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Search for $2\nu\beta\beta$- and $0\nu\beta\beta$-decay with EXO

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This letter reports on the latest results from the EXO-200 collaboration for the search of the $2\nu\beta\beta$- and $0\nu\beta\beta$-decay of ^{136}Xe, as well as on the Ba tagging R&D program running, aims to improve the background suppression. The collaboration has reported $T_{1/2}^{2\nu\beta\beta}$=(2.172±0.017$_{stat}$±0.060$_{sys}$)×10^{21} years [1], this is the most precisely measured half-life of any $2\nu\beta\beta$ decay. The collaboration has also reported $T_{1/2}^{0\nu\beta\beta} > 1.6\times10^{25}$ years [2], with no claim for signal observation, corresponding to effective Majorana masses of less than 140-380 meV, depending on the specific matrix element calculation considered.

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1. Introduction

Double-beta decay is a rare nuclear decay which occurs in those nuclides with even number of protons and neutrons, where the single beta decay is either energetically forbidden or highly spin suppressed [3]. This decay can proceed via two decay modes, $2\nu\beta\beta$- and $0\nu\beta\beta$-decay. The $2\nu\beta\beta$-decay is allowed in the standard model as a second-order weak process, where the two emitted electrons are accompanied by the emission of two anti-neutrinos. This process has been directly observed in nine isotopes with half-lives ranging between 10^{18} and 10^{21} years [4, 5]. The other decay mode $0\nu\beta\beta$-decay is a hypothetical (beyond the standard model) process, can occur only for massive Majorana neutrinos [6], and has not been observed yet. This decay violates the conservation of the total lepton number and may be mediated by the exchange of a Majorana neutrino or by other new particles. The $0\nu\beta\beta$ decay rate is related to the square of an effective Majorana neutrino mass $\langle m \rangle_{\beta\beta}$ by the product of phase space and a nuclear matrix element square. Kinematic measurements restrict the neutrino mass scale to be below (1 eV) [7], leading to $0\nu\beta\beta$ half-lives beyond 10^{24} years. Recently, GERDA Collaboration [8] has published new lower limit for the $0\nu\beta\beta$-decay in ^{76}Ge, $T_{1/2}^{0\nu\beta\beta} > 2.1\times10^{25}$ years, corresponding to effective neutrino mass $m_{\beta\beta} < 0.2$ - 0.4 eV, with no claim for signal observation. EXO-200 and GERDA results strongly contradict the previous positive signal observation for the $0\nu\beta\beta$-decay in ^{76}Ge claimed by Heidelberg-Moscow experiment [9].

The two decay modes are distinguishable from each other by the energy spectrum of the two released electrons in each case. While in case of $2\nu\beta\beta$-decay the two electrons have energies covering the range from threshold to the Q-value, the $0\nu\beta\beta$-decay shows a peak at the Q-value of the decay. The EXO R&D program aims for the development of an ultra low background experiment by involving a technique for identifying the unique final state $^{136}Ba^{+}$ ion. The Ba ion tagging technique enables complete rejection of the radioactive background [10].

2. EXO-200 Detector

The EXO-200 detector, showed in Fig. 1 and explained in detail in [11], uses xenon both as source and detector for the two electrons emitted in its $\beta\beta$ decay. The detector is a cylindrical homogeneous time projection chamber (TPC). It is filled with liquefied xenon (^{enr}LXe) enriched to (80.672±0.14)% in the isotope ^{136}Xe. The remaining 19.328% is ^{134}Xe, with other isotopes present only at low concentration. EXO-200 is designed to minimize radioactive backgrounds, maximize the (^{enr}LXe) fiducial volume, and provide good energy resolution at the ^{136}Xe Q-value of (2457.83±0.37) keV [12]. Energy depositions in the TPC produce both ionization and scintillation signals. The TPC configuration allows for three-dimensional topological and temporal reconstruction of individual energy depositions. This ability is essential for discriminating $\beta\beta$ decays from residual backgrounds dominated by γs.

