Outline

• Xenon-based $\beta\beta^0\nu$ experiments
• The NEXT detection concept
• Results from the NEXT R&D phase
• NEXT-100
• Ideas for a ton-scale detector
Xenon-Based $\beta\beta^0\nu$ Experiments
Xenon-Based Detectors

EXO5.88 uses the xenon as both source and detector in a homogeneous liquid phase TPC. At the operating temperature of $-10$–K and pressure of $0.1$–kPa, the liquid xenon ($LXe$) has a density of $0.68$ g/cm$^3$. The xenon for EXO5.88 is enriched to $86$ in the isotope $^{136}$Xe.

In order to minimize the surface to volume ratio while maintaining a practical geometry, the detector is a double TPC having the shape of a square cylinder with a cathode grid held at negative high voltage at the mid plane. The signal readout is performed at each base of the cylinder, near ground potential. Of the $0.88$ kg of enriched xenon available, $0.8$ kg are in liquid phase, and $0.8$ kg are in the active volume of the detector. A cutaway view of the TPC is shown in Figure 1.

Two considerations were central in designing the detector: the need for good energy resolution at the double beta decay decay $Q$ value of $0.56$ ($keV$ $= 0.76$), and the requirement to achieve exceedingly low backgrounds. Early RyD performed by the EXO collaboration showed that the energy resolution in LXe can be substantially improved by using an appropriate linear combination of ionization and scintillation as the energy estimator. This technique was subsequently used in other contexts. In EXO5.88 both the ionization and the scintillation signals are recorded. Charge is collected at each end of the TPC by wire planes, held at virtual ground, while the $0.28$ nm wavelength scintillation light is collected by two arrays of large area avalanche photodiodes (APD).

KamLAND-Zen

- Liquid scintillator detector
- Inner balloon with 300 kg of $^{136}$Xe

EXO-200

- Time projection chamber
- 90 kg of $^{136}$Xe in liquid phase

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**ββ0ν Searches In $^{136}$Xe**

- $^{136}$Xe: ββ emitter with $Q_{ββ} = 2.458$ MeV
- No evidence for ββ0ν in $^{136}$Xe so far. Best limits in the market.

**KamLAND-Zen**

$T_{1/2}^{0ν}(^{136}$Xe) $> 1.9 \times 10^{25}$ yr (90% CL)

**EXO-200**

$T_{1/2}^{0ν}(^{136}$Xe) $> 1.6 \times 10^{25}$ yr (90% CL)

Combined: $T_{1/2}^{0ν}(^{136}$Xe) $> 3.4 \times 10^{25}$ yr  \[ m_{ββ} < 120-250 \text{ meV} \]
The NEXT Detection Concept
### Relevant parameters and features of the "magnificent nine" double-beta decay candidates.

<table>
<thead>
<tr>
<th>Double-beta candidate</th>
<th>Q-value (MeV)</th>
<th>Phase space $G_{01}(y^{-1})$</th>
<th>Isotopic abundance (%)</th>
<th>Enrichable by centrifugation</th>
<th>Indicative cost normalized to Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.27226 (404)</td>
<td>$6.05 \times 10^{-14}$</td>
<td>0.187</td>
<td>No</td>
<td>—</td>
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<tr>
<td>$^{76}$Ge</td>
<td>2.03904 (16)</td>
<td>$5.77 \times 10^{-15}$</td>
<td>7.8</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.99512 (201)</td>
<td>$2.48 \times 10^{-14}$</td>
<td>9.2</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3.35037 (289)</td>
<td>$5.02 \times 10^{-14}$</td>
<td>2.8</td>
<td>No</td>
<td>—</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.03440 (17)</td>
<td>$3.89 \times 10^{-14}$</td>
<td>9.6</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.81350 (13)</td>
<td>$4.08 \times 10^{-14}$</td>
<td>7.5</td>
<td>Yes</td>
<td>3</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.52697 (23)</td>
<td>$3.47 \times 10^{-14}$</td>
<td>33.8</td>
<td>Yes</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2.45783 (37)</td>
<td>$3.56 \times 10^{-14}$</td>
<td>8.9</td>
<td>Yes</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3.37138 (20)</td>
<td>$1.54 \times 10^{-13}$</td>
<td>5.6</td>
<td>No</td>
<td>—</td>
</tr>
</tbody>
</table>

Potentially very low background from:
- 0.5-1% FWHM energy resolution
- Tracking and dE/dx information for event topology

