Neutrinoless Double Beta Decay with nEXO: Experiment Concept, R&D, and Sensitivity

LNGS Seminar

More details in arXiV:1710.05075

November 8, 2017
Neutrino Physics

Knowns

- $\nu$ flavor change
- Non-zero $\nu$ masses
- 3 light interacting neutrinos
- Observed $\nu$ from atmospheric, reactor, solar, supernovae, beam, outer space

Unknowns

- Absolute $\nu$ masses
- $\nu$ mass ordering
- $\nu$ nature: Majorana or Dirac particles?
- Sterile neutrinos?
- CP violation?
- Why $\nu$ much lighter than other fermions?
- ...

Profound consequences:
- physics beyond the Standard Model Physics
- origin of the matter/antimatter asymmetry in the universe
Double Beta Decay

<table>
<thead>
<tr>
<th>Decay</th>
<th>Q</th>
<th>i.a. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table><p>ightarrow^{48}\text{Ti}$ | 4.271 | 0.187  |
| $^{76}\text{Ge}ightarrow^{76}\text{Se}$ | 2.040 | 7.8    |
| $^{82}\text{Se}ightarrow^{82}\text{Kr}$ | 2.995 | 9.2    |
| $^{96}\text{Zr}ightarrow^{96}\text{Mo}$ | 3.350 | 2.8    |
| $^{100}\text{Mo}ightarrow^{100}\text{Ru}$ | 3.034 | 9.6    |
| $^{110}\text{Pd}ightarrow^{110}\text{Cd}$ | 2.013 | 11.8   |
| $^{116}\text{Cd}ightarrow^{116}\text{Sn}$ | 2.802 | 7.5    |
| $^{124}\text{Sn}ightarrow^{124}\text{Te}$ | 2.228 | 5.64   |
| $^{130}\text{Te}ightarrow^{130}\text{Xe}$ | 2.533 | 34.5   |
| $^{136}\text{Xe}ightarrow^{136}\text{Ba}$ | 2.458 | 8.9    |
| $^{150}\text{Nd}ightarrow^{150}\text{Sm}$ | 3.367 | 5.6    |</p>
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- $\beta\beta0\nu$ observation implies:
  - Lepton number non conservation
  - Existence of new class of particles: Majorana fermions
Under assumption of $0\nu\beta\beta$ being mediated by a light Majorana $\nu$ exchange:

\[
[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m^2_e}
\]

phase space factor
\approx Q^5

nuclear matrix elements » uncertainties

effective Majorana neutrino mass

\[
\langle m_{\beta\beta}\rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|
\]

Fig. 6 Effective Majorana mass as a function of the lightest neutrino mass with the application of the cosmological bound. The different colors correspond to the 1, \ldots, 5 $\sigma$ coverage regions.

Also, arXiv:1705.01945, A. Caldwell et al
$	extbf{0} \nu \beta \beta$ Detection Signatures

- Mono-energetic line at $Q_{\beta \beta}$ in the sum electron-energy spectrum
- Localized interaction
- Position (e.g. correlates with source distribution)
- Emission of two correlated electrons
- Daughter nuclide produced
- Constant decay rate, uncorrelated with other events
0νββ with $^{136}$Xe

- $^{136}$Xe can be employed in a range of highly-scalable detectors, as part of abroad, world-wide program employing multiple isotopes/technologies.

- Existing $^{136}$Xe experiments reach sensitivities of $T_{1/2} > 5 \times 10^{25}$ yr, with next-generation experiments aiming for $\sim 10^{28}$ yr.

Liquid (organic) scintillators:
- KamLAND-Zen
- KamLAND2-Zen

Liquid Xe TPCs:
- EXO-200
- nEXO

Gas Xe TPCs:
- NEXT-100/NEXT-ton
- PandaX 200
- PandaX 1k

From D. Moore
Liquid Xe TPCs
Large LXe TPCs: a Technology for Discovery

- A LXe Time Projection Chamber like nEXO allows a multi-parameter measurement:
  1. Interaction **energy** from combined ionization/scintillation

![Graph showing interaction energy from combined ionization/scintillation](image)

Large LXe TPCs: a Technology for Discovery

- A LXe Time Projection Chamber like nEXO allows a multi-parameter measurement:
  1. Interaction **energy** from combined ionization/scintillation
  2. Interaction **multiplicity** i.e. Single-Site (SS) or Multi-Site (SS)

