Next-generation neutrinoless double beta decay search with LXe

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Neutrinos in the standard model

Neutrinos have non-vanishing masses

\[ \sqrt{\sum_i (m_i U_{ei})^2} < 2.3 \, \text{eV} \]

\[ \sum_i m_i < 250 \, \text{meV} \]

\[ \left| \sum_i m_i U_{ei}^2 e^{i\alpha_i} \right| < 150 \, \text{meV} \]

\[ \nu_{\beta \beta} \] searchess

\( \beta \)-decay end-point of energy spectrum

Cosmology

Fractional Flavor Content varying \( \cos \delta \)
Neutrinos in the standard model

Neutrinos masses stand apart from that of the charged fermions
Neutrinoless double beta decay

\[ T_{1/2}^{0\nu}(0^+ \to 0^+) ]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \left| \langle m_{\beta\beta} \rangle \right|^2 \]

\[ \langle m_{\beta\beta} \rangle = \left| \sum_{k=1}^{2} m_k |U_{ek}|^2 e^{i\alpha_k} \right| \]
Neutrinoless double beta decay

\[
\langle m_{\beta\beta} \rangle = \sum_{k=1}^{3} m_k |U_{e k}|^2 e^{i\alpha_k}
\]
Isotope selection

\[ A = 136 \]

\[ \text{Q value (MeV)} \]

\[ \text{natural abundance (\%)} \]
Nuclear Matrix Elements

Peir Vogel, 2014

[Graph showing nuclear matrix elements for different elements such as Ge, Se, Zr, Mo, Te, Xe, and Nd.]

[Graph showing T_{1/2} for 136 Xe versus T_{1/2} for different elements.]
Other LNV processes

- Low scale seesaw: intriguing example with one light sterile $v_R$ with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass

$$m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2 e^{2i\Phi} m_4$$

Usual phenomenology turned around!
EXO-200 prototype

- 8kV Charge collection
- Ionization Scintillation
- LXe TPC with charge and scintillation light collection
A single-site energy deposition in EXO-200

Scintillation light is seen at both sides. The light is more diffuse on side 1 and more localized on side 2, where the event occurred. The light signal always precedes both charge signals. The induction (V) signal precedes the collection (U) signal.
Data collection

A two-site Compton scattering event

All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

In this case, the gamma ray occurred on side 2. The light hitting side 2 is more localized, while the light hitting side 1 is more diffuse across the plane.
Event topology

Low background data

single site events (SS)

$2\nu\beta\beta$

multiple site events (MS)

$^{228}\text{Th}$ calibration source

Reconstructed Energy (keV)
Particle ID & fiducial volume

Events from the cathode and anodes

Events from the LXe bulk
Energy measurement
EXO-200 backgrounds

The slowest process directly observed!

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

100 kg yr exposure

Backgrounds in 2\sigma ROI

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th-228 chain</td>
<td>16.0</td>
</tr>
<tr>
<td>U-232 chain</td>
<td>8.1</td>
</tr>
<tr>
<td>Xe-137</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>31.1 ± 3.8</td>
</tr>
</tbody>
</table>

\((1.7 \pm 0.2) \text{ keV}^{-1} \text{ ton}^{-1} \text{ yr}^{-1}\)
EXO-200 results

PRC 85, 034316 (2012) for phase space factors


KK&K 68% CL

GERDA Sensitivity

PRL 111, 122503 (2013)

KamLAND-Zen Limit

PRL 110, 062502 (2013)

EXO-200 Limit

Upgraded EXO-200 after 2 years run

Current Bound

Flavor Oscillation Results

Cosmological Limit

NS

IS
Future experiments

**Arguments in favour of a rich and diversified 0νββ search program**

- **Low density trackers**
  - NEXT, PandaX ($^{130}$Xe gas TPC)
  - SuperNEMO (foils and gas tracking, $^{82}$Se)
  
  **Pros:** Superb topological information
  **Cons:** Very large size

- **Liquid (organic) scintillators**
  - KamLAND-ZEN ($^{136}$Xe)
  - SNO+ ($^{130}$Te)
  
