Observation of \(2\nu\beta\beta\) in \(^{136}\text{Xe}\) with EXO-200

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International workshop on double beta decay and neutrinos
Osaka, November 2011
Overview of the EXO experiment

- **EXO-200** (first phase)
  - 200 kg enriched $^{136}$LXe (80%) TPC
  - Currently operating (as of early 2011) underground
  - Probe Majorana $m_\nu \sim 100$ meV scale
  - Confirm or refute KKDC result
  - Demonstrate feasibility of ton-scale xenon experiment

- **“Full-EXO”** (second phase)
  - 1-10 ton-scale enriched $^{136}$Xe 0$\nu\beta\beta$ experiment
  - Probe Majorana $m_\nu \sim 5\text{-}20$ meV scale
  - R&D effort for “Ba-tagging” of 0$\nu\beta\beta$ daughter nucleus as a means of radioactive background rejection
Advantages of Xenon

- No need to grow crystals
- Can be re-purified during the experiment (noble gas, easy with commercially available systems)
- No long-lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Ba tagging (identification of $^{136}$Ba daughter nucleus)
- $^{136}$Xe enrichment
  - World production of Xe $\sim$ 40 ton/yr
  - Noble gas: easy(er) to enrich
  - Centrifugal process very efficient (feed rate in g/sec, efficiency $\sim \Delta m = 4.7$ amu)
Measuring $0\nu\beta\beta$ with EXO-200

- $e^-$: electrons
- $Xe^+$ and $Xe^*$
- $^{136}\text{Ba}^+$
Measuring $0\nu\beta\beta$ with EXO-200

Ionization electrons

$\text{Xe}^+$ and $\text{Xe}^*$

$^{136}\text{Ba}^+$

Avalanche photodiodes
Measuring $0\nu\beta\beta$ with EXO-200

Avalanche photodiodes

Ionization electrons
- $\text{Xe}^+$ and $\text{Xe}^*$
- $^{136}\text{Ba}^+$
Measuring $0\nu\beta\beta$ with EXO-200

- **Ionization electrons**
- **$\text{Xe}^+$ and $\text{Xe}^*$**
- **$^{136}\text{Ba}^+$**

**Avalanche photodiodes**
Measuring $0\nu\beta\beta$ with EXO-200

Ionization electrons

$Xe^+$ and $Xe^*$

$^{136}\text{Ba}^+$
Measuring 0νββ with EXO-200

Ionization
- e^-
- \( \text{Xe}^+ \) and \( \text{Xe}^* \)
- \( \text{Ba}^{136}^+ \)

Ground -HV Avalanche photodiodes
EXO-200 details

- 175 kg $^{136}$Xe at 80.6% enrichment, liquid phase (167±0.1 K), both source and detector of $0\nu\beta\beta$
- Continuous Xe purification
- 468 Avalanche Photodiodes (LAAPDs) for scintillation light detection (ganged in groups of 7x, 67 total channels)
- 38/38 crossed U/V wire channels per side of TPC for ionization charge detection, 9 mm spacing (152 ch. total)
- Source calibration system allows for multiple miniaturized sources spanning wide energy range at different positions around TPC
- U/V charge signals and relative timing between charge and light give x,y,z event position, energy, PID, etc.
- Sited 2150’ (1600 mwe) underground for shielding
- Muon veto system surrounding cleanrooms (~96% efficiency for $\mu$ traversing Pb)
- TPC surrounded by 50 cm (4 tonnes) HFE7000 cryo/shielding fluid (1.8 g/cm3), 2x 5cm low-activity Cu cryostats, 25 cm Pb
- Extensive program on radiopurity
  - All materials screened for low U/Th/K content
  - Thin walled (~ 1.4 mm) Cu TPC for radio-purity
EXO-200 cryostat and TPC

Outer cryostat

Inner cryostat (filled with 4 tonnes HFE7000)

1.5 m

1.5 m

TPC

Central cathode plane (photoetched phosphor bronze)