Multiplicity can be used to characterize backgrounds
Large LXe TPCs: a Technology for Discovery

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  1. Interaction **energy** from combined ionization/scintillation
  2. Interaction **multiplicity** i.e. Single-Site (SS) or Multi-Site (SS)
  3. **Stand-off distance** from interaction 3D position

![Graph showing counts vs standoff distance]

- External backgrounds rapidly reduced by Xe attenuation
- Internal events (signal or background) uniformly distributed
A LXe Time Projection Chamber like nEXO allows a multi-parameter measurement:

1. Interaction **energy** from combined ionization/scintillation
2. Interaction **multiplicity** i.e. Single-Site (SS) or Multi-Site (SS)
3. **Stand-off distance** from interaction 3D position
4. **Particle type**
Large LXe TPCs: a Technology for Discovery

- A LXe Time Projection Chamber like nEXO allows a multi-parameter measure:
  1. Interaction **energy** from combined ionization/scintillation
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  3. **Stand-off distance** from interaction 3D position
  4. **Particle type**

- Homogenous detectors

2.5 MeV $\gamma$ attenuation length 8.5 cm =

- 150 kg
- 5000 kg
- 130 cm
Building on EXO-200 Experience

- Performance:
  - Energy resolution: 1.23% $\sigma/Q_{\beta\beta}$
  - Fraction of SS event: ~20%
  - Electron lifetime ~3 ms

- Multi-parameter analysis

- Background composition
  1. Th+U background from external components
  2. $^{137}$Xe (cosmogenic)
  3. $^{222}$Rn

- Background model from fit match pre-data taking background predictions from radioassay

<table>
<thead>
<tr>
<th>Method</th>
<th>$^{232}$Th cnts in $Q_{\beta\beta}\pm2\cdot\sigma_{\beta\beta}$</th>
<th>$^{238}$U cnts in $Q_{\beta\beta}\pm2\cdot\sigma_{\beta\beta}$</th>
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</thead>
<tbody>
<tr>
<td>EXO-200 data</td>
<td>10.3-13.9</td>
<td>5.3-7.1</td>
</tr>
<tr>
<td>EXO-200 radioassay</td>
<td>0.5-7.7</td>
<td>2.0-9.5</td>
</tr>
<tr>
<td>Pre-data prediction</td>
<td>0.9-10.3</td>
<td>6.3-26.8</td>
</tr>
</tbody>
</table>
nEXO Design

A 5000 kg enriched (90%) LXe TPC, directly extrapolated from EXO-200

nEXO
9.2 x 10^{27} \text{ y proj. sens.}
90\% \text{ CL, after 10 y. arXiv:1710.05075}

EXO-200
3.7 x 10^{25} \text{ y sensitivity}
90\% \text{ CL, 177.6 kg.y. arXiv:1707.08707}
nEXO Design

- Access tunnel
- Underground cavern
- Support structure
- TPC
- LXe
- Refrigerant
- Vacuum
- Inner cryostat
- Outer cryostat
- Water shield
- Process Equipment
- LLNL-PRES-741373
nEXO Technological Improvements

- Charge readout strips (anode)
- SiPM `staves’ covering barrel behind field-shaping rings
- In LXe electronics (charge and SiPMs)
- 1.3 m e⁻ drift
- Cathode & HV
High Voltage R&D Test Setups

30l LXe Bern HV test setup now at Carleton U. with cryogenic cameras

400 cc LXe HV setup at SLAC

Max 800 kg LXe setup at LLNL to accommodate full or near-full size parts horizontally

Upper viewport just below LXe Level.

Lower viewport and Cathode tip

Anode connected to oscilloscope, glitch detector or HV probe setup

Test of breakdown voltage in LXe for different small size geometries

HV tests in LXe for different full-nEXO diameter size geometries
High Voltage & TPC R&D

- Spark mitigation: ensure stable operation at -100 kV
- Protection of electronics and components in case of HV breakdown
- TPC design: high-reflectivity and optically open field cage
- Low radioactivity

Novel high-resistivity Si field cage (SLAC)
Photosensors R&D

- ~4m² of VUV-sensitive SiPMs
- No HV required
- Larger gain & lower noise than APDs
Charge Readout R&D

Charge will be collected on arrays of strips fabricated onto low background dielectric wafers

- Self-supporting/no tension
- Built-on electronics (on back)
- Far fewer cables
- Ultimately more reliable, lower noise, lower activity
Charge Readout Prototyping

