^{136}Xe double beta decay observation with EXO–200

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EXO–200 has begun taking data with enriched xenon. Without a fully optimized detector, analysis of a preliminary data set results in the first measurement of ^{136}Xe double beta decay with a half-life of $2.11 \pm 0.04(\text{stat}) \pm 0.21(\text{syst}) \times 10^{21}$ yr.

1 Introduction

The standard model of particle physics (SM) has been experimentally tested to extremely high precision. The first direct evidence that the SM is incomplete has come with the discovery that neutrinos are massive. The study of neutrino properties, therefore, directly probes new physics beyond the SM. Double beta decay can be the dominant decay mode of some even-even nuclei for which the single beta decay is energetically forbidden or highly spin suppressed. This is a SM second order weak process that produces, among other things, two neutrinos ($2\nu\beta\beta$). Should neutrinos be Majorana in nature, double beta decay could proceed without the emission neutrinos ($0\nu\beta\beta$). The observation of this process would require neutrinos to have Majorana masses, which can be related to the $0\nu\beta\beta$ rate, and lepton number conservation would be violated.

$0\nu\beta\beta$ results in a discrete electron sum energy distribution centered at the Q-value. The allowed, yet also rare, two neutrino double beta ($2\nu\beta\beta$) is characterized by a continuous sum energy spectrum ending at the Q-value. The measurement of the electron sum energy therefore distinguishes $0\nu\beta\beta$ from $2\nu\beta\beta$. To experimentally distinguish the different decay modes good energy resolution is needed. The extremely low rate of double beta decay requires the use of very large low background detectors.

A handful of isotopes have already been observed to undergo $2\nu\beta\beta$. One controversial claimed observation of ^{76}Ge $0\nu\beta\beta$ has been made.[1] There are generic arguments to look for $0\nu\beta\beta$ in any number of these isotopes including the large variation in nuclear matrix element calculations (needed to infer Majorana neutrino mass from decay rate measurements) and to verify or refute claimed observations both with the same isotope and others with different Q-values (thereby excluding the possibility that the signal could be the result of a sole unknown or misunderstood source of background). ^{136}Xe, in particular, is relatively easy to enrich, is a noble gas so it is easy to continuously purify, has no long lived isotopes, and has a relatively low rate of $2\nu\beta\beta$ (which had actually not been observed before this result). The Q-value of ^{136}Xe $\beta\beta$, at 2458 keV, is also above the energy of most natural radioactivity. The greatest advantage ^{136}Xe could have over other $0\nu\beta\beta$ candidates is the potential to tag the decay product ^{136}Ba^{++}, making any measurements virtually background free. Only an observation of the $0\nu\beta\beta$ of ^{136}Xe with barium tagging can discover $0\nu\beta\beta$ without later confirmation from a different isotope.

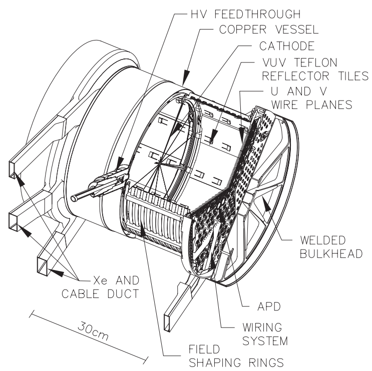

Figure 1: Schematic of the EXO–200 liquid xenon chamber with a cutout of one of the TPCs.

