Recent Results from EXO-200

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Xenon: a great candidate for $0\nu\beta\beta$ searches

- **Xenon is “reusable”:** continuously purify-able & recyclable (no crystal growth).

- **Monolithic detector:** LXe is self shielding.

- **Minimal Cosmogenic activation:** No long lived radioactive isotopes of Xe.
The EXO-200 TPC

Two almost identical halves reading ionization and 178 nm scintillation, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60° (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane
- All signals digitized at 1 MS/s, ±1024S around trigger
- Drift field 376 V/cm

- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue

Comprehensive material screening program

Goal: 40 cnts/2y in 0νββ ±2σ ROI, 140 kg LXe
Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in $^{136}$Xe
Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
The EXO-200 Detector

- **HV Filter and Feedthrough**
- **Veto Panels**
  - High purity Heat transfer fluid
  - HFE7000
  - > 50 cm
- **Double-Walled Cryostat**
  - 25 mm ea
- **LXe Vessel**
  - 1.37 mm
- **Lead Shielding**
  - > 25 cm
- **Veto Panels**

**Notes:**
- Monday, September 10, 12
Muon veto
- 50 mm thick plastic scintillator panels
- surrounding TPC on four sides.
- 95.5 ± 0.6 % efficiency
Veto cuts (8.6% combined dead time)
- 25 ms after muon veto hit
- 60 s after muon track in TPC
- 1 s after every TPC event
Sep 2011 – Hardware upgrades
- APD gain increase by factor 2
- improved U-wire shaping
- added outer lead shield

Purity
At $\tau_e = 3$ ms:
- max. drift time $\sim 110$ $\mu$s
- loss of charge is 3.6% at full drift length

<table>
<thead>
<tr>
<th></th>
<th>Run I</th>
<th>Run 2 (this analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>May 21, 11 – Jul 9, 11</td>
<td>Sep 22, 11 – Apr 15, 12</td>
</tr>
<tr>
<td>Live Time</td>
<td>752.7 hr</td>
<td>2,896.6 hr</td>
</tr>
<tr>
<td>Exposure ($^{136}$Xe)</td>
<td>4.4 kg-yr</td>
<td>26.3 kg-yr</td>
</tr>
</tbody>
</table>

Ultrasound pump:
Rev Sci Instrum. 82(10):105114

Xenon purity with mass spectroscopy:
NIM A675 (2012) 40-46

Gas purity monitors:
NIM A659 (2011) 215-228
The $^{214}$Bi decay coincidence rate is consistent with measurements from alpha-spectroscopy and the expectation before the Rn trap is commissioned.
Low-background spectra

single - cluster

multiple - cluster

zoomed in

31 live-days of data
63 kg active mass
Signal / Background ratio 10:1

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

[PRL 107 (2011) 212501]

Confirmed by Kamland-Zen:
Combining Ionization and Scintillation

Property of liquid xenon: increased scintillation associated with decreased ionization (and vice-versa)

Multi site (MS) and single site (SS) data (black points) are compared to model (blue curve).

- Single site fraction agrees to within 8.5%
- Source activities measured to within 9.4%
Events removed by diagonal cut:
- alpha events (large ionization density -> more recombination -> more scintillation light)
- events near edge of detector, where not all the charge ends up on the collection wires
Low Background Spectrum

Counts / 20 keV vs. Energy (keV)

MS

SS

120.7 days
98.5 kg LXe
(79.4 kg $^{136}$LXe)

Exposure 32.5 kg.yr

Total dead time from vetos: 8.6%

No $0\nu\beta\beta$ signal observed
Background counts in ±1,2σ ROI

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected events from fit</th>
<th>±1σ</th>
<th>±2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn in cryostat air-gap</td>
<td>1.9</td>
<td>±0.2</td>
<td>2.9</td>
</tr>
<tr>
<td>$^{238}$U in LXe Vessel</td>
<td>0.9</td>
<td>±0.2</td>
<td>1.3</td>
</tr>
<tr>
<td>$^{232}$Th in LXe Vessel</td>
<td>0.9</td>
<td>±0.1</td>
<td>2.9</td>
</tr>
<tr>
<td>$^{214}$Bi on Cathode</td>
<td>0.2</td>
<td>±0.01</td>
<td>0.3</td>
</tr>
<tr>
<td>All Others</td>
<td>~0.2</td>
<td>~0.2</td>
<td>~0.2</td>
</tr>
<tr>
<td>Total</td>
<td>4.1</td>
<td>±0.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Observed</td>
<td>1</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Background index ($kg^{-1}yr^{-1}keV^{-1}$)  
$1.5\times10^{-5} \pm 0.1 \, 1.4\times10^{-5} \pm 0.1$

EXO-200 goal:
40 cnts/2y in ±2σ 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
Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$

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

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

$\langle m_{\beta\beta} \rangle < 140–380 \text{ meV}$

(90% C.L.)