The cylindrical TPC is divided into two symmetric volumes separated by a cathode grid. Each end of the TPC is instrumented with 38 charge induction (V) and 38 charge collection (U) wire triplets. The U and V wire grids, crossing at 60°, provide stereoscopic information for charge depositions. At each end of the TPC theres are $\sim$ 250 Large Area Avalanche Photodiodes (LAAPDs) [13]. that record the 178 nm scintillation light. A drift field of 376 V/cm is applied in the TPC volume.

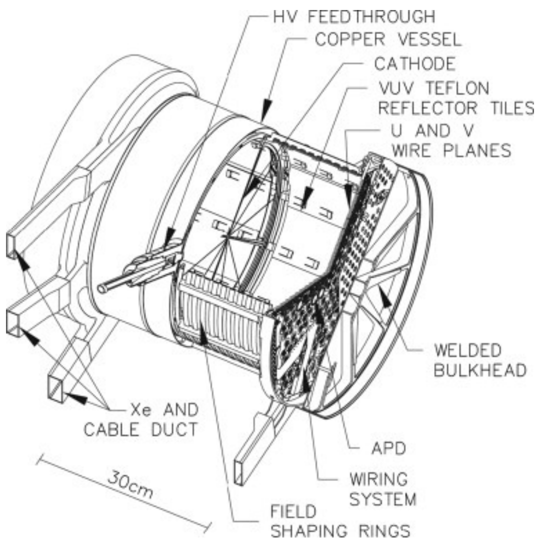

Figure 1: Cutaway view of the EXO-200 TPC.

All signals are digitized at MS/s. All detector components were carefully selected to minimize internal radioactivity. The TPC is placed in the center of a low-background cryostat. The TPC vessel is surrounded by a ≥ 50 cm thick thermal bath of HFE-7000 cryofluid [14], which maintains the temperature of the TPC and which shields the detector from external gamma radiation. The HFE-7000 is housed in a double-walled vacuum-insulated cryostat composed of two nested copper vessels fabricated from low-radioactivity copper plate of 27 mm thickness. The outer cryostat is surrounded in all directions by at least 25 cm of lead. The cryostat features a copper guide tube which allows radioactive sources to be inserted past the lead shield and into the cold HFE volume near the detector. ^{137}Cs, ^{60}Co and ^{228}Th sources of various intensities are available for deployment. The entire assembly is located in a class 100 clean room which is surrounded on four of six sides by a cosmic ray veto system. The veto system consists of twenty-nine 5 cm thick Bicron BC-412 plastic scintillator panels obtained from the concluded KARMEN neutrino experiment [15]. Each panel is observed by eight photomultiplier tubes (PMTs) and is supported by 4 cm of borated polyethylene. The cleanroom is installed underground at the Waste Isolation Pilot Plant near Carlsbad, New Mexico, USA providing 1585 meters water equivalent of over burden [16].

3. Detector Calibration

To optimize the energy resolution of the detector, the microscopic anti-correlation between ionization and scintillation in LXe has been used. Figure 2 shows the energy of events as measured by the ionization and scintillation channels when the ^{228}Th source was deployed. As first discussed in [17] and evident from the tilt of the 2615 keV full absorption ellipse in the figure, the magnitude of the two signals is anticorrelated. The 2D single-site (SS) and multi-site (MS) energy spectra are independently rotated and projected onto a new (1D) energy variable in such a way as to minimize the width of the 2615 keV γ line. Energy spectra from ^{137}Cs, ^{60}Co and ^{228}Th sources are produced using this method and then, the positions of the full absorption peaks at 662, 1173, 1332, and 2615

