Search for neutrinoless double-beta decay with EXO

Igor Ostrovskiy
Stanford University
Outline

• Introduction
  - Neutrino
  - Double beta decay
  - Enriched Xenon Observatory (EXO)

• EXO-200
  - Detector design
  - Data analysis
  - Physics results

• Next steps
Introduction: Neutrino

- From neutrino oscillation experiments we know that neutrino has a non-zero mass. We have measured relative mass-squared differences of different states
  - But what about absolute mass values?
  - How do different states align (normal, inverted hierarchy)?
  - What is the origin of mass term (Dirac, Majorana)?

From Wikipedia
Introduction: Double beta decay

- Two-neutrino mode is a Standard model process
  - though extremely rare, already observed for several isotopes

- Neutrino-less mode violates lepton number conservation
  - can only happen if neutrinos are **massive Majorana** particles
  - provides information about **absolute mass** scale
  - has never been observed*

* a controversial discovery claim exists by a sub-group of Heidelberg-Moscow collaboration
Introduction: Experimental signature

- In the two-neutrino mode electrons have to share energy with undetectable neutrinos
  - A calculable, but broad and featureless spectrum

- In the neutrinoless mode, a mono-energetic peak is expected at Q-value
  - Good energy resolution is essential
  - Large Q-value is preferred

Illustration from P. Vogel, arXiv:hep-ph/0611243, Assumes 2% resolution and 1e2 (1e6 in insert) ratio of 2nu/0nu
Introduction: From half-life to mass

- Observing a peak at Q value gives estimate of half-life (our job!)
- The half-life is then related to the **effective Majorana mass** through
  - Reliably calculable **phase-space factor**
  - Strongly model-dependent **matrix element**

\[
\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q, Z)|M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2
\]

\[
\langle m_{\beta\beta} \rangle = \left| \sum_i |U_{ei}|^2 e^{i\alpha(i)} m_i \right|
\]
Introduction: The two hierarchies

- Cosmology limits sum of neutrino masses to $<\sim0.5$ eV
  
  Hannestad, Prog.Part.Nucl.Phys, 65 (2010)185

- Heidelberg-Moscow limits effective Majorana mass to $<\sim0.3$ eV

  Bilenky, Giunti, arXiv:1203.5250

I.Ostrovskiy, UC Davis, January 2013
### Introduction: Some pursued options

<table>
<thead>
<tr>
<th>$\beta\beta$-decay</th>
<th>$G^{0\nu}_{\beta\beta}$</th>
<th>$Q$ [keV]</th>
<th>nat. abund. [%]</th>
<th>experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca} \to ^{48}\text{Ti}$</td>
<td>$6.3$</td>
<td>$4273.7$</td>
<td>$0.187$</td>
<td>CANDLES</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \to ^{76}\text{Se}$</td>
<td>$0.63$</td>
<td>$2039.1$</td>
<td>$7.8$</td>
<td>GERDA, Majorana</td>
</tr>
<tr>
<td>$^{82}\text{Se} \to ^{82}\text{Kr}$</td>
<td>$2.7$</td>
<td>$2995.5$</td>
<td>$9.2$</td>
<td>SuperNEMO, Lucifer</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \to ^{100}\text{Ru}$</td>
<td>$4.4$</td>
<td>$3035.0$</td>
<td>$9.6$</td>
<td>MOON, AMoRe</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \to ^{116}\text{Sn}$</td>
<td>$4.6$</td>
<td>$2809$</td>
<td>$7.6$</td>
<td>Cobra</td>
</tr>
<tr>
<td>$^{130}\text{Te} \to ^{130}\text{Xe}$</td>
<td>$4.1$</td>
<td>$2530.3$</td>
<td>$34.5$</td>
<td>CUORE</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \to ^{136}\text{Ba}$</td>
<td>$4.3$</td>
<td>$2461.9$</td>
<td>$8.9$</td>
<td>EXO, KamLAND-Zen, NEXT, XMASS</td>
</tr>
<tr>
<td>$^{150}\text{Nd} \to ^{150}\text{Sm}$</td>
<td>$19.2$</td>
<td>$3367.3$</td>
<td>$5.6$</td>
<td>SNO+, DCBA/MTD</td>
</tr>
</tbody>
</table>

