A search for neutrinoless double beta decay with EXO-200
Outline

• Neutrinos and Double Beta Decay
• EXO-200 Detector
• Calibrations and corrections
• Background cuts
• Physics data and results
What we know about neutrinos
What we don’t know

• Majorana nature
  – Is neutrino its own antiparticle?
• Absolute mass scale
• Mass hierarchy
  – Normal or inverted
• CP violating phase
• (Unknown unknowns)

Neutrinoless double beta decay can help answer these
Double beta decay

If first-order beta decay is forbidden energetically or by spin, second-order double beta decay can be observed.
Two modes of double beta decay

Two neutrino mode:
- Standard model process
- Second order

Neutrinoless mode:
- Hypothetical process
- Can only happen if:
  - neutrino has nonzero mass
  - neutrino is its own antiparticle
  - Total lepton number violating
Double beta decay spectrum

The two modes can be distinguished by their energy spectra in a detector with good energy resolution.

Q for $^{136}$Xe is 2458 keV
Neutrinoless mode and mass

\[ \langle m_\nu \rangle^2 = \left( T_{1/2}^{0\nu\beta\beta} G_{0\nu\beta\beta}(E_0, Z) | M_{0\nu\beta\beta} |^2 \right)^{-1} \]

- Effective Majorana mass
- Matrix element (can be calculated with various models)
- Phase space factor (known)
- To be measured

\[ \langle m_\nu \rangle = \sum_i U_{ei}^2 m_i \varepsilon_i \]
Experimental sensitivity

$S_{m_{\beta\beta}} \propto \left( \frac{A}{\epsilon a} \right)^{1/2} \left( \frac{B \Gamma}{MT} \right)^{1/4}$

- $\epsilon$ is efficiency
- $a$ is isotopic abundance
- $A$ is atomic mass
- $M$ is source mass
- $T$ is time
- $B$ is background
- $\Gamma$ is resolution

- To maximize sensitivity
  - Xenon enriched to 80.6% in isotope 136
  - Large mass (98.5 kg fiducial)
  - Low background construction$^\dagger$
  - Makes use of both ionization and scintillation signals to optimize energy resolution$^\ddagger$

### Previous experimental limits

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$0\nu\beta\beta$ half life ($\times 10^{22}$ years)</th>
<th>Experiment</th>
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The EXO-200 Time Projection Chamber (TPC) consists of 2 modules with a common cathode. Large Area Avalanche Photodiodes (LAAPDS) (~200 per side) observe prompt scintillation for energy and longitudinal position (from drift time). Crossed wire grids observe charge signal:
- V wires (induction) (38 triplets per side) for transverse position
- U wires (collection) (38 triplets per side) for transverse position and energy
EXO-200 TPC (half of it)

- Teflon Reflectors (increase light collection)
- APD plane and wire planes (wires are photo-etched)
- Central HV plane (photo-etched phosphor bronze)
- Acrylic supports and field shaping rings
- Kapton flex cables (spring connections eliminate solder joints and glue)

Dimensions:
- 40 cm
- 20 cm (half)
EXO-200 Installation

HFE 7000 fluid provides thermal bath and radiation shielding

Enr LXe: 80.6% $^{136}$Xe
$T = 167$ K
$P = 147$ kPa
$\rho = 3.0$ g/cm$^3$

LEAD SHIELDING
25 cm

M. Auger et al. JINST 7 (2012) P05010
[arXiv: 1202.2192]
EXO-200 at WIPP

The US Department of Energy disposes of nuclear waste at the Waste Isolation Pilot Plant, located SE of Carlsbad, NM

2150 ft depth provides ~1600 m water equivalent shielding

Salt walls are naturally low in uranium, thorium (< 100 ppb)

Radon in air < 10 Bq/m³
EXO-200 History

• Late 2010
  – Engineering run with natural Xe
• May 2011 – July 2011 “2νββ Run”
  – First run with enriched Xe
  – First measurement of 2νββ in $^{136}$Xe
  – 5.4 kg yr exposure (4.4 kg isotope 136)
• August 2011 – September 2011
  – Install final lead shielding
  – Electronics and other upgrades
• October 2011 – March 2012 “Run 2”
  – Data taken for this analysis
  – 32.6 kg yr exposure (26.3 kg isotope 136)
A copper guide tube around the outside of the TPC allows radioactive sources to be deployed to predetermined locations around the TPC.