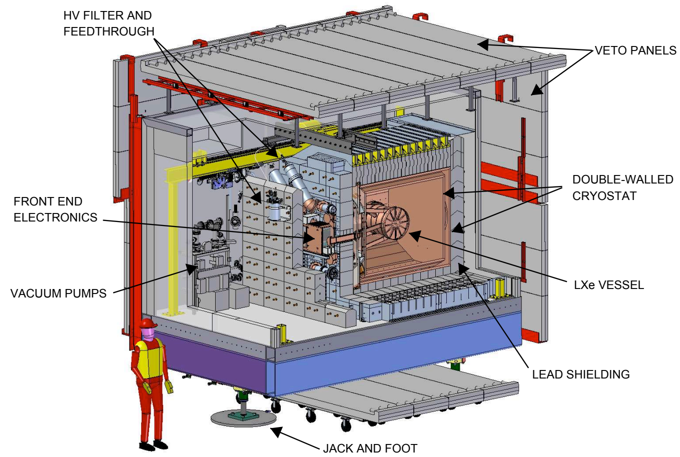

Figure 2: Drawing of the EXO–200 liquid xenon (LXe) vessel with surrounding shielding, clean room, and cosmic-ray veto system.

2 The Enriched Xenon Observatory (EXO)

The EXO Collaboration seeks to observe the $0\nu\beta\beta$ of ^{136}Xe. EXO is currently operating EXO–200 on the 200 kg scale. With a low background and sufficient energy resolution, EXO–200 will test the claimed observation of the $0\nu\beta\beta$ of ^{76}Ge[1], probe Majorana neutrino masses down to $\sim$100 meV, and observe the rare, and until recently unobserved, $2\nu\beta\beta$ of ^{136}Xe. Ultimately, EXO–200 will test the feasibility a larger liquid xenon time projection chamber. A detector containing 2–10 tonnes of xenon enriched to 80% in the $A = 136$ isotope would be sensitive to Majorana neutrino masses well below the inverted hierarchy regime and could probe Majorana neutrino masses down to $\lesssim 20$ meV.

3 EXO–200

Good energy resolution at the decay Q-value and an absolute minimal radioactive background are required to make a significant observation of $2\nu\beta\beta$ or even a significant non-observation of $0\nu\beta\beta$. EXO–200 uses liquid xenon, at a temperature of 167 K and pressure of 147 kPa, as both a source of $\beta\beta$ and as a medium for measuring the summed energy of the decay electrons. This maximizes the efficiency for observing ^{136}Xe $\beta\beta$ while minimizing the detector components that could act as a source of radioactive background.

The liquid xenon is contained within a thin walled cylindrical copper chamber as shown schematically in figure 1. The chamber is instrumented on either end with ~ 250 inward looking large-area avalanche photodiodes (LAAPDs) that are readout in (mostly) groups of 7. Just inside the LAAPDs are two wire grids crossed at a 60° angle[a]. The wires in each plane are separated by 3 mm but readout in groups of three for an equivalent channel separation of 9 mm. All signals are readout in groups to reduce the quantity of signal cables that are a primary source of potential background. A voltage of -8 kV is applied to the cathode plane (parallel to the ends of the chamber) that divides the chamber into two identical time projection chambers (TPCs). Charge deposited in either TPC is drifted to the outer wire plane. Two coordinates of the energy deposition can be reconstructed by the charge collection signal in conjunction with the induced charge signal recorded by the inner shielding grid plane. The third coordinate (the

[a]This angle is set by the angle between the xenon chamber cable ducts which is constrained by the requirement that they also provide structural support for the chamber.

z-coordinate) is reconstructed based on the difference between the arrival of the scintillation light, observed by the LAAPDs, and the first charge, collected on the charge collection wire plane. For the analysis presented in this paper, only the ionization signal, observed by the two sets of wire planes, is used to estimate the energy deposited in the liquid xenon. However, it has been shown by the EXO Collaboration[3] that an appropriate linear combination of the charge and and scintillation light signals can significantly improve the resolution of the energy estimation.

The event topology in the TPCs permits the rejection of cosmic-ray muon and alpha-particle energy depositions from $\beta\beta$. γ-rays produced from radioactive decays can be tagged if interacting in more than one location within the TPCs (MS) whereas $\beta\beta$s are primarily point-like energy depositions (SS)[b] within a single TPC. Beyond event topology, the only manner of reducing radioactive background deposits in the liquid xenon is to minimize its exposure to radiation. This means using a minimal amount of, and as radiopure of, materials in detector construction as possible and employing sufficient low radioactivity shielding of the detector.