Results of first prototype testing at arXiv:1710.05109
nEXO Monte Carlo Simulations

- Detailed GEANT4 Monte Carlo includes all important components

- Reconstruction:
  - 1% energy resolution
  - 3 mm clustering $\rightarrow$ 10% SS fractions
  - $>10$ ms electron lifetime

- Validation via full modeling of the charge (arXiv:1710.05109) and light readout
Background Sources

- Long-lived radionuclides
- Cosmogenic radio-nuclides
- Neutrino-induced backgrounds
- $^{214}\text{Bi}$ from $^{222}\text{Rn}$ in steady-state
- Neutron activation from ($\alpha$,n) reactions
Long-lived Radionuclides

— $^{238}\text{U}$, $^{232}\text{Th}$ gamma and beta decays
— $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{40}\text{K}$ included but negligible near $Q_{\beta\beta}$
— Surface backgrounds manageable (as in EXO-200)

— $2\nu\beta\beta$
No Assumptions on Material Radiopurity

- Measurement campaign is in progress to assay all materials used for nEXO construction using variety of techniques
- Only materials with measured radioassay levels are used in the nEXO sensitivity estimation

<table>
<thead>
<tr>
<th>Material</th>
<th>Supplier</th>
<th>Method</th>
<th>K [ppb]</th>
<th>Th [ppt]</th>
<th>U [ppt]</th>
<th>$^{60}$Co [μBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Aurubis</td>
<td>ICPMS/Ge/GDMS</td>
<td>&lt;0.7</td>
<td>0.13±0.06</td>
<td>0.26±0.01</td>
<td>&lt;3.2</td>
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<tr>
<td>Sapphire</td>
<td>GTAT</td>
<td>NAA</td>
<td>9.5±2.0</td>
<td>6.0±1.0</td>
<td>&lt;8.9</td>
<td>-</td>
</tr>
<tr>
<td>Quartz</td>
<td>Heraeus</td>
<td>NAA</td>
<td>0.55±0.04</td>
<td>&lt;0.23</td>
<td>&lt;1.5</td>
<td>-</td>
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<tr>
<td>SiPM</td>
<td>FBK</td>
<td>ICPMS/NAA</td>
<td>&lt;8.7</td>
<td>0.45±0.12</td>
<td>0.86±0.05</td>
<td>-</td>
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<tr>
<td>Epoxy*</td>
<td>Epoxies Etc.</td>
<td>NAA</td>
<td>&lt;20</td>
<td>&lt;23</td>
<td>&lt;44</td>
<td>-</td>
</tr>
<tr>
<td>Kapton*</td>
<td>Nippon Steel Cables</td>
<td>ICPMS</td>
<td>-</td>
<td>&lt;2.3 pg/cm$^2$</td>
<td>4.7±0.7 pg/cm$^2$</td>
<td>-</td>
</tr>
<tr>
<td>HFE*</td>
<td>3M HFE-7000</td>
<td>NAA</td>
<td>&lt;0.6</td>
<td>&lt;0.015</td>
<td>&lt;0.015</td>
<td>-</td>
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<tr>
<td>Carbon Fiber</td>
<td>Mitsubishi Grafil</td>
<td>Ge</td>
<td>550±51</td>
<td>58±19</td>
<td>19±8</td>
<td>-</td>
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<tr>
<td>ASICs</td>
<td>BNL</td>
<td>ICPMS</td>
<td>-</td>
<td>25.7±0.7</td>
<td>13.2±0.1</td>
<td>-</td>
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<tr>
<td>Titanium</td>
<td>TIMET</td>
<td>Ge</td>
<td>&lt;3.3</td>
<td>57±5</td>
<td>&lt;7.3</td>
<td>-</td>
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<tr>
<td>Water</td>
<td>SNOLAB</td>
<td>Assumed</td>
<td>&lt;1000</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>-</td>
</tr>
</tbody>
</table>
Cosmogenic Radionuclides

- Aboveground: manageable with proper material handling to limit cosmic rays exposure
- Underground: $^{137}$Xe steady-state production from n capture
Neutrino-induced Backgrounds

- Electron-neutrino elastic scattering \( \nu + e^- \rightarrow \nu + e^- \)
  - Calculable
  - Small: \( \sim 0.02 \) SS events/(FWHM.2000kg.y)

