A search for neutrinoless double beta decay with xenon

M. Breidenbach
SLUO
EXO Collaboration

H. Breuer, C. Hall, L. Kaufman, D. Leonard, S. Slutsky, Y-R. Yen
U. of Maryland, College Park MD, USA
K. Kumar, A. Pocar
U. of Massachusetts, Amherst, Amherst MA, USA
M. Auger, G. Giroux, R. Gornea, F. Juget, G. Lutter, J-L. Vuilleumier
Laboratory for High Energy Physics, Bern, Switzerland
SLAC, Menlo Park CA, USA
Physics Dept., Stanford University, Stanford CA USA

K. Barry, E. Niner, A. Piepke
Physics Dept., U. of Alabama, Tuscaloosa AL, USA
P. Vogel
Physics Dept., Caltech, Pasadena CA, USA
A. Bellerive, M. Bowcock, M. Dixit, K. Graham, C. Hargrove, E. Rollin, D. Sinclair, V. Strickland
Carleton University, Ottawa, Canada
C. Benitez-Medina, S. Cook, W. Fairbank Jr., K. Hall, B. Mong
Colorado State U., Fort Collins CO, USA
M. Moe
Physics Dept., UC Irvine, Irvine CA, USA
ITEP Moscow, Russia
Laurentian U., Canada
**ββ Decay**

2ν:

*Conventional 2\textsuperscript{nd} order process in nuclear physics*

0ν mode:

A hypothetical process that can happen only if:

- \( M\nu \neq 0; \)
- \( \nu = \overline{\nu}; \)
- \( |\Delta L| = 2 \)
- \( |\Delta(B-L)| = 2 \)
Current knowledge of the neutrino mass hierarchy

## EXO Sensitivities

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E$ @2.5MeV (%)</th>
<th>$2\nu\beta\beta$ BG (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr) 90%CL</th>
<th>Majorana Mass (meV) QRPA\textsuperscript{1} NSM\textsuperscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>1</td>
<td>70</td>
<td>5</td>
<td>1.6</td>
<td>0.5 (use 1)</td>
<td>$2 \times 10^{27}$</td>
<td>24</td>
</tr>
<tr>
<td>Aggressive</td>
<td>10</td>
<td>70</td>
<td>10</td>
<td>1</td>
<td>0.7 (use 1)</td>
<td>$4.1 \times 10^{28}$</td>
<td>5.3</td>
</tr>
</tbody>
</table>

2) Caurier, et. al., arXiv:0709.2137v1
Experimental $\beta\beta$ observables

Energy resolution is the only tool to separate $2\nu\beta\beta$ from $0\nu\beta\beta$.

Background control is critical. Ba tagging changes EXO to a coincidence experiment – eliminating external backgrounds.

Sensitivity

\[ S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \left[ \frac{MT}{B\Gamma} \right]^{1/2} \]

- \( \varepsilon \) is efficiency
- \( a \) is isotopic abundance
- \( A \) is atomic mass
- \( M \) is source mass
- \( T \) is time
- \( B \) is background
- \( \Gamma \) is resolution

To maximize sensitivity:
- • Large mass - more signal
- • Low background - the biggest challenge by far!!!
- • High detection efficiency - sure
- • Good energy resolution - required to separate 0\( \nu \)\( \beta\beta \) from 2\( \nu \)\( \beta\beta \)

Identification of the daughter isotope rejects all but 2\( \nu \)\( \beta\beta \) background and confirm double beta decay.
Multiple Paths to a Background Free Detector

EXO

High Pressure Gas TPC

Ba Identification in High-Pressure Gas

Cryogenic Liquid TPC

Ba Identification in Liquid

Ba Identification in low-pressure Gas
“EXO is a program aimed at building an enriched xenon double beta decay experiment with a one or more ton $^{136}$Xe source, with the particular ability to detect the two electrons emitted in the decay in coincidence with the positive identification of the $^{136}$Ba daughter via optical spectroscopy”

EXO Strategy:

- Separately develop an understanding of the issues for liquid Xe and for moderate pressure gaseous Xe.
- For both cases, develop techniques for extraction and tagging of the Ba ion.
What, Where & Who

EXO-200:

200 Kg enriched $^{136}$Xe liquid TPC at WIPP.

All features (including all issues of radio purity) except Ba$^+$ tag.

Conceived as a prototype, actually a non-trivial experiment.

Spectroscopic identification of single Ba$^+$

Operational with RF trap at Stanford.

Extraction techniques

Unsolved, work primarily at Stanford, Colorado, SLAC

Various tips that electrostatically attract the ion and then release to trap.

Gas TPC

100 Kg system (not radio quiet) at Carleton, Laurentian

Carry ion to trap through system of nozzles and differential pumping

EXO is an international collaboration of 74 people - senior physicists, post-docs, grad students, engineers, and techs. We are interested in modest expansion with talented experimentalists.
Why Xenon?

Xenon isotopic enrichment is easier: Xe is a gas and $^{136}$Xe is the heaviest isotope.

Xenon is “reusable”: can be re-purified and recycled into new detector (no crystal growth).

Monolithic detector: LXe is self shielding, surface contamination minimized.

Minimal cosmogenic activation: no long lived radioactive isotopes of Xe.

Energy resolution in LXe can be improved: scintillation light + ionization anti-correlation.

... admits a novel coincidence technique: background reduction by Ba daughter tagging.
EXO-200 Goals

- Look for 0νββ decay of $^{136}$Xe with competitive sensitivity:
  0.13 ev (NSM)$^{(1)}$ ; 0.19 ev (QRPA)$^{(2)}$
  ($T^{0\nu}_{1/2} > 6 \times 10^{25}$ y, current limit: $T^{0\nu}_{1/2} > 1.2 \times 10^{24}$ y)

  (2) Caurier et al., arXiv:0709.2137v1

• Measure the standard 2νββ decay of $^{136}$Xe ($Q = 2457.8 \pm 0.4$ keV) and
  measure its lifetime (best upper limit to date: $T^{2\nu}_{1/2} > 1 \times 10^{22}$ y)


• Measure backgrounds on a significant size ultra-clean detector to
  understand the additional advantage of the Ba tag.