Custom Kapton cables for signal readout

Acrylic supports and field shaping rings

Teflon VUV light reflector

APD plane
EXO-200 TPC construction

Signal cabling penetrates TPC and cryostat (no “feedthroughs”)

Cathode

Field shaping rings
EXO-200 TPC construction

Photoetched phosphor bronze U/V wires (9 mm spacing)
EXO-200 TPC construction

- Teflon reflector
- Aluminized APD plane
- Field shaping rings
Large Area Avalanche photodiodes

- Company: Advanced Photonix
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals and metals*)
- Mass ~ 0.5 g/LAAPD
- \( \phi \) 16mm active diameter per LAAPD
- PE yield per photon >1 at 175 nm (NIST)
- Capacitance ~ 200 pF at 1400 V
- V ~ 1500 V, Gain ~ 200
- \( \Delta V < +/- 0.5 \) V
- \( \Delta T < +/- 0.1 \) K (driver for system temperature stability)
- Leakage current of array < 1\( \mu \)A

* Nielson, R. et al., NIM A 608, 1 (2009)
EXO-200 LAAPD installation

LAAPD gang of 7 and cabling

LAAPDs before cabling

Full LAAPD platter
EXO-200 TPC ready for shipment
EXO-200 Installation Site

- EXO-200 installed at WIPP (Waste Isolation Pilot Plant) in Carlsbad, NM
- 1600 mwe (2150-ft, 650m)
- Salt mine for radioactive waste storage
- Salt “rock” low activity relative to hard-rock mine

\[ \Phi_\mu \sim 1.5 \times 10^5 \text{ yr}^{-1} m^{-2} sr^{-1} \]

\[ U \sim 0.048 \text{ ppm} \]

\[ Th \sim 0.25 \text{ ppm} \]

\[ K \sim 480 \text{ ppm} \]

Completed EXO-200 facility at WIPP (2150’ underground)

6 modular cleanrooms
VIEW INSIDE EXO-200 PRIMARY CLEANROOM MODULE
(without front Pb walls)

- Cathode HV
- Pb shielding
- Xenon inlet
- Cryostat + TPC (inside)
- Xenon outlet
- DAQ electronics
Reach of EXO-200 and the future Full EXO experiment

Assumptions:

Majorana neutrinos
Running configuration for spring 2011 2νββ analysis

- Drift field $E = -376 \text{ V/cm}$
- ~ 31 live days
- Source calibration ~ 2 hrs each day ($^{60}\text{Co}$, $^{228}\text{Th}$, multiple locations) for to monitor purity, resolution, calibration, other detector effects
- Continuous Xe recirculation through SAES purifiers at ~ 5 SLPM, LXe purity ~ 210-280 $\mu$s (max drift time ~ 110 $\mu$s)
- Conservative fiducial volume ~ 63 kg chosen for first analysis
Spring 2011 2νββ analysis details

- Developed GEANT4 MC of EXO-200 (including geometry, signal generation, digitization, etc.); agrees well with source calibration

- Use charge + scintillation for event position reconstruction and PID

- Detector energy calibration with radioactive sources (511, 1173, 1333, 1593, 2615 keV)

- Charge signal corrected for Xe purity, monitored daily

- Muons (0.12% dead-time) and ²²⁰Rn events (6.3% dead-time) removed with cuts

- α spectroscopy used to bound ²³⁸U in LXe (daughter ²³⁴mPa β-decay with 2195 keV endpoint)

- 720 keV energy analysis threshold, (includes ~ 65% of 2νββ spectrum)

- Large library of PDFs (natural radioactivity, cosmogenics, exotics) generated for spectral fitting

- Use charge energy spectrum only for fitting (currently optimizing combined ionization + scintillation energy resolution)

- Final signal extraction: simultaneous fit of single and multiple cluster spectra to PDFs
Muon passing through TPC

Induction “V” grids

TPC1

TPC2

Collection “U” grids

Collection signals

Induction signals

FIFO event buffer

Trigger

Wire channel number

Cathode plane

Cathode
Rn identification in LXe

α: strong light signal, weak charge signal
β: weak light signal, strong charge signal

Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector. The $^{214}$Bi decay rate is consistent with measurements from alpha-spectroscopy and the expectation before the Rn trap is commissioned.
Rn identification in LXe

Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector. The $^{214}\text{Bi}$ decay rate is consistent with measurements from alpha-spectroscopy and the expectation before the Rn trap is commissioned.
Source calibration in EXO-200

Various calibration sources can be brought to several positions just outside the detector.

x-y distribution of events clearly shows excess near the source location.