PRL 109 (2012) 032505
References for: Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$

EXO-200 Sensitivity
QRPA-2

\[ 136Xe \, T_{1/2} \, (yr) \]

\[ m_{\beta\beta} \, (meV) \, QRPA-2 \]

- median sensitivity 90% CL
- analysis upgrades
- commission Rn Tent
- EXO-200 limit
- KK&K claim (QRPA-2)
All important EXO-200 subsystems working

Low background running with enriched xenon already producing physics results

$^{136}\text{Xe } 2\nu\beta\beta$: $T_{1/2} = 2.11 \times 10^{21} \text{yr} \ (\pm 0.04 \ \text{stat}) \ (\pm 0.21 \ \text{sys})$ [PRL 107 (2011) 212501]

$^{136}\text{Xe } 0\nu\beta\beta$: $T_{1/2} > 1.6 \times 10^{25} \text{yr}$ [PRL 109 (2012) 032505]

Contradict claimed observation for the decay in $^{76}\text{Ge}$ for most nuclear matrix elements models

new $T_{1/2}^{2\nu\beta\beta} (^{136}\text{Xe}) = (2.23 \pm 0.017 \ \text{stat} \pm 0.22 \ \text{sys}) \times 10^{21} \text{yr}$ agrees with previous EXO-200 and Kamland-Zen’s results

Stay tuned: improved energy resolution, upgraded pattern recognition, reduced backgrounds... & beginning work on nEXO detector concepts
Backup Slides
Ba-tagging research is actively pursued.

Because of the success with EXO-200 the collaboration started to study the case for a ~5 ton Xe experiment, *initially* without Ba-tagging; with tagging remaining an option.

Assume:

- 4 tons of active $^{enr}$Xe (80% or higher).
- 1.4% ($\sigma$) energy resolution.
- Observed EXO-200 backgrounds minus the Rn in the shield.
- $\beta\beta$-scales like the volume, the background like the surface area (assume equal materials thicknesses).
Simulating different shielding configurations from baseline EXO-200 scale-up
nEXO SENSITIVITY

- 5 ton-yr Ge Zero Background
- 5 ton-yr Ge (1 c/ROI/t/yr)
- nEXO 40 ton-yr Zero Background
- nEXO 40 ton-yr (7.5 c/ROI/t/yr)

$T_{1/2}^{76}$Ge (yr)

$T_{1/2}^{136}$Xe (yr)
Common cathode for 2 TPCs

APDs see prompt scintillation
(t₀ for drift time)

V: induction on shielding grid

U & ionization: charge on collection grid
Calibration

Guide tube brings various sources to several positions outside detector

x-y distribution shows excess near source location
Wire Gains

• gains of wire channels measured with charge calibrations
• This is further corrected using the pair production peak (1593 keV) from $^{232}$Th 2615 keV gamma depositions.
• Have also individually measured the electronic transfer function of each channel, which are used to reconstruction the charge signals
• With all this, and the excellent purity, the charge resolution improved from 4.5% to 3.4% at 2615 keV
Calibration runs compared to simulation
-GEANT4 based simulation
-charge & scintillation propagation
-signal generation
-energy resolution parameter is added from after the fact

Rate is not a free parameter
poorest agreement is +8%
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 ββ decays
Energy Calibrations: charge only

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 β and ββ decays)
reproduced in simulation
Peak widths also recorded and their dependence on energy is parameterized.
Correcting for light response

EXO-200 light response (Averaged over \( \phi \))

- APD Plane
- Cathode Ring

Disabled APD gang

Lightmap near APD plane
At $Q_{\beta\beta}$ (2458 keV):
- $\sigma/E = 1.67\%$ (SS)
- $\sigma/E = 1.84\%$ (MS)

Energy resolution model:

$$\sigma_{Tot}^2 = p_0^2 E + p_1^2 + p_2^2 E^2$$

Dominated by constant (noise) term $p_1$
Pinpoint source location using a Compton Telescope technique

Detector measures $E$, $x$, $y$, $z$ for each site

Use scattering formula

$$\phi = \arccos \left[ 1 - m_e c^2 \cdot \left( \frac{1}{E_\gamma - E_1} - \frac{1}{E_1} \right) \right]$$

From each site a cone is drawn and adding up these cones produces the image to the right.
Systematic uncertainties: $2\nu\beta\beta$

- Fiducial volume: 9.3%
- Multiplicity assignment: 3%
- Energy calibration: 1.8%
- Background models: 0.6%
2νββ signal is clearly in the LXe bulk, while other gamma background contributions decrease with increasing distance from the walls.