Scalability to ton-scale relatively easy
NEXT Detection Concept

Idea #1:
Use a xenon gas TPC

Idea #2:
Use electroluminescence to amplify ionization signal

Idea #3:
Ionization used for separated energy and tracking measurements

Idea #4:
Energy sensors detect also primary scintillation for $t_0$ determination

Idea #5:
Shift 170 nm Xe light to longer wavelength
Results From The NEXT R&D Phase
NEXT R&D Main Goals

• Demonstrate good energy resolution in a large active volume

• Reconstruct the topological signature of electrons in high-pressure xenon gas

• Test long drift lengths and high voltages

• Understand gas recirculation and purification in a large volume (eg, gas leaks)

• Understand light collection and use of wavelength shifters
## R&D Tools and Operating Conditions

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototypes</td>
<td>NEXT-DBDM, NEXT-DEMO, NEXT-MM</td>
</tr>
<tr>
<td>Sources</td>
<td>$^{22}\text{Na}$ (30-511 keV), $^{137}\text{Cs}$ (30-662 keV), $^{226}\text{Ra}$ (5.5-7.7 MeV)</td>
</tr>
<tr>
<td>Xenon pressure</td>
<td>10-15 bar</td>
</tr>
<tr>
<td>Wavelength shifting</td>
<td>none, with TPB coating (170→430 nm)</td>
</tr>
<tr>
<td>Energy plane</td>
<td>Hamamatsu R7378A PMT</td>
</tr>
<tr>
<td>Tracking plane</td>
<td>Hamamatsu R7378A PMT, S10362-11-025P/050P SiPM</td>
</tr>
<tr>
<td>Drift field</td>
<td>0.16-1.03 kV/cm</td>
</tr>
<tr>
<td>Electroluminescence field</td>
<td>1-3 kV/(cm·bar)</td>
</tr>
</tbody>
</table>
Energy Resolution

• 1% FWHM energy resolution accomplished for 662 keV gammas

• Extrapolates to 0.5% FWHM at $Q_{\beta\beta}$

• Only factor of 2 worse than intrinsic limit from Fano factor

• Photon statistics and PMT charge resolution affect energy resolution

NEXT Coll., arXiv: 1211.4474, to appear in NIM A

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Energy Resolution

• Good energy resolution maintained also in larger fiducial volume: 1.75% FWHM for 511 keV gammas

• Requires mapping energy response in plane perpendicular to drift field

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Tracking

SiPM-based tracking system successfully reconstructing:

- Straight cosmic ray muon tracks
- MCS-dominated electron tracks from 511 keV gammas
- Isolated X-ray energy depositions (30 keV)

dE/dx

- Counting number of “Bragg peaks” provides background suppression:
  - Signal: two “blobs” from two e- from common vertex
  - Background: one “blob” (1 e-)

- Blobs can be identified by projecting dE/dx into drift direction (PMT-only)

- Full 3D dE/dx information from (PMT + SiPM) system to be explored

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Xenon Properties

- Ionization electron transport properties measured with alpha particles and X-rays
  - Drift velocity, longitudinal diffusion

- Electron-ion recombination studies:
  - First observation of correlated fluctuations between ionization and scintillation in xenon gas
  - Important only for highly ionizing particles (not for electrons)
• TPC filled with $^{136}$Xe gas (90% enrichment) at $\sim$15 bar pressure
• First-generation experiment with $\sim$100 kg fiducial mass: NEXT-100
• To be installed in Laboratorio Subterraneo de Canfranc (LSC, Spain)
Pressure Vessel and Inner Copper Shield

- Pressure vessel made of low-activity stainless steel. Under construction
- 12 cm thick inner copper shield against pressure vessel radio-activity

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max pressure</td>
<td>15 bar</td>
</tr>
<tr>
<td>Diameter</td>
<td>140 cm</td>
</tr>
<tr>
<td>Length</td>
<td>230 cm</td>
</tr>
<tr>
<td>Mass, pressure vessel</td>
<td>1,200 kg</td>
</tr>
<tr>
<td>Mass, inner copper shield</td>
<td>10,000 kg</td>
</tr>
</tbody>
</table>
Time Projection Chamber

- Field cage made of high-density polyethylene
- Wire meshes and TPB-coated reflector panels similar to NEXT-DEMO