  **Pros:** “simple”, large detectors exist, self-shielding
  **Cons:** Not very specific, 2ν background

- **Crystals**
  - GERDA, Majorana ($^{76}$Ge)
  - CUORE, CUPID ($^{130}$Te)
  
  **Pros:** Superb energy resolution, possibly 2-parameter measurement
  **Cons:** Intrinsically fragmented

- **Liquid TPC**
  - nEXO ($^{136}$Xe)
  
  **Pros:** Homogeneous with good E resolution and topology
  **Cons:** Does not excel in any single parameter

- **Other considerations**
  - There could be unknown gamma transitions and a line observed at the “end point” in one isotope does not necessarily imply the 0νββ decay discovery
  - Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities
  - Different isotopes correspond to vastly different experimental techniques
  - 2 neutrino background is different for various isotopes
  - The elucidation of the mechanism producing the decay requires the analysis of more than one isotope
### Future experiments

*Agostini et al., arxiv:1705.02996 [hep-ex]*

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Iso. Mass [kg_{iso}]</th>
<th>σ</th>
<th>ROI</th>
<th>ε_{FV}</th>
<th>ε_{sig}</th>
<th>E</th>
<th>B</th>
<th>3σ disc.</th>
<th>T_{1/2}</th>
<th>m_{\beta\beta}</th>
<th>Required Improvement</th>
<th>Iso. Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEGEND 200 [61, 62]</td>
<td>76 Ge</td>
<td>1.3</td>
<td>[-2, 2]</td>
<td>93</td>
<td>77</td>
<td>119</td>
<td>1.7 \cdot 10^3</td>
<td>8.4 \cdot 10^{26}</td>
<td>40–73</td>
<td>3</td>
<td>1</td>
<td>5.7</td>
</tr>
<tr>
<td>LEGEND 1k [61, 62]</td>
<td>76 Ge</td>
<td>1.3</td>
<td>[-2, 2]</td>
<td>93</td>
<td>77</td>
<td>503</td>
<td>2.8 \cdot 10^{-4}</td>
<td>4.5 \cdot 10^{27}</td>
<td>17–31</td>
<td>18</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>SuperNEMO [68, 69]</td>
<td>82 Se</td>
<td>51</td>
<td>[-4, 2]</td>
<td>100</td>
<td>16</td>
<td>221</td>
<td>5.2 \cdot 10^{-4}</td>
<td>6.1 \cdot 10^{28}</td>
<td>82–138</td>
<td>49</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>CUPID [58, 59, 70]</td>
<td>82 Se</td>
<td>2.1</td>
<td>[-2, 2]</td>
<td>100</td>
<td>69</td>
<td>221</td>
<td>5.2 \cdot 10^{-4}</td>
<td>1.8 \cdot 10^{27}</td>
<td>15–25</td>
<td>n/a</td>
<td>6</td>
<td>n/a</td>
</tr>
<tr>
<td>CUORE [52, 53]</td>
<td>130 Te</td>
<td>2.1</td>
<td>[-1.4, 1.4]</td>
<td>100</td>
<td>81</td>
<td>141</td>
<td>3.1 \cdot 10^{-1}</td>
<td>5.4 \cdot 10^{28}</td>
<td>66–164</td>
<td>6</td>
<td>1</td>
<td>19</td>
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<tr>
<td>CUPID [58, 59, 70]</td>
<td>130 Te</td>
<td>2.1</td>
<td>[-2, 2]</td>
<td>100</td>
<td>81</td>
<td>422</td>
<td>3.0 \cdot 10^{-4}</td>
<td>2.1 \cdot 10^{27}</td>
<td>11–26</td>
<td>3000</td>
<td>1</td>
<td>50</td>
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<tr>
<td>SNO+ Phase I [66, 71]</td>
<td>130 Te</td>
<td>57</td>
<td>[-0.5, 1.5]</td>
<td>28</td>
<td>97</td>
<td>1326</td>
<td>3.6 \cdot 10^{-2}</td>
<td>1.6 \cdot 10^{26}</td>
<td>46–115</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>SNO+ Phase II [67]</td>
<td>130 Te</td>
<td>1357</td>
<td>82</td>
<td>[0, 1.4]</td>
<td>64</td>
<td>194</td>
