Enriched Xenon Observatory
for double beta decay

Jesse Wodin for the EXO collaboration
Enriched Xenon Observatory for double beta decay

D. Leonard, A. Piepke  
*Physics Dept, University of Alabama, Tuscaloosa AL*

P. Vogel  
*Physics Dept Caltech, Pasadena CA*

A. Bellerive, M. Bowcock, M. Dixit, I. Ekchtout, C. Hargrove, D. Sinclair, V. Strickland  
*Carleton University, Ottawa, Canada*

W. Fairbank Jr., S. Jeng, K. Hall  
*Colorado State University, Fort Collins CO*

M. Moe  
*Physics Dept UC Irvine, Irvine CA*

D. Akimov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Kovalenko, D. Kovalenko, G. Smirnov, V. Stekhanov  
*ITEP Moscow, Russia*

J. Farine, D. Hallman, C. Virtue  
*Laurentian University, Canada*

M. Hauger, F. Juget, L. Ounalli, D. Schenker, J-L. Vuilleumier, J-M. Vuilleumier, P. Weber  
*Physics Dept University of Neuchatel, Switzerland*

*SLAC, Menlo Park CA*

R. DeVoe, P. Fierlinger, B. Flatt, G. Gratta, M. Green, F. LePort, M. Montero-Diez, R. Neilson, A. Pocar, J. Wodin  
*Physics Dept Stanford University, Stanford CA*
Outline

- Double beta decay
- The EXO-200 experiment
- Ba\(^+\) tagging progress for EXO
Two types of $\beta\beta$ decay

- $\Delta L_e = 0$
- standard second order process observed in multiple isotopes

- Lepton number violation ($\Delta L_e = 2$)
- $m_\nu \neq 0$
- $\nu = \bar{\nu}$ (“Majorana neutrinos”)

$2\nu\beta\beta$  

$0\nu\beta\beta$
ββ decay observables

Energy deposition from two electrons ($Q_{ββ} = 2457.9±0.4^* \text{ keV}$)

Daughter nucleus (ion)

* M. Redshaw, J., McDaniel, E. Wingfield and E.G. Myers (Florida State Precision Penning Trap), to be submitted to Phys. Rev C.
If $0\nu\beta\beta$ is due to light Majorana $\nu$ masses

$$\langle m_\nu \rangle^2 = \left( T_{1/2}^{0\nu\beta\beta} G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right| \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phase space factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{e,i}^2 m_i \varepsilon_i \right|$$ effective Majorana $\nu$ mass

($\varepsilon_i = \pm 1$ if CP is conserved)
Outline

• Double beta decay

• The EXO-200 experiment

• Ba\(^+\) tagging progress for EXO
The EXO-200 Experiment

EXO-200 is a LXe TPC with ionization and scintillation readout that employs 200 kg of enriched Xe (80% $^{136}\text{Xe}$) as both a source and detector. EXO-200 has no $^{136}\text{Ba}^+$ identification.

Goals:

• look for $0\nu\beta\beta$ decay of $^{136}\text{Xe}$ with competitive sensitivity and test backgrounds of large LXe detector at ~2000 mwe depth
  \[ T^{0\nu}_{1/2} > 6 \times 10^{25} \text{ y}, \text{current limit: } T^{0\nu}_{1/2} > 1.2 \times 10^{24} \text{ y} \]
• measure $2\nu\beta\beta$ decay of $^{136}\text{Xe}$ ($Q = 2457.8 \pm 0.4$) and measure lifetime (currently $T^{2\nu}_{1/2} > 1 \times 10^{22} \text{ y}$)
• test LXe technology and enrichment on a large scale
• test TPC components, light readout, radio-purity of materials, Xe handling and purification

Use (anti-)correlation between ionization and scintillation to improve energy resolution in LXe
Energy resolution improvement in LXe

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

Ionization & Scintillation:
\[ \sigma(E)/E = 3.0\% \text{ @ } 570 \text{ keV} \]
or \[ 1.4\% \text{ @ } Q_{\beta\beta} \]
(a factor of 2 better than the Gotthard TPC)

EXO-200 will collect 3-4 times as much scintillation...
Further improvement possible

Compilation of Xe resolution Results*

EXO ionization only †

EXO ionization + scintillation †

* Aprile, E. et al., NIM A 302 (1991) 177
Materials Qualification

Massive effort on material radio-purity qualification using:

- NAA
- Low background $\gamma$ spectroscopy
- $\alpha$-counting
- Radon counting
- High performance ICP-MS

At present, database include $>100$ materials

Material selection is based on full MC of detector. Impact of every screw inside Pb shielding is evaluated before acceptance
EXO-200 LXe Chamber

• 200 kg of LXe in thin vessel (ultra pure copper, 1.5 mm thick)

• 50 cm of ultra pure cryofluid, providing large thermal bath for uniform temperature (3M HFE-7000, hydrofluoroether C₃F₇OCH₃)

• double walled vacuum insulated cryostat (ultra pure copper, 2.5 cm thick)
200 kg $^{136}\text{Xe}$ and Natural Xe

- 200 kg Xe enriched at 80% in hand
- 200 kg natural Xe for testing purposes in hand
EXO-200 Detector