- Charge-current neutrino capture \( \nu + ^{136}\text{Xe} \rightarrow e^- + ^{136}\text{Cs} \)
  - Estimated \( \sim 20 \) interactions / (2000kg.y)
  - Prompt radiation: negligible fraction of e\(^-\) have right energy
  - Delayed \(^{136}\text{Cs} \) decay: very high single-site rejection

- Neutral-current inelastic scattering
Steady-state $^{222}\text{Rn}$: an “external” background

- $^{222}\text{Rn}$ from emanation of materials in the xenon piping
- Estimate ~600 atoms steady-state in nEXO based on EXO-200 extrapolation
- Three components:
  - LXe inside TPC (17%)
  - LXe outside TPC + Cathode (84%)
- Bi-Po tagging
Analysis and Fit Results

- Frequentist approach to sensitivity calculation
- "Toy" experiments generated from radioassay values and fit using log-likelihood technique
- Simultaneous fit of energy, standoff distance, and multiplicity (SS/MS)
- Example of fit result for one toy experiment
Fit Results in the FWHM around $Q_{\beta\beta}$

Counts

LXe volume [kg]

Standoff [mm]

- Toy Data
- Best Fit
- $0\nu\beta\beta$
- $2\nu\beta\beta$
- Far components
- Internals $^{232}\text{Th}$
- Internals $^{238}\text{U}$
- $^{222}\text{Rn}$
- LXe $^{137}\text{Xe}$
- TPCVessel $^{232}\text{Th}$
- TPCVessel $^{238}\text{U}$
The Advantages of a Homogenous Detector

- Power of using a simultaneous fit of energy, multiplicity and event position. This is not a one-dimensional peak search.

- Optimal use of the LXe mass: the inner mass provides sensitivity to signal while the outer regions allow to constrain the background.
The Advantages of a Homogenous Detector

- Power of using a simultaneous fit of energy, multiplicity and event position. This is not a one-dimensional peak search.
- Optimal use of the LXe mass: the inner mass provides sensitivity to signal while the outer regions allow to constrain the background.
nEXO background index is not a single number!

- Single background index not sufficient to describe nEXO
- External backgrounds dominate
nEXO background index is not a single number!

For nEXO, the simple physics of $\gamma$ attenuation in LXe, coupled with multi-parameter discrimination, drives the background estimation.

Majorana Demon. / GERDA arXiv:1710.11608 / 1710.07776

10 cts/tonne in 10 y

1 cts/tonne in 10 y
Goal for LEGEND-1000 & CUPID

~ Background free

~3x10^{-4} cts/(FWHM.kg.y)
Estimated Background Budget

- Same procedure validated for EXO-200
- Internal components dominate, as expected
- Several radioassay entries with only 90% CL limit (more measurements may improve the estimated background)
Exclusion limit at 90% CL computed as the median upper limit of an ensemble of $10^4$ toy experiments and without assuming Wilks’s theorem

The (Small) Role of Energy Resolution

- Only relatively small improvement from improved energy resolution
- Further improvements not critical to reach compelling sensitivity

- $2\nu\beta\beta$ is almost negligible in nEXO: 0.34 counts in 10 years in the entire LXe
- Rapidly worsen with increasing energy resolution
Sensitivity with improved backgrounds

- “Baseline” = radioassay-based background estimate
- “Aggressive” = arising from plausible improvements from R&D
- “2νββ-only” = limit case
- Power law fit gives: $T_{1/2} \propto \frac{1}{B^{0.35}}$.

nEXO is not as sensitive to backgrounds as a naïve $\sqrt{B}$ scaling would imply.
Conclusions

- $0\nu\beta\beta$ could reveal fascinating new physics
- LXe TPC is a proven technology for $0\nu\beta\beta$ search. Multi-parameter reconstruction in a homogenous detector allows to optimally ”resolve” signal and backgrounds.
- nEXO’s sensitivity reach is solidly grounded in
  - EXO-200 experience
  - $\gamma$ attenuation in a large LXe detector
  - measured material radiopurity
- The nEXO collaboration is ready to build an experiment with:
  - ultra-low background: $\sim 3 \times 10^{-4}$ cts/(FWHM.kg.y) in the inner 2000 kg
  - compelling discovery potential ($5.7 \times 10^{27}$ y at 3$\sigma$)
  - reach on the Majorana neutrino mass $\sim 10$ meV range

The nEXO Collaboration

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