Introduction: Enriched Xenon Laboratory

- A multistage program to search for neutrinoless double beta-decay of Xe-136

- Xenon is a good candidate for $\text{bb0n}$ search
  - Can serve as both source and detector
  - Q-value larger than energy of gammas from most natural radionuclides
  - Relatively easy to enrich in Xe-136 isotope
  - No need to grow high-purity crystals, continuous purification is possible, more easily scalable
  - No long-lived cosmogenically activated isotopes
  - Final state (Ba-136 ion) can, in principle, be tagged, greatly reducing backgrounds
EXO-200

- First stage of the experiment
- 200 kg of Xe enriched to 80.6% Xe-136 total procured
  - 175 kg in liquid phase inside a cylindrical Time Projection Chamber
  - 98.5 kg current fiducial mass
- Located at 1585 m.w.e. in the Waste Isolation Plant near Carlsbad, NM
  - Muon rate reduced to the order of $10^{-7}$ Hz/cm$^2$/sr
  - Salt has inherently lower levels of U/Th, compared to rock
- Carefully selected radioactively clean materials used in construction, rigorous cleaning procedures, the detector installation is inside class 1000 clean room
  - Goal of 40 counts/2yrs in 2-sigma 0nu energy window (assuming 140 kg LXe, 1.6% resolution)

I.Ostrovskiy, UC Davis, January 2013
EXO-200: TPC

- Common cathode + Two Anodes
  - 376 V/cm drift field
- Each half records both charge and scintillation information with
  - 38 U (charge collection) + 38 V (charge induction) triplet wire channels, crossed at 60 degrees
    - Wire pitch 3 mm (9 mm / channel)
    - Photo-etched Phosphor bronze
  - 234 large area avalanche photo-diodes, in groups of 7 (178 nm Xe light)
    - Copper support plane with Au (Al) plating for contact (reflection)
- Teflon reflectors
- Copper field shaping rings
- Acrylic supports
- Flexible bias/readout cables: copper on kapton, no glue

I.Ostrovskiy, UC Davis, January 2013
Copper vessel 1.37 mm thick
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
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
EXO-200: Calibration system

- A guide-tube to allow insertion of miniature radioactive calibration sources
- Several positions in cathode and anode planes and several sources to map out the detector response
  - Th-228
  - Co-60
  - Cs-137
- Frequent calibrations with most important Th-228 (2.6 MeV peak close to end-point energy) for purity, stability of energy scale, other corrections

I.Ostrovskiy, UC Davis, January 2013
EXO-200: Data

A single-site energy deposition in EXO-200

I.Ostrovskiy, UC Davis, January 2013
A two-site Compton scattering event

I. Ostrovskiy, UC Davis, January 2013
EXO-200: Milestones

- **Late 2010**
  - Engineering run with natural Xe

- **May 2011 – July 2011 Run 1 “two-neutrino Run”**
  - First run with enriched Xe
  - First successful measurement of two-neutrino double beta decay in Xe-136
  - 5.4 kg*yr exposure (4.4 kg Xe-136)

- **August 2011 – September 2011**
  - Installation of final lead shielding
  - Electronics and other upgrades

- **October 2011 – March 2012 “Run 2”**
  - 32.6 kg*yr exposure (26.3 kg Xe-136)
EXO-200: Event Reconstruction

- Identify signals on individual U, V wires, summed APDs signals using matched filters
- Fit by waveform templates to determine time, amplitude in both charge and light channels
- Apply channel dependent correction for wire gain
- Combine U and V signals in one or more charge clusters (single- vs. multi-site events) based on time and U position, associate with nearest preceding scintillation signal
  - U and V coordinate, together with time since scintillation pulse, provide 3D coordinate of an event
  - Can distinguish clusters ~6 mm in z dimension, ~18 mm in u dimension
- Apply position dependent corrections
  - for light collection and APD gain inhomogeneity
  - for charge loss due to finite xenon purity
  - shielding grid inefficiency
EXO-200: wire gains

- Use 1593 keV pair production events from Th-228 to measure collection wire transfer functions and gains for each channel
- Improves resolution in the charge channel to 3.4%, from 4.5% (@2.6 MeV)
Xenon gas is circulated through a heated zirconium getter using a custom-built ultra-clean pump†.