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift length</td>
<td>130 cm</td>
</tr>
<tr>
<td>EL gap</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Cathode voltage</td>
<td>-58 kV</td>
</tr>
<tr>
<td>Gate voltage</td>
<td>-22.5 kV</td>
</tr>
<tr>
<td>Anode voltage</td>
<td>0</td>
</tr>
<tr>
<td>Drift field</td>
<td>0.3 kV/cm</td>
</tr>
<tr>
<td>EL field</td>
<td>3 kV/(cm·bar)</td>
</tr>
<tr>
<td>Optical gain</td>
<td>2,500 photon/e</td>
</tr>
</tbody>
</table>
Energy Plane

- 60 low-radioactivity PMTs enclosed in pressure-resistant enclosures
- 30% photo-cathode coverage

Hamamatsu R11410-10
• 7,000 SiPMs mounted on TPB-coated Cuflon boards, at 1 cm pitch
• Channels extracted through 3 custom-made pressure-tight connectors
• 20 cm thick lead castle structure
Material Screening

• Careful selection for components that are either massive or inside the vessel

• Germanium gamma-ray spectrometry measurements at Canfranc

NEXT Coll., JINST 8 (2013) T01002
Backgrounds

- Main backgrounds around $Q_{\beta\beta} = 2.458$ MeV from de-excitation gammas of $^{208}$Tl and $^{214}$Bi decay daughters

### Background model

### Estimated background rates

<table>
<thead>
<tr>
<th>Component</th>
<th>$^{208}$Tl $(10^{-4}/(\text{keV} \cdot \text{kg} \cdot \text{yr}))$</th>
<th>$^{214}$Bi $(10^{-4}/(\text{keV} \cdot \text{kg} \cdot \text{yr}))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy plane</td>
<td>2.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Tracking plane</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Pressure vessel</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Field cage</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&lt;4.5</strong></td>
<td><strong>&lt;2.5</strong></td>
</tr>
</tbody>
</table>

Activities from material screening results.

Background rejection factors from simulations. $2 \times 10^{-7}$ or better.
Physics Case

NEXT-100 sensitive to Majorana masses as small as 100 meV after 5 years of operation.

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Figure 22

The exposure (kg year)

- Sensitivity to Majorana (ββ) computed following the method described in [21].
- The solid blue line corresponds to the baseline scenario where 211 kg of enriched xenon are used, whereas the dashed red line shows the sensitivity of the detector with 261 kg of source mass.

Such a design provides both optimal energy resolution and event topological information for background rejection.

The expected background rate is $9 \times 2^{17} \text{ counts/ (keV} \cdot \text{kg} \cdot \text{y)}$: this results in a sensitivity to see figure 33 after 6 years of data-taking of about $6 \times 2^{36}$. This is better than 211 meV.

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y- RY(y3119)
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- (European Commission under the European Research Council Starting Grant St%351165)
- (Director Office of Science)
- (Office of Basic Energy Sciences)

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EXO200

GERDA1

CUORE

KamLAND-Zen

SNO+

GERDA2

CUORE

NEXT

SuperNemo D.

Majorana D.
Ideas For A Ton-Scale Detector
Requirements for Full Exploration of Inverted Hierarchy

- If successful, NEXT-100 to be followed by high-pressure xenon gas detector at ton or multi-ton scale.

- Exposure requirement: \( \geq 10 \text{ ton} \cdot \text{yr} \)

- Background requirement: \( \leq 0.1\text{-}1 \text{ count}/(\text{ton} \cdot \text{yr}) \)

- Hierarchical spectrum, inverted ordering

- 10 cts/yr
- 1 cts/yr
- 0.1 cts/yr
- Bgr-free

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NEXT at Ton-Scale: Possible Improvements Over NEXT-100

- Mild increase in operating pressure
- Gas additives to shift 175 nm xenon light
- Higher light collection and better PMT shielding by guiding light to PMTs through WLS plastic bars
- Explore alternatives to (EL+SiPM)-based system for more powerful identification of $\beta\beta$ topology
- Active outer detector operated as veto system against vessel and external backgrounds

• Xe-based experiments providing best $\beta\beta 0\nu$ constraints to date

• NEXT high-pressure xenon gas TPC concept may outperform EXO and KamLAND-Zen thanks to better energy resolution and event topology information

• Successful NEXT R&D phase now under completion

• NEXT-100 detector under construction. Commissioning run at Canfranc (Spain) in 2014, physics run starting in 2015

• Started to plan ton-scale extensions of NEXT concept