All of the components of the detector, from the smallest screws inside the TPCs to the massive lead shielding, have been rigorously tested for radio-purity.[4] The impact of the remaining trace radioactivity, and that due to potential cosmic-ray activation of the copper components of the detector, has been estimated on the signal regions of interest[5] and found to be compatible with both measuring ^{136}Xe $2\nu\beta\beta$ and testing the claimed observation[1] of $0\nu\beta\beta$ with ^{76}Ge. External backgrounds, from the environment surrounding the experiment, are essentially eliminated by: a low background lead shield that is, at its minimum, 25 cm thick; the 5 cm of low background copper that make up the detector cryostat; and at least 50 cm of low background heat transfer fluid (HFE-7000[6]) that provides thermal contact between the inner cryostat wall and the liquid xenon vessel. The last remaining potential source of backgrounds was found to be due to radiation associated with the residual cosmic-ray muon flux, even with EXO–200 being ~ 1600 m.w.e. underground at the Waste Isolation Pilot Plant (WIPP). It has been calculated[5] that a reduction of 90% of cosmic-ray related backgrounds would be compatible with the goals of EXO–200. The tagging of cosmic-ray muons passing through the TPCs is achieved, to better than 95%, by an extensive array of $5 \times 65 \times (315|375)$ cm plastic scintillator panels around the clean room that contains inner detector. The inner detector vessel, cooling system and cryostat, external shielding, and cosmic-ray veto system are all shown in figure 2. A threshold of 720 keV was chosen for this analysis, above which event reconstruction is 100% efficient.

4 First EXO–200 data

Of the 200 kg of enriched xenon, 175 kg resides inside the inner vessel in liquid phase. Only data reconstructed within the inner 63 kg of liquid xenon are presented by this work.[7] Data collected between May 21 and July 9 of 2011 amounts to 752.55 h under optimal noise and background conditions. The primary source of down time during this period was time devoted to daily radioactive source calibrations to monitor the stability of this newly commissioned detector. The energy spectra, showing good agreement with a GEANT4 based detector simulation, of ^{228}Th calibration source data is shown in figure 3. The disagreement between the absolute activity of the calibration sources and that determined by comparing simulation to the radioactive source calibration data is better than $\pm 8\%$.

The electron lifetime (τ_{e}) in the liquid xenon is determined by analysis of such calibration data. After the initial filling of the detector, the τ_{e} rose to $\sim 250\,\mu$s. The electron loss due to the finite τ_{e} is corrected for in the energy estimation. The uncertainty in τ_{e} is considered as a systematic error in the error estimation in subsequent analysis utilizing reconstructed energy.

[b]This is strictly true to within our position reconstruction resolution. However, $\beta\beta$ electrons can deposit energy non-locally due to bremsstrahlung.

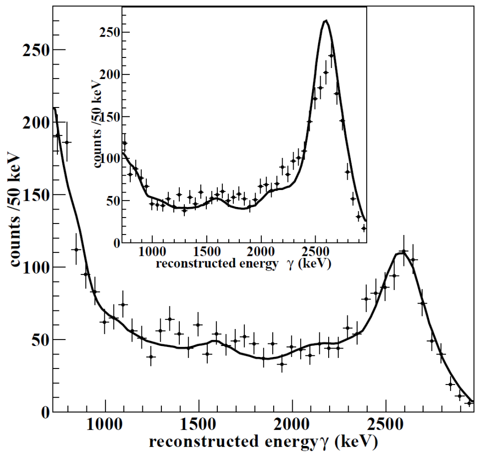

Figure 3: SS and MS (inset) spectra from ^{228}Th calibration data. The intensity of the simulation (the solid lines) is not derived from a fit to the data; the overall scale of the simulated spectrum tests the agreement between the calibration data and the simulation modulo the error on the calibration source activity ($\sim 1\%$).

