EXO status and prospects

Jesse Wodin for the EXO collaboration

SLAC
Topics

• EXO-200 introduction and status
• Barium tagging
• Full EXO conceptual design
Neutrinoless double beta decay $0\nu\beta\beta$

Emitted $\nu_i$ is mostly right-handed, with small left handed component $\sim m_i/E_\nu$ absorbed at second vertex.

$$\sum_i m_i U_{ei}^2 \equiv \langle m_{\beta\beta} \rangle$$

Effective Majorana mass is a coherent sum over mass eigenstates

$$\left( T_{1/2}^{0\nu\beta\beta} \right)^{-1} = G_{0\nu\beta\beta} (Q_{\beta\beta}, Z) M_{0\nu\beta\beta} \langle m_{\beta\beta} \rangle^2$$

Decay rate observed in a detector

$0\nu\beta\beta$ requires that neutrinos are **massive Majorana particles, and lepton number non-conservation**

$$\bar{\nu}_i = \nu_i \quad m_\nu \neq 0 \quad \Delta L \neq 0$$
Experimental $\beta\beta$ observables

Energy spectrum of two emitted electrons (both $\beta\beta$ modes shown, can be distinguished with good $\Delta E/E$)

Charged daughter nucleus residing in detector after $0\nu\beta\beta$ event

Experimental $0v\beta\beta$ sensitivity

To maximize sensitivity:
- large mass
- low backgrounds
- high detection efficiency
- good energy resolution

Additionally, identification of the daughter isotope would reject most sources of background and confirm $0v\beta\beta$ on a single event basis.
Measuring $0\nu\beta\beta$ with EXO-200

- 200kg $^{136}$Xe (80% enrichment) liquid phase (-113° C), both source and detector of $0\nu\beta\beta$
- $Q_{\beta\beta}^{Xe-136}$ ~ 2.5 MeV $\beta\beta$ endpoint energy
- $0\nu\beta\beta$ electrons deposit energy as charge (slow) and scintillation (fast)
- Collect scintillation on APDs
- Collect ionization on wires -> charge preamplifiers
- Energy reconstruction, PID, from ionization+scintillation ($\Delta E/E = 1.4\%$ at $Q_{\beta\beta}$)
- Event position from charge distribution and $t_{SCINT}t_{ION}$ (useful for Ba tagging on full EXO)
EXO-200 TPC and cryostat

- Inner cryostat filled with 50 cm HFE7000 cooling/shielding fluid (~ 1.8 g/cm³ at 170 K)
- Central HV plane (photoetched phosphor bronze)
- Outer cryostat
- Custom kapton signal cables (ion. + scint. readout)
- TPC (1.5m x 1.5m)
- Central HV plane (photoetched phosphor bronze)
- Teflon light reflector
- Acrylic supports and field shaping rings
- APD plane (avalanche photodiodes, scintillation detection)

10/2/2010
Shielding

• Shielding MUCH HARDER for $0\nu\beta\beta$ 2.5 MeV electromagnetic signal than for low energy nuclear recoil DM search

• *Thin walled ~ 1.4 mm thick Cu TPC* surrounded by
  – 4000kg HFE7000 (~50 cm), density ~ 1.4 g/cm$^3$
  – 25 cm Pb shielding on all sides

• For comparison with DM experiments, assume N-ton spherical LXe $0\nu\beta\beta$ detector, using 50% LXe for shielding

<table>
<thead>
<tr>
<th>Incident $\gamma$ energy</th>
<th>$\gamma$ attenuation factor (1-ton spherical LXe)</th>
<th>$\gamma$ attenuation factor (10-ton spherical LXe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 keV</td>
<td>36</td>
<td>2200</td>
</tr>
<tr>
<td>2.5 MeV</td>
<td>1.08</td>
<td>1.2</td>
</tr>
</tbody>
</table>
EXO-200 material screening

- Stringent requirements on K/Th/U concentrations on materials inside cryostat
- In particular:

<table>
<thead>
<tr>
<th>Component</th>
<th>K $10^{-9}$ g/g</th>
<th>Th $10^{-12}$ g/g</th>
<th>U $10^{-12}$ g/g</th>
<th>$^{210}$Po Bq/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M Novec HFE-7000, 1-methoxyheptafluoropropane</td>
<td>&lt;1.08</td>
<td>&lt;7.3</td>
<td>&lt;6.2</td>
<td></td>
</tr>
<tr>
<td>Lead shielding</td>
<td>&lt;7</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>17-20</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt;55</td>
<td>&lt;2.4</td>
<td>&lt;2.9</td>
<td></td>
</tr>
<tr>
<td>Acrylic</td>
<td>&lt;2.3</td>
<td>&lt;14</td>
<td>&lt;24</td>
<td></td>
</tr>
<tr>
<td>TPC grid wires</td>
<td>&lt;90</td>
<td>47 +/- 2</td>
<td>320 +/- 2</td>
<td></td>
</tr>
</tbody>
</table>
EXO-200 Xe handling system: designed around 1.4mm thin-walled TPC, constant purification