• Measure backgrounds at ~2000 m.w.e. depth

• Test LXe technology (purification, control, and enrichment on a large scale)

• Test liquid TPC strategy, position and energy
• 200kg $^{136}$Xe (80% enrichment) liquid phase (~160K), both source and detector of $0\nu\beta\beta$
• $Q_{\beta\beta}^{Xe-136} \sim 2.5$ MeV $0\nu\beta\beta$ endpoint energy
• $0\nu\beta\beta$ electrons deposit energy as charge (slow) and scintillation (fast)
• Collect ionization on wires -> charge preamplifiers
• Collect scintillation on APDs
• Energy reconstruction from ionization + scintillation ($\Delta E/E = 1.4\%$ at $Q_{bb}$)
• Event position from charge distribution and $t_{SCINT}-t_{ION}$ (useful for Ba tagging on full EXO)
LXe Data Show Anticorrelation between Scintillation and Ionization

- Timing of the event:
  Scintillation light gives \( t = 0 \) for drift time (z)

- Position of the event:
  Crossed wires at the anode \((x-y)\) collect charge at \( t=z \)

- Event energy:
  Ionization + scintillation light

**Ionization alone:**
\[
\sigma(E)/E = 3.8\% \text{ @ } 570 \text{ keV} \text{ or } 1.8\% \text{ @ } Q(\beta\beta)
\]

**Ionization & Scintillation:**
\[
\sigma(E)/E = 3.0\% \text{ @ } 570 \text{ keV} \text{ or } 1.4\% \text{ @ } Q(\beta\beta)
\]

TPC Design

- Acrylic supports
- LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)
- Teflon light reflectors
- Central HV plane (photo-etched phosphor bronze)
- Field shaping rings (copper)
- Flex cables on back of APD plane (copper on kapton, no glue)
- X-y crossed wires, 60°
EXO-200

- Copper cryostat
- ~1.5m
- Copper liquid xenon vessel
- HFE7000 cooling/shielding fluid
- Surrounded by 25 cm Pb shield
Looking into EXO-200 detector without APDs
Detector after cable and APD installation, before final endcap welding
EXO-200 installation site: WIPP

- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- U.S. DOE salt mine for low-level radioactive waste storage
- Salt “rock” low activity relative to hard-rock mine

\[ \Phi_\mu \sim 1.5 \times 10^5 \text{ yr}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \]
\[ U \sim 0.048 \text{ ppm} \]
\[ Th \sim 0.25 \text{ ppm} \]
\[ K \sim 480 \text{ ppm} \]

EXO-200 facility at WIPP

Cryostat, Pb shielding, and xenon transfer lines installed at WIPP in EXO cleanrooms for 4/2009 cryogenic commissioning.
Centrifugally Enriched $^{136}$Xe

200 kg of xenon enriched to 80% = 160 kg of $^{136}$Xe:
The most isotope in possession by any $\beta\beta$0ν collaboration
Ba\textsuperscript{+} Tagging Schematic for Liquid Phase EXO

- Ba\textsuperscript{+} grabber
- Quadrupole linear ion trap
- APDs
- Grid plane
- CCD
Single Ba\(^+\) ion detection

Daughter identified by optical spectroscopy of Ba\(^+\), well studied in ion traps for more than 25 years


- Very specific signature
  ("Λ" shelving)

- Cycling 493/650 nm transitions gives a fluorescence rate of \(~10^8\) Hz (in vacuum)

\[\text{Ba}\(^+\)}\]
\[^2P_{1/2}: \sim 7.9\text{ns}\]

\[\text{Ba}\(^+\)}\]
\[^2D_{3/2}: \text{metastable} \sim 83\text{s}\]

\[^2S_{1/2}\]

\[493\text{nm}\]

\[650\text{nm}\]

Plenty of light!
Single Ba\(^+\) tagging in a quadrupole ion trap

- Observed LIF of a single Ba\(^+\) in a buffer gas filled ion trap (~ 10\(^{-3}\) torr He, some Xe)
- ~ 9\(\sigma\) observation at 25s storage time

B.Flatt et al., NIM A 578 (2007) 409
Liquid Phase Extraction

Resonant Ion Spectroscopy

- UV multimode optical fiber (~400µm core)
- Ba atom on tip
- Semitransparent Metallic Coating
- Ion trap

- Ba⁺ ion in vacuum/gas

Cryogenic Probe

- Au-coated leads
- Vespel sleeves
- Read-out cables
- Cu cold finger

- W heater wire

- 2mm sensor
EXO gas phase R&D

- Several gas-phase advantages
  - Improved $DE/E$
  - Tracking
  - In-situ ID of Ba?
- Gas-phase R&D underway at Laurentian and Gotthard (U. Bern)

- 10 bar GXe chamber
- 1 MeV $e^-$ source
- Segmented readout (tracking)
- CsI photocathode

One GXe concept

Ba extraction test setup
SLAC Context

As accelerator based particle physics opportunities at SLAC (on site) have gone, the lab appears interested in playing a stronger role in national underground physics.

SLAC has involvement with EXO and CDMS, both have interests at DUSEL and SNOLab.

EXO has an S4 cooperative agreement to provide university support for a full EXO proposal and needed R&D.

SLAC has committed to a significant engineering effort to complement the NSF S4 support.

The primary focus of SLAC is EXO-200.