EXO-200: Xenon purity

~3 ms electron lifetime or ~4% maximum correction, given ~110 µs maximum drift time.
EXO-200: light correction

- Use full absorption peak of 2615 keV gamma from Th-228 to map light response in TPC
- Linearly interpolate between 1352 voxels

**EXO-200 light response (Averaged over φ)**

- Gap between teflon reflector and APD plane
- Cathode Ring
- APD Plane
- Disabled APD gang

I.Ostrovskiy, UC Davis, January 2013
EXO-200: Anti-correlation

- Good energy resolution is essential for successful \(0\nu\) search

- It is known that charge and light production in liquid Xe are anti-correlated

\[
\text{Scintillation: } 6.8\% \\
\text{Ionization: } 3.4\% \\
\text{Rotated: } 1.6\% \\
\text{(}\sigma/E\text{ at 2615 keV gamma line)}
\]

- Use the combination of charge, light channels that optimizes resolution as an energy estimator

I.Ostrovskiy, UC Davis, January 2013
Energy calibration residuals are less than 0.1% with quadratic calibration.

Energy resolution in the rotated space is 1.67% (1.84%) for single (multi) site events.
EXO-200: Generating prediction for signal/backgrounds

• We will fit the data by probability density functions (PDFs) describing shape of the signal and various expected background components

• We employ a combination of MC and data driven approaches
  - Use Geant4 to simulate true energy depositions given source/position
  - Pass through digitization / reconstruction algorithms to perform single- vs. multi-site assignment
  - Perform a Gaussian convolution of the true MC energy with energy-dependent resolution function, measured from the data
EXO-200: Source agreement

- To validate our ability to accurately describe data using PDFs, we use calibration sources to quantify
  - Shape agreement
    - Deemed compatible by $\chi^2$, KS tests
  - Rate agreement
    - 9.4% maximum deviation from measured source activities (used as systematic)
  - Single-site fraction agreement
    - 8.5% maximum deviation with source data (used as systematic)
EXO-200: Source agreement

- To validate our ability to accurately describe data using PDFs, we use calibration sources to quantify
  - Shape agreement
    - Deemed compatible by \( \chi^2 \), KS tests
  - Rate agreement
    - 9.4% maximum deviation from measured source activities (used as systematic)
  - Single-site fraction agreement
    - 8.5% maximum deviation with source data (used as systematic)
EXO-200: Final data analysis cuts

- Veto cuts (8.6% total dead-time)
  - 60 s after muon track in TPC to avoid muon-induced activity
  - 25 ms after muon veto hit (possible shoulder-clippers)
  - 1 s after every TPC events to exclude coincidences, e.g. Bi-Po
- “Diagonal” cut to remove events with large light/charge ratio (alphas and events with imperfect charge collection)
- Keep events with all 3 coordinates reconstructed
- 700 keV low energy cut (trigger fully efficient)
- Fiducial cut
  - 5 mm from cathode, 10 mm from anodes, 2 cm standoff from Teflon reflector
- 71% total efficiency for 0nu
  - Estimated by MC and verified by comparing 2nu to the data over broad range of energies
EXO-200: Final data analysis cuts

- Veto cuts (8.6% total dead-time)
  - 60 s after muon track in TPC to avoid muon-induced activity
  - 25 ms after muon veto hit (possible shoulder-clippers)
  - 1 s after every TPC events to exclude coincidences, e.g. Bi-Po
- “Diagonal” cut to remove events with large light/charge ratio (alphas and events with imperfect charge collection)
- Keep events with all 3 coordinates reconstructed
- 700 keV low energy cut (trigger fully efficient)
- Fiducial cut
  - 5 mm from cathode, 10 mm from anodes, 2 cm standoff from Teflon reflector
- 71% total efficiency for 0nu
  - Estimated by MC and verified by comparing 2nu to the data over broad range of energies
EXO-200: 0nu analysis final fit

- Binned maximum likelihood fit to 0nu, 2nu, and various backgrounds PDFs
- Simultaneous fit to SS and MS spectra
  - SS fractions float with 8.5% constraint
- Rn in LXe and in air gap between cryostat/led wall float with constraints by dedicated studies
- Calibration offset/resolution parameters float, constrained by corresponding error/matrix
- Slightly different energy scales for betas/gammas used, as preferred by dedicated profile likelihood tests
  - Live-time: **120.7 days**
  - Active mass: **98.5 kg** (79.4 Xe-136)
  - Exposure: **32.5 kg*yr**
I.Ostrovskiy, UC Davis, January 2013