We use $^{228}\text{Th}$ (2615 keV), $^{60}\text{Co}$ (1173 and 1333 keV), and $^{137}\text{Cs}$ (662 keV) gamma ray sources.
Triggering

• For physics data:
  – Can trigger on
    • Sum APD signal
    • Individual APD signal
    • Sum collection wire signal
    • Individual collection wire signal

• A frame of ±1024 µs is saved around every trigger
A single-site event in EXO-200

- Scintillation signal
  - Observed in both sides (but more localized in side 2)
  - Precedes ionization signal
- Ionization signal
  - Observed on both wire planes in side 2
A two-site Compton scattering event

- All scintillation light arrives at a single time, indicating the two energy depositions were simultaneous
- Two separate ionization signals visible in side 2
Event reconstruction

- Stages are roughly:
  - Signal finding with matched filters on U, V, APD signals
  - Extract energies and times for found signals, applying channel-based corrections
  - Assign signals to clusters
    - Single Site (SS) or Multiple Site (MS)
    - Can distinguish clusters ~6 mm in z dimension, ~18 mm in u dimension
  - Apply position-based corrections
  - Apply calibrations

- Reconstruction efficiency for $0\nu\beta\beta$ is 71%. This is estimated with Monte Carlo simulations and verified by comparing the MC estimated efficiency for $2\nu\beta\beta$ with data over a broad energy range
Electron Lifetime Corrections

Electron lifetime correction

~3 ms electron lifetime (110 μs maximum drift time means 4% effect)

Electronegative impurities cause exponential attenuation of ionization. Measuring this attenuation with full-absorption peaks from gamma ray sources allows us to correct for it.

Xenon gas is circulated through a heated zirconium getter using a custom-built ultraclean pump†. For this analysis, the recirculation rate was increased to 14 slpm, leading to long electron lifetimes in the TPC.

† Rev Sci Instrum. 2011 Oct;82(10):105114
Wire Gain Corrections

- Use 1593 keV pair production events from $^{228}$Th to measure collection wire transfer functions and gains.
Light Response Correction

Use full absorption peak of 2615 keV gamma from $^{228}$Th to map light response in TPC

Linearly interpolate between 1352 voxels

Gap between teflon reflector and APD plane
Combining Ionization and Scintillation

Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)†


Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(σ/E at 2615 keV gamma line)

Use projection onto a rotated axis to determine event energy
Calibration Process

• Use 2615 keV gamma line to determine optimal angle independently for SS and MS events

• Combine scintillation and ionization using these angles for all gamma lines

• Fit to peak energies and apply calibration

\[ E_{\text{true}} = a + bE_{\text{reconstructed}} + cE_{\text{reconstructed}}^2 \]

• Residuals given by

\[ \text{residual} = \frac{E_{\text{fit}} - E_{\text{true}}}{E_{\text{true}}} \]

• Parameterize resolution

\[ \sigma_{\text{tot}}^2 = a\sigma^2_{\text{noise}} + b\sigma^2_{\text{stat}} + c\sigma^2_{\text{drift}} \]

\[ \sigma_{\text{tot}}^2 = (w\sigma_{\text{elec}})^2 + \left(\sqrt{w}\sqrt{F} \sqrt{E}\right)^2 + (kE)^2 \]
Calibration

- After correction and applying a quadratic calibration, residuals are less than 0.1%

Energy resolution at Q value:
- 1.67% (σ/E) SS
- 1.84% (σ/E) MS
Spectral Shape Agreement – $^{228}$Th

- Fraction of single site events agrees with simulation to within 8.5%
- Absolute source activity agrees to within 9.4%
Spectral Shape Agreement – $^{60}$Co