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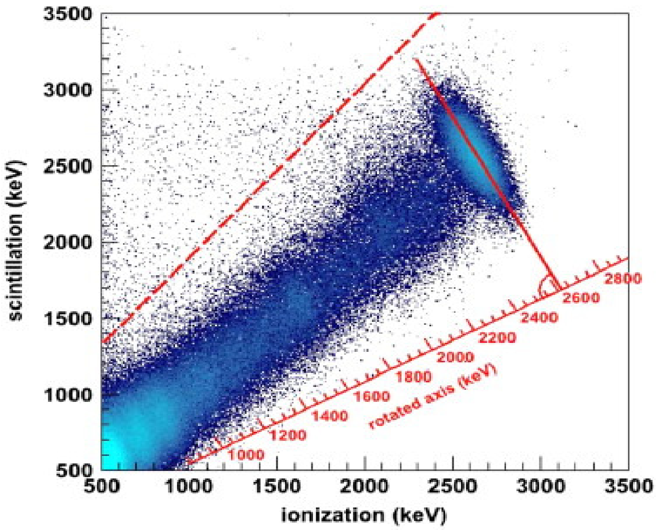

Figure 2: Anti-correlation between ionization and scintillation for SS events from ^{228}Th source.

keV are fitted. The time-averaged energy resolution value at the $\beta\beta$ decay Q value found to be (1.84 $\pm$ 0.03)% and (1.93 $\pm$ 0.05)% for SS and MS events, respectively.

4. Results

4.1 $0\nu\beta\beta$-decay Results

The results presented in this section are from the data collected between September 22, 2011 and April 15, 2012, (Run 2a) for a total of 2896.6 hours live time under low background conditions. The best-fit energy scale for the SS and MS low background spectra is shown in figure 3. Primarily due to the bremsstrahlung, a fraction of the $\beta\beta$ events are MS. The MC predicts that 82.5% of $0\nu\beta\beta$ events are SS. Using a maximum likelihood estimator, the SS and MS spectra are simultaneously fit with PDFs of the $2\nu\beta\beta$ and $0\nu\beta\beta$ of ^{136}Xe along with PDFs of various backgrounds. The resolution at $\pm1\sigma$ and $\pm2\sigma$ regions around $Q_{\beta\beta}$ are shown in the figure too. The number of events in the SS spectrum are 1 and 5, respectively , with the 5 events in the $\pm2\sigma$ region accumulating at both edges of the interval. Therefore, no evidence for the $0\nu\beta\beta$ decay is found. The upper limit on $T^{0\nu\beta\beta}_{1/2}$ is obtained by the profile likelihood fit to the entire SS and MS spectra. Systematic uncertainties are incorporated as constrained nuisance parameters. The fit yields an estimate of 4.1 $\pm$ 0.3 background counts in the $\pm1\sigma$ region, giving an expected background rate of (1.5 $\pm$ 0.1)$\times10^{-3}$ kg^{1-}yr^{-1}keV^{-1}. It also reports $0\nu\beta\beta$ decay limits of < 2.8 counts at 90% CL. This corresponds to a $T^{0\nu\beta\beta}_{1/2} > 1.6 \times 10^{25}$ yr at 90% CL.

4.2 $2\nu\beta\beta$-decay Results

EXO-200 has published its first measurement of the $2\nu\beta\beta$ half-life of ^{136}Xe in [18], with data set collected between May 21, 2011 and July 9, 2011 (Run 1). The data set used in the new $2\nu\beta\beta$ measurement presented here depends on the same data set of the $0\nu\beta\beta$-decay measurements with