<td>3.9 \cdot 10^{-2}</td>
<td>1.6 \cdot 10^{26}</td>
<td>47–108</td>
<td>1.5</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>KamLAND-Zen 800 [60]</td>
<td>136 Xe</td>
<td>60</td>
<td>[0, 1.4]</td>
<td>80</td>
<td>97</td>
<td>325</td>
<td>2.1 \cdot 10^{-3}</td>
<td>8.0 \cdot 10^{26}</td>
<td>21–49</td>
<td>15</td>
<td>2</td>
<td>2.9</td>
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<tr>
<td>KamLAND-Zen 200 [60]</td>
<td>136 Xe</td>
<td>114</td>
<td>[0, 1.4]</td>
<td>64</td>
<td>97</td>
<td>1741</td>
<td>4.4 \cdot 10^{-4}</td>
<td>4.1 \cdot 10^{27}</td>
<td>9–22</td>
<td>400</td>
<td>1.2</td>
<td>30</td>
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<tr>
<td>nEXO [72]</td>
<td>136 Xe</td>
<td>7.8</td>
<td>[-1.2, 1.2]</td>
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<td>85</td>
<td>1741</td>
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<td>4.1 \cdot 10^{27}</td>
<td>9–22</td>
<td>400</td>
<td>1.2</td>
<td>30</td>
</tr>
<tr>
<td>NEXT 100 [64, 73]</td>
<td>136 Xe</td>
<td>5.2</td>
<td>[-1.3, 2.4]</td>
<td>88</td>
<td>37</td>
<td>398</td>
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<td>7.9 \cdot 10^{26}</td>
<td>21–49</td>
<td>n/a</td>
<td>1</td>
<td>20</td>
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<tr>
<td>NEXT 1.5k [74]</td>
<td>136 Xe</td>
<td>31</td>
<td>[-2, 2]</td>
<td>100</td>
<td>35</td>
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<td>4.2 \cdot 10^{-2}</td>
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<td>65–150</td>
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<td>n/a</td>
<td>n/a</td>
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<tr>
<td>PandaX-III 200 [65]</td>
<td>136 Xe</td>
<td>10</td>
<td>[-2, 2]</td>
<td>100</td>
<td>35</td>
<td>301</td>
<td>1.4 \cdot 10^{-3}</td>
<td>9.0 \cdot 10^{26}</td>
<td>20–46</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>PandaX-III 1k [65]</td>
<td>136 Xe</td>
<td>10</td>
<td>[-2, 2]</td>
<td>100</td>
<td>35</td>
<td>301</td>
<td>1.4 \cdot 10^{-3}</td>
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<td>n/a</td>
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</tr>
</tbody>
</table>
Future experiments

Agostini et al., arxiv:1705.02996 [hep-ex]
nEXO - 5 t LXe TPC

@ SNOLab
nEXO - 5 t LXe TPC
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Background contributions in the ROI for the 3000 kg fiducial cut (2.1 events/year total rate)
Ba ion tagging concept

Ba\(^{+}\) collection tip

Cavity ionizer

Quadrupole linear ion trap

Mass filter

CCD
Ba ion detection

Using a relatively simple and well understood fluorescing system

Demonstrated ion cloud imaging and accurate position control

Demonstrated single ion sensitivity using intermodulation technique (background control)
Expected performance

- Improved Background Rejection

- $^{136}$Xe $0
\beta\beta$ $T_{1/2}$ [yr]

- $1.9 \times 10^{25}$
  *Nature 510, 229 (2014)*

- nEXO Sensitivity (90% C.L.)
- nEXO Discovery 3σ, Prob. 50%
- EXO-200 Sensitivity (90% C.L.)

Livetime [yr]
Expected performance

- Improved EXO-200 after 2 years
- nEXO after 5 years
- nEXO + Ba tagging after 5 years