Status and Results from EXO-200

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DPF 2013
**Neutrinoless Double Beta Decay**

**2νββ**: 2nd order process, only observable when single beta decay is highly suppressed. EXO-200 first to see in $^{136}\text{Xe}$

**0νββ**: SM-forbidden process
Possible New Physics

Observation of $0\nu\beta\beta$ would imply new physics concerning:

- *Majorana nature of neutrinos*
- *Neutrino mass scale*
- *Lepton number conservation*
Advantages of $^{136}\text{Xe}$

Xenon isotopic enrichment is easier. Xenon is a gas & $^{136}\text{Xe}$ is the heaviest isotope.

Xenon is “reusable”. Can be repurified & recycled into new detector.

Large monolithic detector. LXe is self shielding, rejection of Compton scatterings.

Minimal cosmogenic activation. No long lived radioactive isotopes of Xe.

Energy resolution in LXe can be improved. Scintillation light/ionization correlation.

… admits a novel coincidence technique. Background reduction by barium daughter tagging.
Goals of EXO-200

• Use Time-Projection Chamber (TPC) detector, filled with 200 kg LXe, 80.6% enriched

• Observe $2\nu\beta\beta$ in $^{136}\text{Xe}$

• Probe majorana mass range of 100-200 meV

• Demonstrate feasibility of a ton-scale experiment
University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke
California Institute of Technology, Pasadena CA, USA - P. Vogel
Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., N. Kaufhold, T. Walton
Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith
University of Illinois, Urbana-Champaign IL, USA - D. Beck, J. Walton, M. Tarka, L. Yang
IHEP Beijing, People’s Republic of China - G. Cao, X. Jiang, Y. Zhao
Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman
University of California, Irvine, Irvine CA, USA - M. Moe
Laurentian University, Sudbury ON, Canada - E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, B. Mong, U. Wichoski
University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen
University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, M. Lodato, C. MacDowell, K. Malone, A. Pocar, J.D. Wright
University of Seoul, South Korea - D. Leonard
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino
EXO-200 Detector

- Two TPCs with common cathode in middle
- APD planes observe prompt scintillation for drift time measurement.
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.
Anti-Correlation (Ioniz. vs Scint.)

Resolution:
- Scintillation: 6.8%
- Ionization: 3.4%
- Rotated: 1.6%
  (at 2615 keV γ line)
EXO-200 is installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM

- 1600 mwe flat overburden (2150 feet, 650 m)
- U.S. DOE salt mine for radioactive waste storage
- Salt rock low activity relative to hard-rock mine
EXO-200 Running

<table>
<thead>
<tr>
<th>Run</th>
<th>Period</th>
<th>Live Time</th>
<th>Exposure</th>
<th>Publ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>May 21, 11 – Jul 9, 11</td>
<td>752.7 hr</td>
<td>3.2 kg-yr</td>
<td>PRL 107 (2011) 212501</td>
</tr>
<tr>
<td>Run 2a</td>
<td>Sep 22, 11 – Apr 15, 12</td>
<td>2896.6 hr</td>
<td>32.5 kg-yr</td>
<td>PRL 109 (2012) 032505</td>
</tr>
<tr>
<td>Run 2a (this analysis)</td>
<td>Sep 22, 11 – Apr 15, 12</td>
<td>3062.4 hr</td>
<td>23.14 kg-yr</td>
<td>arXiv:1306.6106 (Jun 2013)</td>
</tr>
</tbody>
</table>

- Review previous two results
- Improvements made for this 2013 analysis
- Precision 2νββ measurement
First observation of the $2\nu\beta\beta$ decay in $^{136}$Xe

With first 31 live-days of data:

$$T_{1/2} = (2.11 \pm 0.04\, \text{stat} \pm 0.21\, \text{sys}) \cdot 10^{21}\, \text{yr}$$


The slowest physics process ever directly observed in nature

Later confirmed by KamLAND-Zen

$$T_{1/2} = (2.38 \pm 0.02\, \text{stat} \pm 0.14\, \text{sys}) \cdot 10^{21}\, \text{yr}$$

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$

Interpret as lepton number violating process with effective Maroijana mass $\langle m_{\beta\beta} \rangle$:

$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G^{0\nu} |M_{nucl}|^2 \langle m_{\beta\beta} \rangle^2$$

