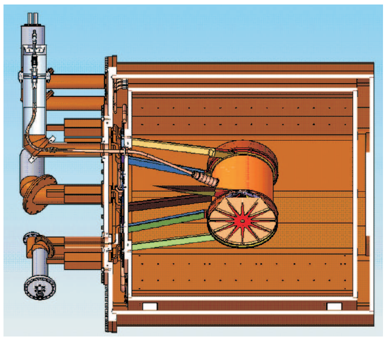

Figure 4. Diagram of the EXO-200 cryostat.

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 4. This cryogenic scheme has been fully commissioned including the xenon and HFE handling systems.

3.3. EXO-200 installation

The WIPP underground experimental area is located in a salt mine at a depth of 665 m. EXO has been allocated a vast space provided with utility services. The collaboration installed a series of clean room modules supported by adjustable pillars in which the detector and its support infrastructure are enclosed. Figure 5 shows pictures of the EXO-200 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×). Data taking using natural xenon will start in November 2010. These test runs will commission the detector and its data acquisition system. Operation with enriched xenon is expected for the first half of 2011.

Figure 5. EXO-200 underground experimental facility. 180° panoramic view inside the clean room (top) and outside in the drift (bottom).

4. Final state R&D

Precise ion location in the drift volume is important for an efficient final state detection. Therefore, the barium ion drift properties in liquid (for the baseline option) and in gas (for the gaseous option) xenon must be investigated. 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. A 493.41 nm and a 649.69 nm laser 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 tagging techniques are also explored.

4.1. Barium tagging

The double beta decay of xenon produces Ba^{++} ions and, for the liquid phase, charge reduction to Ba^+ is expected. For the gas phase, various additives can be employed with xenon to obtain singly ionized barium. Laser based Ba^+ tagging has been accomplished in a RF trap using low pressure helium cooling ($P = 10^{-3}$ torr) [11, 12]. Figure 6 illustrates the excellent resolving power of this method for counting ions.

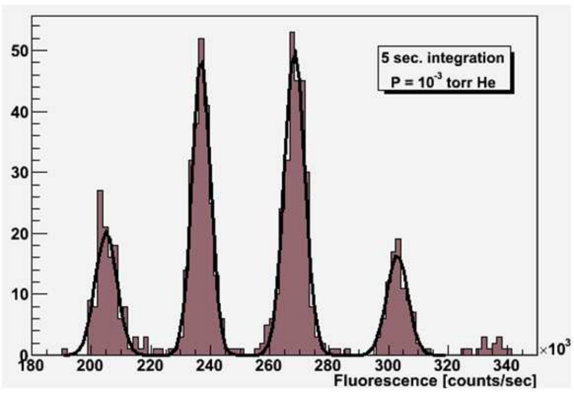

Figure 6. Histogram of the light scattered from barium ions (5 s time slices). The first peak is associated with the background and the following peaks correspond respectively to 1, 2 and 3 ions trapped.

4.2. Barium ion extraction

A cryostat able to cool 100 kg of liquid xenon has been developed to test the insertion of the collection probe and to study its effects on the TPC performance. The test cryostat remains to be commissioned for operation with argon and xenon. COMSOL based simulations have been conducted to determine the design of the cathode and the tip. A mechanical displacement device and the adapted TPC will be built and then integrated with the cryostat. Measurements with gamma sources and a custom barium ion source [14] will establish the optimal procedure for barium ion extraction. Later, this setup will be combined with either a cryogenic collection tip or a tip providing a surface with high ablation resistance and the efficiency for collecting barium ions will be measured.

4.3. Ion collection probe

Several techniques are being investigated. The concept of a cryogenic collection probe revolves around the idea of trapping the barium ion in a few layers of xenon to secure its transport and delivery to the analysis chamber [13]. Such a tip requires liquid He cooling to reach a sufficiently low temperature (≈ 40 K) to inhibit xenon sublimation in vacuum. It is also possible to adsorb the ion on a clean surface with the disadvantage of neutralization. A promising technique, resonant ionization spectroscopy (RIS), has been explored for pyrolytic graphite and silicon. In 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 7 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. Presently, an efficiency of 0.1% has been reached and a significant improvement is expected for the next generation setup targeting single ion detection.

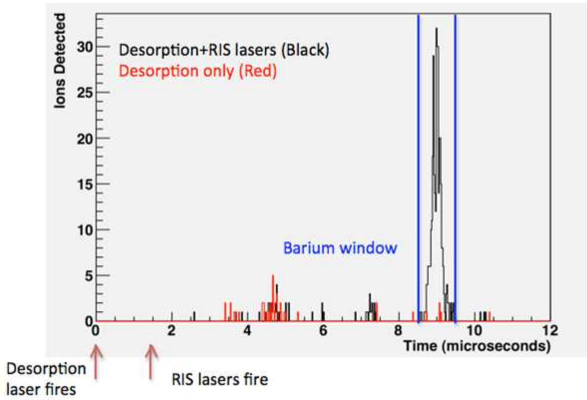

Figure 7. Time of flight spectrum for desorbed ions from a silicon surface with a thin layer of barium. The red curve illustrates the signal when only the desorption laser is employed. When RIS lasers, tuned to barium transitions, are also used then a large number of barium ions is observed as indicated by the black curve.

4.4. In-situ tagging

The collaboration is also exploring the feasibility of in-situ tagging by combining the cryogenic probe concept with in-situ laser irradiation. Spectral broadening effects occur in matter and therefore only a weak fluorescence signal is obtained (weak in respect to resonant light scattering in vacuum). In liquid, tests demonstrated sensitivity to 10^5 barium atoms. Large improvements in the laser intensity and in the efficiency of the fluorescence light collection are needed to reach single atom detection. In gas, EXO is also investigating the possibility of ion transport through a combination of electric drift fields and RF carpets.

5. Conclusion

EXO has finalized the commissioning of EXO-200 and data taking with natural xenon will start in November 2010. The enriched xenon will be used in 2011 for physics runs. The EXO-200 detector will provide valuable data for future phases and hopefully interesting physics results. Various techniques for final state tagging are explored in preparation for the ton-scale detector.

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