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

(In agreement with previously reported value by EXO-200 and KamLAND-ZEN collaborations)
EXO-200: Region of interest

- No signal found
- Background from the fit in 1 sigma ROI:
  - $1.5 \times 10^{-3} \pm 0.1 \text{ /kg /yr /keV}$
- Upper limit with profile likelihood method
  - $T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{25} \text{ yr @90\% C.L}$
  - $<m_{\beta\beta}> < 140-380 \text{ meV}$
I.Ostrovskiy, UC Davis, January 2013

222Rn in cryostat air-gap: 1.9 ± 0.2
238U in LXe Vessel: 0.9 ± 0.2
232Th in LXe Vessel: 0.9 ± 0.1
214Bi on Cathode: 0.2 ± 0.01
All Others: ~0.2
Total: 4.1 ± 0.3

Best-fit background estimates in 1 sigma ROI:

Observed:
1 count in 1 sigma ROI
(0.0015 /kg /yr /keV)
5 counts in 2 sigma ROI
(0.0014 /kg /yr /keV)

Design goal: 40 /2yrs /140kg /2sigma,
Or ~4.6 counts for this dataset

I.Ostrovskiy, UC Davis, January 2013
90% C.L. limit compared with Recent Xe-136 constraints (KamLAND-ZEN) >2.5 factor improvement.

EXO-200 contradicts Klapdor claim at the 90% C.L. for most matrix element calculations.
What's next?

- Basically, doubled the dataset
- Will continue to run with EXO-200 for few more years
- Further improvements in the works
  - New radon purge in the air gap between lead shield and cryostat
  - Possible further improvements to resolution, reconstruction efficiency
  - Incorporate position-dependency in PDFs – additional handle on backgrounds
- R&D for the next generation of EXO (nEXO) has started
  - A multi-ton TPC
  - Initially, without Ba-tagging
| University of Alabama, Tuscaloosa AL, USA | D. Auty, M. Hughes, A. Piepke, K. Pushkin, M. Volk |
| California Institute of Technology, Pasadena CA, USA | P. Vogel |
| Colorado State University, Fort Collins CO, USA | C. Benitez-Medina, C. Chambers, A. Craycraft, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, T. Walton |
| Drexel University, Philadelphia PA, USA | M.J. Dolinski |
| 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, L. Wen, 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 |
| University of Illinois, Urbana-Champaign IL, 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. Mackeen, 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 |

I.Ostrovskiy, UC Davis, January 2013
Comparison with KamLAND-ZEN latest result (arXiv:1211.3863)

FIG. 1: Comparison with KamLAND-ZEN spectrum.

KamLAND-ZEN spectrum

EXO-200 spectrum

(PRL 109 (2012) 032505)
Bi-214 – Po-214 coincidence in EXO-200

Bi-214 rate is consistent with a steady state source of radon in the system (no radon trap installed)

360 ± 65 μBq/kg in fiducial volume
Circular & Hexagonal volumes

Standoff distance measured from Teflon wall to hexagon

I.Ostrovskiy, UC Davis, January 2013
• 31 live-days of data
• 63 kg active mass
• Signal / Background ratio 10:1

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


I.Ostrovskiy, UC Davis, January 2013
Run 1 source agreement
Introduction: Neutrino mass scale

- Normal hierarchy
- Inverted hierarchy

- $m^2$ vs. $m^2$
- $\nu_e$, $\nu_\mu$, $\nu_\tau$

- $<2.3\ eV$
- $<0.3\ eV$
- $<1.7\ or\ <0.68\ eV$

- Tritium Endpoint
- Majorana Neutrino
- From $0\nu\beta\beta$

- Solar $\sim 5 \times 10^{-5}\ eV^2$
- Atmospheric $\sim 3 \times 10^{-3}\ eV^2$

I. Ostrovskiy, UC Davis, January 2013
References for nuclear matrix elements:


Phase space factors for the $0\nu\beta\beta$ decay from F. Boehm and P. Vogel, Vogel, 9/2010 Physics of Massive Neutrinos, Table 6.1

(slide from L.Kaufman, Physics in Collision 2012)
Given our estimated background, we expect a 90% CL on T1/2 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.
- Measured 2nu rate does not change with choice of fiducial volume
- Rates of backgrounds gammas are less deeper inside the detector