Sources: $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{228}\text{Th}$
Example: 228Th energy calibration

- Calibration runs compared to simulation
  - GEANT4 based simulation
  - charge propagation
  - scintillation propagation
  - signal generation
  - energy resolution parameterization is added in after the fact
- There are no free parameters for these comparisons (worst agreement is +8%)
Energy calibration from pair production events from $^{228}\text{Th}$ source

- Identifying 3-site events from pair-production and annihilation provides 2 extra charge calibration peaks
  - 511 keV gammas are our lowest energy calibration sources
  - 1592 keV pair production very similar topology to $\beta\beta$ decays
Xenon purity monitoring with calibration sources

- Use sources to measure purity of LXe in TPC
- Rapid achievement of ms lifetimes results is a clear benefit of recirculation.

maximum drift time $\sim 100\ \mu s$
Energy calibration for charge-only $2\nu\beta\beta$ analysis

- After purity correction, calibrated single and multiple cluster peaks across energy region of interest (511 to 2615 keV)
  - uncertainty bands are systematic
- Point-like depositions have large reconstructed energies due to induction effects
  - observed for pair-production site (similar to $\beta$ and $\beta\beta$ decays)
  - reproduced in simulation
- Peak widths also recorded and their dependence on energy is parameterized.
Event reconstruction threshold

• Events $> 100$ keV well above charge trigger and reconstruction thresholds

• 3D reconstruction still requires determination of $t_0$ from scintillation signal

• Compare ratio of fully reconstructed events to triggered events to determine reconstruction efficiency

• Early software threshold $\sim 700$ keV

• Recent dramatic decrease with change in APD bias voltages $\sim 300$ keV

Scintillation threshold curve after APD gain change

Scintillation threshold curve for spring 2011 2νββ run

APD Reconstruction efficiency

gain 100

LAAPD gain 200

energy (keV)
• Investigate alpha spectrum for scintillation signals from $^{238}\text{U}$
• Calibrate spectrum with alphas in Rn chain
• Can constrain contamination of $^{238}\text{U}$ in bulk LXe by searching for 4.5 MeV alphas < 0.3 counts per day in our fiducial volume
  - The same limit applies to its daughter $^{234}\text{mPa}$ which $\beta$ decays with a Q-value of 2195 keV, which cannot then explain our LXe bulk signal
Measurement of $2\nu\beta\beta$ with EXO-200

- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1
  - as good as 40:1 for some extreme fiducial volume cuts

$T_{1/2} = 2.11 \cdot 10^{21}$ yr ($\pm 0.04$ stat) yr ($\pm 0.21$ sys) [arXiv:1108.4193]
Low background spectra

- constant in time
- $2\nu\beta\beta$ signal is clearly in the LXe bulk, while other gamma background contributions decrease with increasing distance from the walls.

Total background rate in $0\nu\beta\beta$ window < $4\times10^{-3}$ cts/kg/yr/keV

- Backgrounds will further improve from
  - Rn tent installation
  - Closing of front outer Pb shield
  - Improvements in multicluster rejection
Systematic error budget for spring 2011 $2\nu\beta\beta$ analysis

\[ T_{1/2}^{2\nu\beta\beta} = 2.11 \times 10^{21} \text{ yr (± 0.04 stat) (± 0.21 sys)} \]

- Fiducial volume 9.3%
- Multiplicity assignment 3.0%
- Energy calibration 1.8%
- Background models 0.6%
- Working hard to reduce these for upcoming analyses
CURRENT CONFIGURATION (NOVEMBER 2011)

Rn tent

Front Pb wall
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