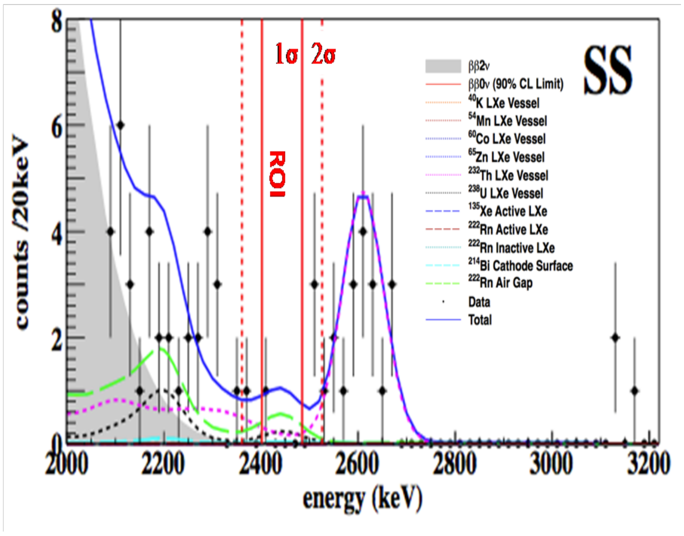

Figure 3: $0\nu\beta\beta$ SS events energy spectra. The best-fit line (solid) is shown. The background components are $2\nu\beta\beta$ (shaded region) and others solid and dashed lines.

some major improvements discussed in [1]. Figure 4 shows the best-fit energy spectrum, data and PDFs for SS events projected onto the energy axes. The best-fit value for the $2\nu\beta\beta$ corresponds to 18984 events above 700 keV. The total error on this value is estimated by performing a profile likelihood scan, yielding a 1σ error of 541 events. the total exposure of ^{136}Xe is 23.14 kg.year and the overall detection efficiency (including the energy spectral cut) for the $2\nu\beta\beta$ events is 57.88%. This with the molar mass of 135.514 g/mol translates into a $2\nu\beta\beta$ half-life of $T_{1/2}^{2\nu\beta\beta}$ = $(2.172 \pm 0.017_{stat} \pm 0.060_{sys}) \times 10^{21}$ years.

4.3 Ba tagging R&D

In order to detect the Ba ion in the $\beta\beta$ final state, its drift properties in the LXe must be investigated. Reliable ion extraction and transport techniques to the tagging apparatus are essential for a practical device. The spectroscopy of the Ba^+ ion is characterized by three atomic levels: a ground level $s_{1/2}$ state, an excited $p_{1/2}$ state and a metastable $d_{3/2}$ state. The s and p states are separated by a 493 nm (blue) transition, while the p and d states are separated by a 650 nm (red) transition. When a Ba^+ ion is illuminated with lasers at these two wavelengths, it rapidly cycles between all three states. The scattering rate can be as large as 10^7 photons/s for a single ion, which is large enough to be seen by naked eyes.

Several techniques are being investigated for an ion collection probe. 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 specifically ionize the Ba atom. The 553.5 nm and 389.7 nm lasers are tuned to Ba 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 (TOF) spectrum of ions ejected by a desorption laser from a silicon surface with a thin Ba layer produced by sputtering. When the RIS lasers are also employed, Ba ions

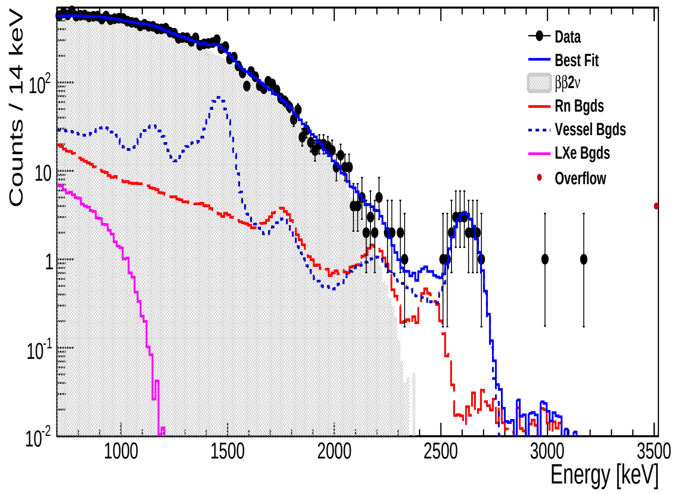

Figure 4: Energy distributions for $2\nu\beta\beta$ single-site events. The result of a likelihood fit to a model including the $2\nu\beta\beta$ decay and several backgrounds is shown (solid and dashed lines) along with the $2\nu\beta\beta$ component (shaded region).