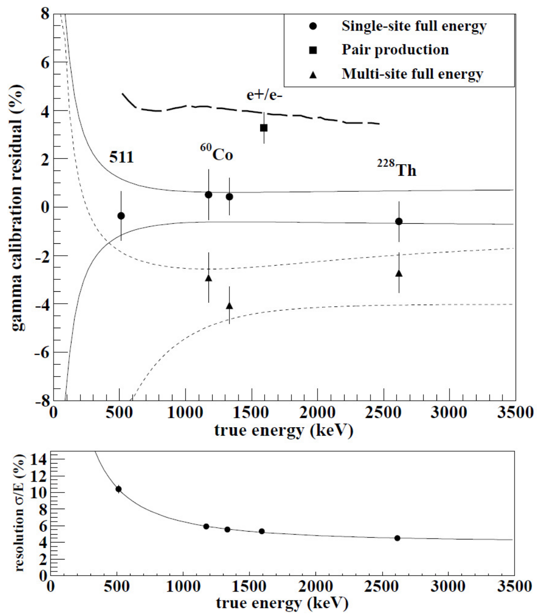

Figure 4: Top: Residual of fully absorbed γ-ray energy for both SS and MS events. The solid and dashed lines represent the systematic errors on the SS and MS energy scales respectively. The long dash line represents the simulations prediction of the shifted energy scale of direct electron energy depositions. Bottom: Measured energy resolution with a parametrization.

The reconstructed energy residual of two ^{60}Co and two ^{228}Th γ-ray full absorption peaks is shown in figure 4. The three highest energy γ-rays each provide a sample of both SS and MS (defined hereafter as two energy depositions separated by $\gtrsim 15$ mm on the charge collection wire plane or by $\gtrsim 17$ mm in z) calibration events. The energy scale of the two event types differs due to the finite energy threshold of single wire channels. e^+e^- pairs created by the highest energy γ-ray deposit 1592 keV of energy in the liquid xenon. This energy deposition is more similar, topologically, to that of $\beta\beta$. This pure sample of electron energy deposition again results in a different energy scale as the ionization of the xenon takes place over a smaller volume than electrons that have interacted with a γ-ray. However, this shift is well reproduced by the simulation. The uncertainty in these energy scale offsets, the remaining discrepancy between calibration data and the simulation, are assigned as systematic errors in the subsequent analysis.

The energy resolution at 2615 keV was measured to be $\sigma_E = 4.5\,\%$ utilizing only the ionization signal. The parametrization of σ_E shown in figure 4 is incoporated into the detector simulation.

Two data selection cuts were applied to this data. Cosmic-ray muon induced backgrounds are rejected from the data set by a 5 ms veto following any veto system trigger. The dead time induced by this cut amounts to only 0.12% of the total live-time. A cut to remove β-particles potentially in coincidence with α-particles, such as those from the decays of/following ^{220}Rn and ^{222}Rn, reduces the live-time by a further 6%. The remaining data is shown as a function of energy, separately for SS and MS events, as the data points in figure 5.

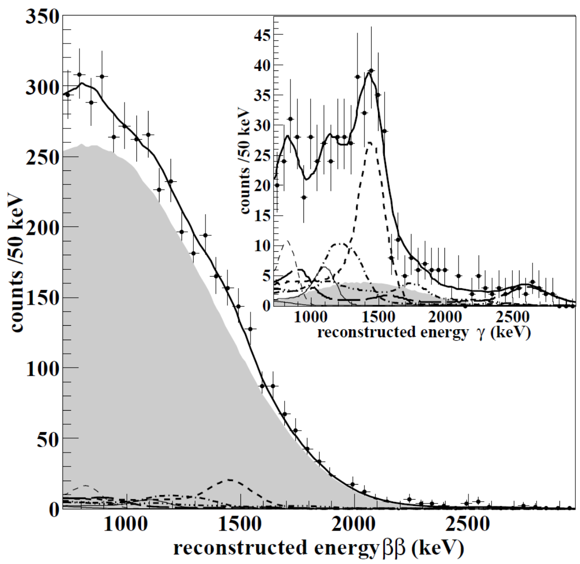

Figure 5: Reconstructed energy of SS and MS (inset) events contained within the data set described in the text. The solid region represents the contribution to the total spectra (data points) of ^{136}Xe $2\nu\beta\beta$ as determined by a maximum likelihood estimator. Prominent background contributions, also included in the fit, include ^{54}Mn (835 keV), ^{65}Zn (1.12 MeV), ^{60}Co (1.17-1.33) MeV, ^{40}K (1.46 MeV), and multiple ^{232}Th and ^{238}U γ-rays consistent with having originated in the copper vessel. The solid line is the fit to the data.

