Status and Prospects for the EXO-200 and nEXO Experiments

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Use Liquid Xenon Time Projection Chambers (TPC) to Search for $0\nu\beta\beta$ Decay

- Xe is used both as the source and detection medium.
- Simultaneous collection of both ionization and scintillation signals.
- Full 3-D reconstruction of all energy depositions in LXe.
- Monolithic detector structure, excellent background rejection capabilities.

EXO-200 is a running LXe detector with ~110 kg active volume. It has demonstrated key performance parameters for $0\nu\beta\beta$ search, and can reach $0\nu\beta\beta$ half-life sensitivity of $5.7 \times 10^{25}$ yrs after Phase-II operation.

nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach $0\nu\beta\beta$ half-life sensitivity of ~ $10^{28}$ yrs.
Monolithic Detectors

<table>
<thead>
<tr>
<th>LXe mass (kg)</th>
<th>Diam. or length (cm)</th>
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<tbody>
<tr>
<td>5000</td>
<td>130</td>
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<tr>
<td>150</td>
<td>40</td>
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<td>5</td>
<td>13</td>
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2.5MeV gamma ray attenuation length 8.5 cm = ——

Monolithic detector is essential for background rejection:
• Rejection of surface background
• Self-shielding, containment of Compton scattering
• Inner fiducial volume extremely clean
TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.

SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.
EXO-200 has achieved $\sim 1.25\%$ energy resolution at the $Q$ value. nEXO will reach resolution $< 1\%$, sufficient to suppress background from $2\nu\beta\beta$. Combining Ionization and Scintillation energy to enhance energy resolution.

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D (E. Conti et al. Phys Rev B 68 (2003) 054201)
While LXe TPCs provide many handles to discriminate backgrounds, energy resolution is the only handle to discriminate $2\nu\beta\beta$ background.

Future very large scale detectors should have sufficient energy resolution to suppress the $2\nu\beta\beta$ mode.

The $2\nu\beta\beta$ background is smallest for $^{136}\text{Xe}$, as it has the longest $2\nu\beta\beta$ half-life.
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)
- All signals digitized at 1 MHz, ±1024 µs around trigger (2 ms total)
- Drift field 376 V/cm
- TPC housed in a copper vessel with 1.37 mm wall thickness
EXO-200 Phase-I Results

Precision $^{136}$Xe 2$\nu\beta\beta$ Measurement

EXO-200 start data taking in June 2011

Discovery of 2$\nu$ mode \cite{PRL107,212501(2011)}

Confirmation by KamLAND-Zen \cite{PRC85,045504(2012)}

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

\cite{PhysRevC89,015502(2014)}

Longest and most precisely measured 2$\nu\beta\beta$ half-life
EXO-200 Phase-I Results

$^{136}$Xe 0νββ search with 100 kg·yr exposure

Background in the 0ν ROI: $(1.7\pm0.2)$·keV$^{-1}$ ton$^{-1}$ yr$^{-1}$

From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr $\langle m_{\beta\beta}\rangle < 190 - 450$ meV (90% C.L.)

Nature (2014) doi:10.1038/nature13432
Recovery from Underground Incidents

WIPP Events:

- 5 Feb. 2014 - Fire in WIPP underground
- 14 Feb. 2014, ~23:00 – Unrelated airborne radiological event

Recovery:

- 18 Feb 2014, remote recovery of enriched xenon
- Sept. 2014 – June 2015, drift and clean room cleanup and TPC health diagnostics (no measureable radioactive contamination inside or outside the cleanrooms.
- June – Oct. 2015, equipment repair and Infrastructure maintenance

(EXO-200 detector and control systems worked well despite trying circumstances.)

Phase-II Restart:

- Feb. – April 2016, detector upgrades (electronics and derandonator)
- April 2016, Phase-II Physics data taking begins
EXO-200 Phase-II Operation

- EXO-200 Phase-II operation begins on 1/31/2016, after enriched liquid xenon fill.
- Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.

