Searching for $0\nu\beta\beta$ with EXO-200 and nEXO

- Motivation for $\beta\beta$ search
- The EXO-200 and nEXO experiments

Thomas Brunner for the nEXO collaboration
Neutrino oscillations

Pontecorvo–Maki–Nakagawa–Sakata matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
U_{e1} U_{e2} U_{e3} \begin{pmatrix}
\nu_{m1} \\
\nu_{m2} \\
\nu_{m3}
\end{pmatrix}
\]

Relative mass scale

- Indicate a neutrino mass
- Determination of mixing angle $\theta_{ij}$
- Indicate mass hierarchy
- Determination of $\delta m^2$

Normal Hierarchy

Inverted Hierarchy (only if $m_1^2 \geq \Delta m_{atm}^2$)

\[
\begin{align*}
\Delta m_{\odot}^2 & \approx m_1^2 = ? \\
\Delta m_{atm}^2/4 & \Rightarrow m_3^2
\end{align*}
\]

$m_\nu = 0$
Neutrino oscillations

Pontecorvo–Maki–Nakagawa–Sakata matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_{m1} \\
\nu_{m2} \\
\nu_{m3}
\end{pmatrix}
\]

What oscillation experiments cannot tell us about $\nu$'s

- What is the absolute mass scale
- Why is the neutrino mass so small?
- What is the nature of the $\nu$: Dirac or Majorana?

→ Search for $0\nu\beta\beta$ decay

Relative mass scale

- Indicate a neutrino mass
- Determination of mixing angle $\theta_{ij}$
- Indicate mass hierarchy
- Determination of $\delta m^2$
Double beta decay

M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512

\[ 2\nu\beta\beta \]
Double beta decay

The process can only occur for a Majorana neutrino!

Lepton number is violated in this decay!

\[ 2\nu\beta\beta \]

\[ 0\nu\beta\beta \]

This process can only occur for a Majorana neutrino!
Neutrinoless double beta decay

![Diagram of neutrinoless double beta decay](image)

- **$0\nu\beta\beta$ peak** (normalized to $10^{-6}$)
- **$0\nu\beta\beta$ peak** (normalized to $10^{-2}$)

**kinetic energy $K_e$ of the two electrons**

in units of kinematic endpoint ($Q$)

Smeared by the energy resolution of the hypothetical detector

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Neutrinoless double beta decay

\[
\left[ T^{0\nu}_{1/2} \right]^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \left\langle m_\nu \right\rangle^2
\]

Effective Majorana mass:

\[
\left\langle m_\nu \right\rangle = \left| \sum_i U_{ei}^2 m_i \epsilon_i \right| \quad \text{(light neutrino exchange mechanism only)}
\]

\( G^{0\nu} \) is a phase space factor

\( M^{0\nu} \) is the nuclear matrix element

\( 0_{\nu\beta\beta} \) peak (normalized to \( 10^{-6} \))

\( 0_{\nu\beta\beta} \) peak (normalized to \( 10^{-2} \))
If first-order beta decay is forbidden energetically or by spin, second-order double beta decay (a weak nuclear process) can be observed. True for several isotopes such as: $^{48}\text{Ca}$, $^{76}\text{Ge}$, $^{130}\text{Te}$, $^{136}\text{Xe}$.
Searching for $0\nu\beta\beta$ in $^{136}$Xe with EXO

Liquid-Xe Time Projection Chamber
- Liquid Xe at 168K
- Cryogenic electronics in LXe
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity
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**Natural radiation decay rates**
- A banana: $\sim 10$ decays/s
- A bicycle tire: $\sim 0.3$ decays/s
- 1 l outdoor air: $\sim 1$ decay/min
- 100 kg of $^{136}$Xe (2$\nu$): $\sim 1$ decay/10 min

T_{1/2}^{0\nu} > 10^{25}$ years !!

→ Need:
- high target mass
- high exposure
- low background rate
- good energy resolution

$0\nu\beta\beta$ decay >1000 x rarer than $2\nu\beta\beta$
Age of universe 1.4 x $10^{10}$ years
Advantages of $^{136}$Xe

- **Easy to enrich**: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- **Can be purified** continuously, and reused
- **High $Q_{\beta\beta}$** (2458 keV): higher than most naturally occurring backgrounds
- **Minimal cosmogenic activation**: no long-life radioactive isotopes
- **Energy resolution**: improves using scintillation and charge anti-correlation
- **LXe self shielding**
- **Background can be potentially reduced by Ba$^{++}$ tagging**

Phased approach:

1. EXO-200: 200kg liquid-Xe TPC
2. nEXO: 5-ton liquid Xe TPC with Ba tagging option (SNO lab cryopit)
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See talks by
- Y. Lan M1-4
- R. Gornea T1-5
EXO-200

- Located at the Waste Isolation Pilot Plant at 32°22’30”N 103°47’34”W (Carlsbad, NM).
- 2150 feet depth (~655m), ≈1585 mwe flat overburden
- U.S. DOE permanent repository for nuclear waste
- Low radioactivity levels:
  - U, Th <100ppb
  - Radon background < 10 Bq/m³