Also constant in time
Low Background Spectrum

Zoomed around $0\nu\beta\beta$ region of interest (ROI)

Constraints:
- SS to MS ratio within ±8.5% of values predicted by MC (set by largest variations in source data)
- Energy resolution
- Energy calibration
- Beta energy scale
- Some PDFs (e.g. $^{222}\text{Rn}$ in LXe)

No $0\nu$ signal observed
From estimated background, expect to quote a 90% CL upper limit on $T_{1/2}$:

- $\geq 1.6 \times 10^{25}$ yr 6.5% of the time
- $\geq 7 \times 10^{24}$ yr 50% of the time
EXO-200 Sensitivity
R-QRPA
EXO-200 Sensitivity
NSM

The graph shows the sensitivity of the EXO-200 experiment for measuring the half-life of $^{136}$Xe and the mass of the NSM. The x-axis represents the EXO-200 livetime in years, while the y-axis shows the $^{136}$Xe half-life in years and the NSM mass in meV. The sensitivity is illustrated with various lines and markers representing different scenarios, such as median sensitivity, 90% CL, analysis upgrades, commission Rn Tent, EXO-200 limit, and KK&K claim (NSM).
EXO-200 Sensitivity
GCM
Systematics Uncertainties

Error breakout: expected 90% CL limit given absolute knowledge (0 error) of a given parameter or set of parameters

<table>
<thead>
<tr>
<th>Term</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume</td>
<td>12.34</td>
</tr>
<tr>
<td>β scale</td>
<td>9.32</td>
</tr>
<tr>
<td>SS / (SS + MS)</td>
<td>0.93</td>
</tr>
<tr>
<td>$^{232}$Th LXe Vessel</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{238}$U LXe Vessel</td>
<td>0.04</td>
</tr>
<tr>
<td>$^{222}$Rn Air Gap</td>
<td>0.04</td>
</tr>
<tr>
<td>Calibration offsets</td>
<td>0.04</td>
</tr>
</tbody>
</table>
**Spatial Distributions**

- $2\nu\beta\beta$ rate does not change with fiducial volume
- Background gammas rates drop towards the inside of the detector
- Events in the $\pm 1,2\sigma$ ROIs: statistics is too low to conclude on their parent distribution
Simulated spectra generation

Dotted line is Geant4 simulated energy deposition from $^{228}$Th source.

Solid line is energy spectra resulting from the convolution of the MC energy deposition with the energy resolution model.
Muon track signals

Muon traverses both TPCs

Collection

Induction
- Investigate alpha spectrum for scintillation signals from $^{238}$U
- Calibrate spectrum with alphas in Rn chain
- Can constrain contamination of $^{238}$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 $^{234m}$Pa which $\beta$ decays with a Q-value of 2195 keV, which cannot then explain our LXe bulk signal
Event reconstruction

- Signal finding – matched filters applied on U, V and APDs waveforms
- Signal parameter estimation \((t, E)\) for charge and light
- Cluster finding – assignment to Single Site (SS) or Multiple Site (MS): separation resolution 18mm in U and 6 mm in Z

Amplitudes corrected by channel for gain variation
Scintillation response corrected for position in TPC
Require events to be fully reconstructed in 3D
Reconstruction efficiency for 0νββ is 71% – estimated by MC and verified by comparing the 2νββ MC efficiency with low background data, over a broad range in energy
Fiducial volume uncertainty

Uncertainty determined from the fidelity with which calibration events are reconstructed within a chosen volume as compared to simulation.
3D reconstruction threshold

- Events >100 keV well above charge detection threshold
- 3D reconstruction still requires $t_0$ from scintillation signal
- Compare ratio of fully reconstructed events to triggered events to determine reconstruction efficiency
- Early software threshold $\sim$700 keV
- Recent dramatic increase with change in APD bias voltages $\sim$300 keV