- Fraction of single site events agrees with simulation to within 8.5%
- Absolute source activity agrees to within 9.4%
Simulating spectra for PDFs

- Use a GEANT4 simulation of detector (and surroundings) to simulate
  - Signals (2νββ, 0νββ)
  - a variety of backgrounds (uranium, thorium, radon, etc.)
  - in various locations (TPC vessel, dissolved in liquid, outside of cryostat)
- Use the energy deposition information to form single-site and multi-site PDFs
- These are smeared according to the energy resolution, but not until the final stage of fitting
Fiducial Volume

Circular & Hexagonal volumes

Standoff distance 20 mm Measured from Teflon wall to hexagon

In z dimension, 5 mm < |z| < 182 mm

5 mm from cathode
10 mm from wire plane
Cosmic ray muons in the TPC

- Cosmic rays can create short-lived isotopes that have high energy gamma or beta decays
- Cosmic ray muons can be identified by the distinctive tracks they leave in the TPC
  - Cut all events within 60 s of a tagged muon in the TPC
- The muon veto panels that surround the clean rooms also have 96% efficiency at detecting muons that could pass through the TPC
  - Cut all events within 25 ms of a panel hit
Physics 2D data diagonal cut

\[ \alpha \text{ particles are highly ionizing, which leads to more scintillation} \]

Small population of events with imperfect charge collection

Cut Region
Bismuth Polonium Coincidences

\[ ^{214}\text{Bi} \text{ decays are followed by } ^{214}\text{Po} \text{ decays} \]

- Cut any events that are within 1 s of another event (this also eliminates other potential coincident backgrounds)

\[ \alpha: \text{ strong light signal, weak charge signal} \]
\[ \beta: \text{ weak light signal, strong charge signal} \]
Radon dissolved in the Xe

\[ {^{222}\text{Rn}} \text{ atoms in xenon} \]

\[ T_{1/2} = 3.8 \text{ d} \]

4.5 \(\mu\text{Bq kg}^{-1}\)

\(~1\text{ per hour}\)

- \( {^{214}\text{Bi}} \) rate is consistent with a steady state source of radon in the system (no radon trap installed)
  - \(360 \pm 65 \mu\text{Bq/kg}\) in fiducial volume
Physics data 2D spectrum

- After all cuts, this is our spectrum
Physics data rotated spectrum

- Trigger fully efficient above 700 keV
- Low background live time: **120.7 days**
  - Total dead time due to vetoes: 8.6%
- Active mass: **98.5 kg**
  - (79.4 $^{136}$Xe)
- Exposure: **32.6 kg yr**
  - (26.3 $^{136}$Xe)
- Simultaneous fit to signal and background for SS and MS events

$$T_{1/2}^{2
u\beta\beta \ (^{136}\text{Xe})} = (2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys}) \cdot 10^{21} \text{ yr}$$

(In agreement with previously reported value by EXO-200 and KamLAND-ZEN collaborations)
\[ T_{1/2}^{2\nu\beta\beta} (^{136}\text{Xe}) = (2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys}) \cdot 10^{21} \text{ yr} \]

(In agreement with previously reported value by EXO-200 and KamLAND-ZEN collaborations)
Low background around Q value

- No signal observed
- Background in ±1σ ROI (from fit):
  \[ 1.5 \times 10^{-3} \pm 0.1 \text{ kg}^{-1}\text{yr}^{-1}\text{keV}^{-1} \]
- Profile likelihood study to extract limits for \( T_{1/2}^{0\nu\beta\beta} \)

\[ T_{1/2}^{0\nu\beta\beta} (^{136}\text{Xe}) > 1.6 \times 10^{25} \text{ yr (90\% C.L.)} \] [arXiv:1205.5608]
Backgrounds in ± 1σ ROI

Zoomed around 0νββ region of interest (ROI)

Observe 1 count expect from fit:

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<td>±0.1</td>
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<tr>
<td>$^{214}$Bi on Cathode</td>
<td>0.2</td>
<td>±0.01</td>
</tr>
<tr>
<td>All Others</td>
<td>~0.2</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4.1</td>
<td>±0.3</td>
</tr>
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$1.5 \cdot 10^{-3} \pm 0.1 \text{ kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$ in ± 1σ ROI
Systematic Error Breakdown

- Bars show the expected 90% confidence limit if we assume perfect knowledge of parameters that contribute to systematic errors.
Sensitivity

- Given our estimated background, we expect a 90% CL on $T_{1/2}$ of $1.6 \times 10^{25}$ years or better $6.5\%$ of the time.
- We would quote a 90% CL upper limit of $7 \times 10^{24}$ years or better $50\%$ of the time.
## New experimental limit

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‡[arXiv:1205.5608]
Graphical Comparison

- The EXO-200 90% CL is a factor of 2.5 improvement over the KamLAND-Zen limit
- EXO-200 CL contradicts the claim of discovery in $^{76}$Ge by a subset of the Heidelberg-Moscow collaboration for most (all) nuclear models at the 90% (68%) confidence level

$m_\nu < 140-380$ meV
EXO-200 Limit

- EXO-200 will explore deeper into the degenerate hierarchy with continued operation
Future Plans and Improvements

Better APD gain calibration through laser pulser

Other energy resolution improvements

\[ S_{m_{\beta\beta}} \propto \left( \frac{A}{\varepsilon \alpha} \right)^{1/2} \left( \frac{B \Gamma}{M T} \right)^{1/4} \]

Radon purge for air gap between lead wall and cryostat (this is half of our background in the ROI)

Further background reduction through improved multiplicity assignment

This analysis uses ~7 months of data

So continue running
Conclusions

• EXO-200 has completed its first low background run in search of $0\nu\beta\beta$

• Energy resolution $\sigma/E = 1.67\%$ at $Q_{\beta\beta}$

• Low background rate

\[ b = (1.5 \pm 0.1) \cdot 10^{-3} \text{kg}^{-1}\text{yr}^{-1}\text{keV}^{-1} \]

• Confirmed measurement of $2\nu\beta\beta$

\[ T_{1/2}^{2\nu\beta\beta} = 2.23 \times 10^{21} \pm 0.017\text{(stat.)}\pm 0.22\text{(sys.)} \]

• Lower limit on $0\nu\beta\beta$

\[ T_{1/2}^{0\nu\beta\beta}\bigg|_{90\%CL} > 1.6 \times 10^{25} \text{yr} \]

• And upper limit on Majorana mass

\[ \langle m_\nu \rangle\bigg|_{90\%CL} < 140 - 380\text{meV} \]
The EXO Collaboration

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Backup: Detector Photos

- APDs
- Teflon reflector
- Field shaping rings
- Cathode
- Signal cables
- Charge detection wires

2012-06-12
Backup: Rates vs Fiducial Cuts

- Measured $2\nu\beta\beta$ rate does not change with choice of fiducial volume
- Rates of backgrounds gammas are less deeper inside the detector
Backup: Spatial Distribution

- Events within $\pm 1 \sigma$
- Events within $\pm (1-2) \sigma$
Backup: Backgrounds in ±2σ ROI

Zoomed around 0νββ region of interest (ROI)

Observe 5 counts expect from fit:

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<th>Source</th>
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<td>0.3</td>
<td>±0.02</td>
</tr>
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<td>~0.2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7.5</td>
<td>±0.5</td>
</tr>
</tbody>
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$1.4 \cdot 10^{-3} \pm 0.1 \text{ kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$ in ±2σ ROI
Backup: $2\nu\beta\beta$ Measurement

- 31 live days with 63 kg active mass
- Ionization only
- Signal:background = 10:1
- [PRL 107 (2011) 212501]

$$T_{1/2}^{2\nu\beta\beta} = 2.11 \times 10^{21} \pm 0.04 \text{(stat.)} \pm 0.21 \text{(sys.)}$$