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EXO-200 Time Projection Chamber (TPC) Basics

- **Z-position** from the time difference between scintillation and ionization
- **Event energy** from the combination of ionization and scintillation
- **TPC allows rejection of some gamma backgrounds** because Compton scattering results in multiple energy deposits

Avalanche photodiode (APD) array observes prompt scintillation

Crossed shielding and charge collection grids give x,y position

Common cathode

TPC modules

-8kV
EXO-200 TPC

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)
• 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)
Energy measurement

Combination of charge and light

Energy resolution is dominated by APD noise

‘Rotation angle’ determined weekly using $^{228}$Th source data, defined as angle which gives best ‘rotated’ resolution

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Position/multiplicity reconstruction

Background measurement/reduction

$^{228}\text{Th}$ calibration source in EXO-200 detector

Events with $> 1$ charge cluster: multi-site (MS) events
Event with 1 charge cluster: single-site (SS) events

$0\nu\beta\beta$: $\sim 90\%$ SS
$\gamma_s$: $\sim 30\%$ SS at $0\nu\beta\beta$ energy

MS events used to constrain background models
Recent $0\nu\beta\beta$ decay result

Run 2 data consists of:
- Run 2a already used for PRC 2014 and PRL 2012
  09/22/2011 – 04/15/2012
- Runs 2b and 2c
  04/16/2012 – 09/01/2013
- 477.60$^{+0.01}_{-0.01}$ days of data

$^{136}$Xe exposure: 99.8 kg yr

Simultaneous fit to energy and standoff distance for SS and MS

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Nature 510, 229 (2014)
Recent $0\nu\beta\beta$ decay result

39 counts in $\pm 2\sigma$ ROI

<table>
<thead>
<tr>
<th>Decay</th>
<th>Count</th>
</tr>
</thead>
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<tr>
<td>$^{232}\text{Th}$</td>
<td>16.0</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>8.1</td>
</tr>
<tr>
<td>$^{137}\text{Xe}$</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31.1 \pm 3.8</strong></td>
</tr>
</tbody>
</table>

From profile likelihood:

- $T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr
- $\langle m_{\beta\beta} \rangle < 190 - 450$ meV
  (90\% C.L.)

Nature 510, 229 (2014)
EXO-200 (0ν)ββ search

2011  First measurement of $2\nu\beta\beta$ in $^{136}$Xe [PRL 107, 212501 (2011)]
2012  First $0\nu\beta\beta$ result, best $m_{\beta\beta}$ limit [PRL 109, 032505 (2012)]
2013  Most precisely measured $2\nu\beta\beta$ rate — and the lowest → slowest process ever directly measured in nature! [PRC 89, 015502 (2014)]
2014  Improved sensitivity to $m_{\beta\beta}$ [Nature 510, 229 (2014)]

$T_{1/2}^{2\nu\beta\beta} = 2.165 \pm 0.016 (\text{stat}) \pm 0.059 (\text{syst}) \times 10^{21} \text{ yr}$

$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25} \text{ yr @ 90% C.L.}$
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The future of EXO-200

EXO-200 is about 1.2 km from the radiation event

- **Feb. 5 2014**: Fire in WIPP underground
- **Feb. 14, 2014**: Radiation release event
- So far no radioactivity has been measured at EXO-200
- EXO clean up finished
- Low background data taking resumed in early 2016
- Stay tuned for new results
0νββ search with EXO

Multi-phase program:

- **EXO-200** – operational at WIPP mine:
  - ~175kg xenon enriched at ~80%
  - Current limit on 0νββ: 1.1 x 10^{25} years (EXO-200)
  - Continue data taking for 2 more years
  - Sensitivity: 100-200 meV

- **nEXO** - R&D underway:
  - 5T xenon enriched at ~90%
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba tagging

→ Development of nEXO is well advanced

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0νββ search with EXO

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  - ~175kg xenon enriched at ~80%
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For more information on Ba tagging:
- Y. Lan M1-4
- R. Gornea T1-5
Searching for \(0\nu\beta\beta\) with nEXO

- Next-generation neutrinoless double beta decay detector
- 5 t liquid xenon TPC similar to EXO-200 (50x the size)
- Possible location in SNOLab Cryo Pit (6010 mwe)
- SiPM for light detection
- Tiles for charge read out
- 3D event reconstruction
- Expected \(\sigma/E\) of 1% at Q-value
- Possible addition of Ba-tagging after 5 years

EXO-200 for size comparison
Searching for $0\nu\beta\beta$ with nEXO

• Next-generation neutrinoless double beta decay detector
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SiPM Photodetector

- Hamamatsu produces devices with QE= ~12% @ 175nm but encapsulation is too radioactive → trying to procure un-encapsulated devices
- First nEXO-specific run at FBK (Italy) provided ~10% QE [I.Ostrovskiy et al. IEEE TNS 62 (2015) 1825.]
- New FBK “RGB” devices reach 15% QE with 7.7x7.7mm$^2$.