5 Analysis of first EXO–200 data

The detector simulation, with calibrated energy scale and resolution, is used to generate $2\nu\beta\beta$ events[c] and various sources of backgrounds from various detector components as indicated by the exhaustive materials screening. The simulated data is divided into SS and MS spectra to form probability distribution functions (PDFs) for the signal and each of the backgrounds. Using a maximum likelihood estimator, the signal and background PDFs were fit simultaneously to both the SS and MS data sets, the MS data acting as the primary constraint on the low levels (relative to the apparent $2\nu\beta\beta$ signal) of backgrounds in the SS data set. These low levels of residual radioactive contamination in the SS data set are consistent with the materials screening measurements.

α-particle spectroscopy was used to constrain the levels of ^{238}U in the liquid xenon. A decay of ^{238}U eventually leads to the beta decay of ^{234m}Pa that has a Q-value of 2195 keV. The α-particle scintillation spectrum was calibrated with those observed from ^{222}Rn decays in the liquid xenon. The limits on ^{238}U restrict the total number of ^{234m}Pa decays in this data set to < 10 counts. Further, studies of fast neutron production, resulting in neutron capture, and thermal neutron capture in the liquid xenon bound backgrounds from neutron activated xenon to < 10 events in this data set.

The result of the fit is shown in figure 5 as the solid line through the data points with a χ^2 per degree of freedom equal to 85/90. The resulting ^{136}Xe $2\nu\beta\beta$ half-life is $2.11 \pm 0.04(\text{stat}) \pm 0.21(\text{syst}) \times 10^{21}$ yr. The dominant systematic uncertainty contributions arise from fiducial volume (9.3%), event multiplicity (3.0%), energy calibration (1.3%), and γ-ray background model (0.6%) uncertainties. The fiducial volume uncertainty is derived from the disagreement between the measured and simulated calibration source event distributions.

[c]The $2\nu\beta\beta$ events are generated using the Fermi function calculation of Schenter and Vogel.[?]

6 Conclusion

This initial period of data taking by EXO–200, filled with enriched xenon, has produced the first observation of ^{136}Xe $2\nu\beta\beta$. The half-life measured is significantly lower that the previous half-life limits reported by Bernabei *et al.*[8] and Gavriljuk *et al.*[9] and equates to a ^{136}Xe $2\nu\beta\beta$ nuclear matrix element of $0.019\,\mathrm{MeV}^{-1}$ This is the as yet smallest measured among $0\nu\beta\beta$ candidate isotopes.

The background measured within 2σ of $Q_{\beta\beta}$, $4 \times 10^{-3}\,\mathrm{counts\,kg^{-1}yr^{-1}kev^{-1}}$, is already very competitive among $0\nu\beta\beta$ experiments. This is without the lead shielding for the cryostat penetrations, without a blanket of reduced radon air within the lead shielding, without fully three dimensional MS event selection, and with sub-optimal energy resolution. More recent results from EXO–200[10] demonstrate a background rate of only $1.5 \times 10^{-3}\,\mathrm{counts\,kg^{-1}yr^{-1}kev^{-1}}$, primarily through improved reconstruction techniques, and an energy resolution, with the additional information provided by the scintillation yield, at $Q_{\beta\beta}$ of 1.67%. Both of these parameters are already consistent with the design goals of EXO–200 and a projected sensitivity down to a 100 meV Majorana neutrino mass.

Acknowledgments

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