Xenon purity since Jan. 31, 2016

Rn level in TPC since Jan. 31, 2016

\[ A(t=0) = 189.9 \pm 2.9 \, \mu\text{Bq/kg}, \quad t_{1/2} = 3.82 \, \text{d (fixed)} \]

\[ \text{Phase1 rate ( 4.2 \, \mu\text{Bq/kg})} \]
Further improvements in detector energy resolution may be possible with better signal reconstruction and detector non-uniformity corrections.
EXO-200 Phase II Upgrade Performance (Deradonator)

Air gap (need low Rn)

Rn tent

Lead shield

Copper cryostat

EXO-200 Clean Room Module 1

Deradnator can deliver 0.85 m³/min of low Rn air

Measurements show that the Rn level in the air gap has been reduced by a factor ~ 10, sufficient to suppress this background for $0
\nu \beta \beta$ search.
Phase-II Analysis Improvements

**Xe-137 Veto**

Muon veto coincident MS data:

$^{136}\text{Xe}(n,\gamma)$ capture line

Tagging neutron capture events using both veto panel and prompt gamma information can suppress $^{137}\text{Xe}$ background.

**Improved SS/MS discriminators**

Discriminating gamma/beta events using the pulse rise time can suppress U and Th background.

Many other analysis techniques under study:

- Enhance energy resolution through corrections of spatial and temporal non-uniformity
- Reduce systematics through detector simulation and calibration
- Implement continuous multiplicity metrics to improve event classification
- Develop multivariate discriminators and other machine learning algorithms
EXO-200 can reach $0\nu\beta\beta$ half-life sensitivity of $5.7 \times 10^{25}$ ys.

With lower threshold, EXO-200 can improve measurement of $^{136}$Xe $2\nu\beta\beta$ and searches in other physics channels.

EXO-200:
Nature (2014),
doi:10.1038/nature13432

GERDA Phase 2:
Public released result. June, 2016 (frequentist limit)

KamLAND-Zen:
From EXO-200 to nEXO

- EXO-200 has surpassed design energy resolution and SS/MS rejection capability, and is expected to have surpassed the design background goals.
- nEXO is a ~ 5 tonne LXe TPC with better detector performance.
- 4.7 tonnes of active \( \text{enrXe} \) (90% or higher), < 1.0% \((\sigma/E)\) energy resolution.

![Diagram showing dimensions of EXO-200 and nEXO detectors. The nEXO detector is labeled as ~5 tonne LXe TPC with better detector performance. The diagram indicates 1.3 m width and 46 cm height.](image-url)
Preliminary artist view of nEXO in the SNOlab Cryopit

6,000 m.w.e. depth sufficient to shield cosmogenic background.
Baseline concept: (Improved TPC design).

- Single drift volume
- Charge collection on the anode plane
- Light collection on the barrel behind field shaping rings
A modular and pad-like charge collection scheme is under study to replace a more traditional wire readout.

Prototype 3mm pitch, crossed strip quartz tile has been produced and tested in liquid xenon.

First nEXO-specific run at FBK (Italy) provided ~10% PDE. New generation devices have reached PDE > 15% @ 170nm. Radio assay results of the FBK devices are also very encouraging.

Recent substantial progress in radio-assay and simulation assists the detector design optimization and provides more accurate predictions of $0\nu\beta\beta$ sensitivity.
nEXO sensitivity as a function of time for the best-case nuclear matrix element (GCM).

P4.056 The sensitivity of the nEXO experiment to majorana neutrinos C. Licciardi
Tagging $\beta\beta$ decay daughter Ba

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^- + 2\bar{\nu}_e$$

$\leq 27$ atoms

$\leq 9$ atoms

$\leq 2.4$ atoms

0 atoms

Images of the blue points are shown.
University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
University of Bern, Switzerland — J-L Vuilleumier
University of California, Irvine, Irvine CA, USA — M Moe
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Drexel University, Philadelphia PA, USA — E Callaghan, MJ Dolinski, YH Lin, E Smith, Y-R Yen
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The EXO-200 Detector

- High purity Heat transfer fluid HFE7000
  - > 50 cm
- DOUBLE-WALLED CRYOSTAT
  - 25 mm ea
- LXe VESSEL
  - 1.37 mm Wall
- Radio Quiet Environment
- LEAD SHIELDING
  - > 25 cm
- VETO PANELS
EXO-200 Phase II Upgrade Performance (Front-End Electronics)

- After electronics upgrade, the coherent sum noise of the APD channels is reduced by a factor 2.5.
- There is only 20% excessive coherent noise remaining.