- Working closely with manufacturers to develop SiPMs to reach >15% QE at 175nm
- Radioassay of SiPMs to determine radioactivity
- Development of integration of 1x1cm$^2$ SiPMs into 10x10cm$^2$ tiles
- Tests in liquid Xe planned
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  - Tests in liquid Xe planned

For more information on SiPM:
- F. Retiere W2-4

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Charge Readout Tiles

- EXO-200 used wires for charge-readout
- Produced by IHEP/IME; functional testing in LXe in the US.
- 10 x 10cm² Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30)
- 3mm strip pitch
- Strip intersections isolated with SiO₂ layer
- Currently testing in LXe with a ²⁰⁷Bi source

Preliminary tests at Stanford in small LXe test cell

MC scaled to match 570-keV peak height

Data
MC Smearing Energy Dependent

IHEP/IME tile anode, mounted to underside of cell lid

Low capacitance crossing

10µm

10cm
• EXO-200 is operational and taking low background data
• nEXO is the next generation $0\nu\beta\beta$ experiment with 5 T isotopically enriched LXe
• nEXO expands on the success of EXO-200 and improves performance via R&D efforts
• nEXO will have many handles on background
• nEXO has discovery potential in Inverted Hierarchy pushing the lower bound of $<m_{\beta\beta}>$
• The 10meV region is within reach
• Strong Canadian contribution to EXO-200 and nEXO
The nEXO Collaboration

University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
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University of California, Irvine, Irvine CA, USA — M Moe
Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA — O Alford, J Brodsky, M Heffner, G Holtmeier, A House, M Johnson, S Sangiorgio
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Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers
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University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, D Moore, I Ostrovskiy, A Schubert, M Weber
Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya, M Tarka
Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, Y. Lan, F Retière, V Strickland
Thanks to my Canadian collaborators:

Carleton University

McGill University

Université de Sherbrooke

TRIUMF
Backup
nEXO - Homogeneity is Crucial

- Increased mass
- Taking full advantage of self shielding
  - more effective
- Improve Compton tag efficiency by double-hit recognition

<table>
<thead>
<tr>
<th>LXe mass (kg)</th>
<th>Diameter or length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>130</td>
</tr>
<tr>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
</tr>
</tbody>
</table>

→ Benefits of monolithic detector compared to segmented detectors
Physics searches with EXO-200

An Optimal Energy Estimator to Reduce Correlated Noise for the EXO-200 Light Readout
C.G. Davis et al. Submitted to JINST (May 2016). arxiv:1605.06552 [physics.ins-det]

Cosmogenic Backgrounds to 0νββ in EXO-200

First Search for Lorentz and CPT Violation in Double Beta Decay with EXO-200
J.B. Albert et al., Phys. Rev. D 93, 072001

Search for 2νββ decay of 136Xe to the 01+ excited state of 136Ba with EXO-200
J.B. Albert et al., Phys. Rev. C 93, 035501

Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200

Investigation of radioactivity-induced backgrounds in EXO-200

Search for Majoron-emitting modes of double-beta decay of 136Xe with EXO-200

Search for Majorana neutrinos with the first two years of EXO-200 data

An improved measurement of the 2νββ half-life of Xe-136 with EXO-200

Search for Neutrinoless Double-Beta Decay in 136Xe with EXO-200

Observation of Two-Neutrino Double-Beta Decay in Xe-136 with EXO-200
EXO-200 0νββ search

2011  First measurement of 2νββ in $^{136}$Xe [PRL 107, 212501 (2011)]

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---

NMEs used:

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_{0\nu}$</th>
<th>Reference</th>
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<tbody>
<tr>
<td>EDF</td>
<td>4.20</td>
<td>PRL 105, 252503 (2010)</td>
</tr>
<tr>
<td>ISM</td>
<td>2.19</td>
<td>Nucl Phys A 818, 139 (2009)</td>
</tr>
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<td>IBM-2</td>
<td>3.05</td>
<td>PRC 91, 034304 (2015)</td>
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<td>SkyrmeQRPA</td>
<td>1.55</td>
<td>PRC 87 064302 (2013)</td>
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<tr>
<td>QRPA</td>
<td>2.02</td>
<td>PRC 89, 064308 (2014)</td>
</tr>
</tbody>
</table>

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Good energy resolution requires efficient readout of the scintillation light to be combined with the ionization signal.

EXO-200 reaches 1.4% at $Q_{\beta\beta}$

Better than 1% resolution required for nEXO
The role of the standoff distance in background identification and suppression

Example: nEXO, 5 yr data, 0νββ @ $T_{1/2} = 6.6 \times 10^{27}$ yr, projected backgrounds from subsets of the total volume

<table>
<thead>
<tr>
<th>Fid. LXe Mass</th>
<th>4780kg</th>
<th>3000kg</th>
<th>1000kg</th>
<th>500kg</th>
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</thead>
</table>

SS

MS

The fit gets to see all this information and use it in the optimal way

June 13, 2016

Thomas Brunner