$T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{25} \text{ yr}$

$\langle m_{\beta\beta} \rangle < 140–380 \text{ meV (90\% C.L.)}$


KamLAND-ZEN
Background counts in $\pm 1,2 \sigma$ ROI

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected events from fit $\pm 1 \sigma$</th>
<th>Expected events from fit $\pm 2 \sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn in cryostat air-gap</td>
<td>1.9 $\pm$ 0.2 2.9 $\pm$ 0.3</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U in LXe Vessel</td>
<td>0.9 $\pm$ 0.2 1.3 $\pm$ 0.3</td>
<td></td>
</tr>
<tr>
<td>$^{232}$Th in LXe Vessel</td>
<td>0.9 $\pm$ 0.1 2.9 $\pm$ 0.3</td>
<td></td>
</tr>
<tr>
<td>$^{214}$Bi on Cathode</td>
<td>0.2 $\pm$ 0.01 0.3 $\pm$ 0.02</td>
<td></td>
</tr>
<tr>
<td>All Others</td>
<td>~0.2</td>
<td>~0.2</td>
</tr>
<tr>
<td>Total</td>
<td>4.1 $\pm$ 0.3 7.5 $\pm$ 0.5</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Background index (kg$^{-1}$yr$^{-1}$keV$^{-1}$)</td>
<td>$1.5 \cdot 10^{-3} \pm 0.1$</td>
<td>$1.4 \cdot 10^{-3} \pm 0.1$</td>
</tr>
</tbody>
</table>

EXO-200 goal:

40 cnts/2y in $\pm 2\sigma$ ROI, 140 kg LXe

In this data 120 days, 98.5 kg: 4.6

Expected from the fit: 7.5
Observed: 5

Background within expectation
Since then

• **Improved event reconstruction**

• **Improved and more detailed**(geometry) **Monte Carlo simulations**

• **More precise detector response calibration**

• **And other improvements**
Induction Signals

- Identify Induction Signals on Collection Wires
- Mistakenly reconstructing as collection leads to SS/MS misclassification
- 77% induction rejection, with 99.9% collection efficiency

Fit to Induction and Collection Signal Models
Corrections

Optimal rotation angle measured weekly

New iterative approach developed to extract energy resolution curve

Time-averaged energy resolution used for final LB fit
Source Agreement

Improved MC and event reconstruction

- Source rate agreement to within 4% (9.4% in 0νββ analysis)
- Excellent spectral shape agreement
- Sufficient SS/MS agreement

![Graphs showing energy spectra for ²²⁸Th and ⁶⁰Co](image)
Fiducial Volume

Previous analysis: 79.4 kg of $^{136}$Xe
This analysis: 66.2 kg of $^{136}$Xe

2νββ analysis is systematics-dominated

Chose smaller fiducial volume where detector response is better understood
Decrease related systematic uncertainties
Fiducial Volume Cut

Hexagonal cut in U,V based on:
• $2\nu\beta\beta$ rate vs apothem

Z cut based on:
• Field non-uniformity near cathode

• Grid-efficiency correction due to V-Wire plane
Standoff Fits

Previously: simultaneously fit SS and MS event datasets using energy PDFs

Now: added Standoff Distance as an additional fit dimension (PDFs are 2D, energy and standoff)

Energy-only LB fit returns 2.4% less 2νββ counts than reported result

SD improves background estimates (bkgd contribution on total error: 1.2% -> 0.83%)
Improved Measurement of $T_{1/2}^{2\nu\beta\beta}$

$$T_{1/2}^{2\nu\beta\beta} = \left( 2.172 \pm 0.017 \text{(stat)} \pm 0.060 \text{(sys)} \right) \cdot 10^{21} \text{ years}$$

Total relative uncertainty: 2.85%

Improved analysis of $T_{1/2}^{2\nu\beta\beta}$ submitted to PRC (arxiv:1306.6106)
This result is the most precisely measured half-life of any 2νββ decay process to date.
Looking Forward

- For the future $0\nu\beta\beta$ result, will have $\sim 3x$ more data
- Further electronics upgrades
- Deradonator to remove $^{222}\text{Rn}$ from air around cryostat

R&D for nEXO, proposed ton-scale successor of EXO-200