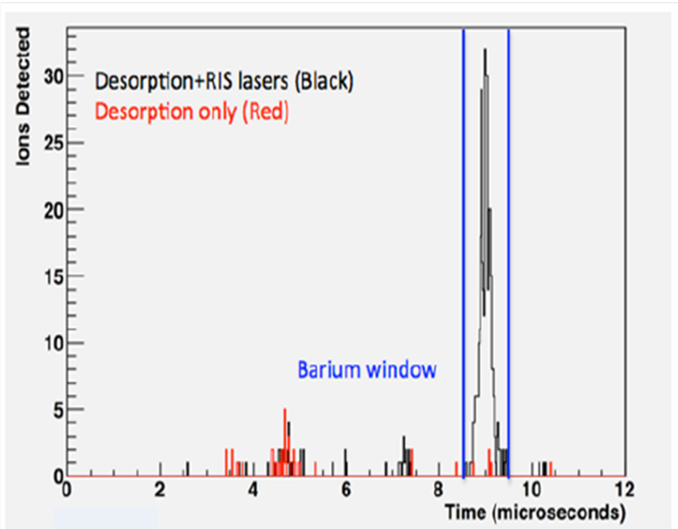

Figure 5: TOF spectrum for desorped ions from a silicon surface with a thin layer of Ba.

greatly dominates the spectrum. Presently, an efficiency of 0.1% has been reached and a significant improvement is expected for the nest generation setup targeting single ion detection.

4.4 Conclusion

EXO-200 has reported on an improved measurements of the $2\nu\beta\beta$ decay of ^{136}Xe using 127.6 days of live-time. This half-life corresponds to a nuclear matrix element of $M^{2\nu}$ = (0.0217 ± 0.0003) MeV^{-1}, the smallest among the isotopes measured to date. EXO-200 also reported on its measurements on $0\nu\beta\beta$ decay of ^{136}Xe with effective Majorana masses of less than 140-380 meV. We also reported on the various R&D efforts for tagging the final state of the ^{136}Xe decay in order to improve the background suppression.

References

[1] J.B. Albert *et al.*, arXiv:1306.6106 (2013).

[2] M. Auger *et al.*, PRL **109**, (2012) 032505.

[3] I. Ogawa *et al.*, J. Phys.: Conf. Ser. **375**, (2012) 042018.

[4] J. beringer *et al.*, (Particle Data Group), Phys. Rev. D **86**, (2012) 010001.

[5] A. Gando *et al.*, (KamLAND-Zen Collaboration), Phys. Rev. C **85**, (2012) 045504.

[6] J. Schechter and J.W.F. Valle, Phys. Rev. D **25**, (1982) 2951.

[7] V.N. Aseev *et al.*, Phys. Rev. D **84**, (2011) 112003.

[8] M. Agostini *et al.*, arXiv:1307.4720 (2013).

[9] H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett. A **21**, (2006) 1547.

[10] M. Danilov *et al.*, Phys. Lett. B **480**, (2000) 12.

[11] M. Auger *et al.*, JINST **7**, (2012) P05010.

[12] M. Redshaw *et al.*, Phys. Rev. Lett. **98**, (2007) 053003.

[13] R. Neilson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **608**, (2009) 68.

[14] 3M, see http://www.3m.com/product/index.htmel.

[15] H. Gemmeke *et al.*, Ncul. Inst. & Meth. A **289**, (1990) 490.

[16] E.-I. Esch *et al.*, Nucl. Inst. & Meth. A **538**, (2005) 516.

[17] E. Conti *et al.*, Phys. Rev. B **68**, (2003) 054201.

[18] N. Ackerman *et al.* (EXO-200 Collaboration), Phys. Rev. Lett. **107**, (2011) 212501.