Class 100 clean room
The EXO-200 Cleanrooms

- Modular cleanrooms
- 7ft. thick concrete roof
- Milling machine for Xe chamber
- Soft wall clean room: pre-assembly and cleaning
- HFE storage dewar in shipping container
EXO-200 construction well underway

Cryostat on Pb cradle in cleanroom

Plumbing and feedthrough installation

Prototype chamber machining

Refrigerators in cleanroom 2
APD testing and construction

APD testing/calibration system

APD flex cable wiring

APD plane machining
First cryostat cooldown successful

- Used only 1 refrigerator (out of 4)
- No problems, good stability at 100°C (LXe temp.)
- Successful test of control systems

Next...
- Test with HFE
- Test with natural Xe in dummy chamber
- Test with natural Xe in real chamber
Muon flux at WIPP (~ 1700 m.w.e.):

\[4.77 \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1}\]

\[(3.10 \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \sim 15 \text{ m}^{-2} \text{ h}^{-1})\]


EXO 200 kg prototype is being assembled and commissioned at Stanford, then the six clean rooms will be shipped to WIPP (April 2007)
EXO-200 Majorana mass sensitivity

Assumptions:
1) 200kg of Xe enriched to 80% in 136Xe
2) $\sigma(E)/E = 1.4\%$ obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background: 20 events/year in the $\pm 2\sigma$ interval centered around the 2.481MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2}^{2\nu} > 1 \times 10^{22}\text{yr}$; R. Bernabei et al. measurement)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E @ 2.5\text{MeV}$ (%)</th>
<th>Radioactive Background (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr, 90%CL)</th>
<th>Majorana mass (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype</td>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6*</td>
<td>40</td>
<td>6.4$\times 10^{25}$</td>
<td>0.27†</td>
</tr>
</tbody>
</table>

If Klapdor’s observation is correct...

Central value $T_{1/2}^{(\text{Ge})} = 1.2^{+3}_{-0.5} \times 10^{25}$, $\pm 3\sigma$ range (0.24eV – 0.58eV) (Phys. Lett. B 586 (2004) 198-212)

In EXO-200, 2yr:
Worst case (QRPA, upper limit) 15 events on top of 40 events $\text{bkgd} \to 2\sigma$
Best case (NSM, lower limit) 162 events with 40 $\text{bkgd} \to 8.5\sigma$

† Rodin et al Phys Rev C 68 (2003) 044302
* Courier et al. Nucl Phys A 654 (1999) 973c
Assumptions:
1) 80% enrichment in $^{136}\text{Xe}$
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res. only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2.481MeV endpoint
4) \(2\nu\beta\beta \ T_{1/2} > 1 \times 10^{22}\text{yr} \) (Bernabei et al. measurement)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_{E}/E @ 2.5\text{MeV}$ (%)</th>
<th>2νββ Background (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr, 90%CL)</th>
<th>Majorana mass (meV)</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>50</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>11</td>
</tr>
</tbody>
</table>

* $\sigma(E)/E = 1.4\%$ obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
† $\sigma(E)/E = 1.0\%$ considered as an aggressive but realistic guess with large light collection area
# Courier et al. Nucl Phys A 654 (1999) 973c

EXO Majorana mass sensitivity
Outline

• Double beta decay

• The EXO-200 experiment

• $\text{Ba}^+$ tagging progress for EXO
Xe offers a qualitatively new tool against background: $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} \text{ e}^- \text{ e}^-$ final state can be identified using optical spectroscopy (M. Moe, Phys. Rev. C 44 (1991) 931)

- $\text{Ba}^+$ system well studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
- Very specific signature
- Single ions can be detected from a photon rate of $10^7$/s

- **Important additional constraint**
- **Drastic background reduction**
$^{136}\text{Ba}^+$ Tagging schematic

$^{136}\text{Ba}^+$ grabber

Buffer gas cooled quadrupole linear ion trap

Observe single ion here

CCD
Ba\(^+\) Linear Ion Trap Schematic

\[ V_{RF}\cos(\Omega t) + U_{DC} \]

**Trap operation**

- Single Ba\(^+\) loaded at one end of trap
- Ba\(^+\) radially trapped by RF fields
- Ba\(^+\) transported by DC gradient
- Ba\(^+\) cooled by buffer gas collisions to trap minimum
- Ba\(^+\) excited by resonant lasers, and fluorescence observed by CCD
Ba$^+$ Linear Ion Trap System

~ 60 cm

Ba$^+$ lasers

Ion trap vacuum system

DPF 2006
Single Trapped \( \text{Ba}^+ \) in \( 10^{-3} \) Torr He

- Can reliably trap single \( \text{Ba}^+ \) in He, Ar
- Lifetime of individual ion ~ hundreds of sec (only need ~ 10 sec for ID)
Ba\textsuperscript{+} tagging future plans

- Learn more about single ion trapping in different buffer gasses
  - Xe, Xe+He, etc...
- Currently working on multiple “tip” ideas
  - Cryo-tip (a lot of progress here!)
  - RIS tip
  - AFM tip
- Test ion grabbing/release “tips” with trap