Design goals:
1. **20 SLPM circulation rate** for continuous purification (uses heater, pump, condenser) while TPC full
2. **Continuous purification** with commercial (SAES) getters
3. **Continuous purity monitoring** of circulating gas (GPMs – see A. Odian’s talk on Wed.)
4. Differential pressure across TPC walls $|dP| = |P_{Xe} - P_{HFE}| < 15$ torr at all times, due to thin-walled (~1.5mm) TPC construction (driven by radiopurity requirements)
5. **Xe recovery to bottle farm with compressors**
6. **Triply redundant cryocooling system** (3x Polycold refrigerators)
EXO-200 detector construction

Signal cabling penetrates TPC and cryostat (no “feedthroughs”)

Cathode

Field shaping rings
EXO-200 crossed ionization collection wires

Photoetched wire triplets

Kapton signal cabling
Looking into EXO-200 detector without APDs
EXO-200 LAAPD specs

- Mass ~ 0.5 g/LAAPD
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals & metals)\(^a\)
  - QE > 1 at 175 nm (NIST)
  - Gain set at 100-150
  - V ~ 1500V
  - ΔV < ±0.5V
  - ΔT < ±1K  APD is the driver for temperature stability
- Leakage current cold < 1μA
- Capacitance ~ 200 pF at 1400 V
- φ16 mm active area per LAAPD

EXO-200 APD installation
EXO-200 TPC after cable and APD installation, before final endcap welding
EXO-200 TPC ready for packaging at Stanford
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)
- Salt mine for low-level radioactive waste storage
- Salt “rock” low activity relative to hard-rock mine

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

EXO-200 infrastructure
Active muon veto

- Active muon veto system installed 2009
- Testing and integration into DAQ underway
TPC arrival & installation at WIPP

• TPC shipped from Stanford to WIPP 11/2009 in shielded container
• TPC installed in cryostat 12/2009
• LXe line re-hookup, followed by DAQ testing at WIPP
• Natural Xe run scheduled to begin late-2010
EXO-200 Majorana mass $<m_{\beta\beta}>$ sensitivity

Assumptions
1. 200 kg of $^{136}$Xe, 80% enrichment
2. Low but finite radioactive background: 20 events/yr in ±2σ interval around $Q=2.481$ MeV
3. Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1\times10^{22}$ yr, Bernabei et al.)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass [ton]</th>
<th>Efficiency [%]</th>
<th>Run time [yr]</th>
<th>$\sigma_e/E$ @ 2.5 MeV [%]</th>
<th>Radioactive background [events]</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]</th>
<th>Neutrino majorana mass [eV]</th>
<th>QRPA</th>
<th>NSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-200</td>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6</td>
<td>40</td>
<td>6.4x10^{25}</td>
<td>0.135 (1)</td>
<td>0.109 (2)</td>
<td></td>
</tr>
</tbody>
</table>

If Klapdor’s observations are correct, EXO-200, 2-yr runtime:
1. 46 events on top of 40 (QRPA) → 5σ measurement
2. 170 events on top of 40 (NSM) → 11.7σ measurement

Full EXO R&D

- Full EXO ~ ton scale gas or liquid TPC
- “Tagging” of $0\nu\beta\beta$ daughter nucleus $^{136}$Ba ion for background rejection – R&D underway
  - Ion extraction from a TPC
  - Ion trapping
  - Ion identification with
    - Laser Induced Fluorescence (LIF)
    - Resonant ionization spectroscopy (RIS)
  - Single ion RIS
  - Others...
- GXe TPC R&D underway
  - 10 bar GXe TPC under construction
  - Test tracking, ionization+scintillation readout, $\Delta E/E$, Ba tagging interface, etc.

“Tagging” $^{136}$Ba ion in real time may allow for rejection of all backgrounds except $2\nu\beta\beta$. 
Single $^{136}\text{Ba}^+$ identification with Laser Induced Fluorescence

Goal: extract and ID single $^{136}\text{Ba}$ ions in real time from liquid or gas TPC for background rejection

- $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2\text{e}^-$
- $^{136}\text{Ba}^{++} \rightarrow ^{136}\text{Ba}^+$ in LXe
- Isolate single ion in an ion trap
- Identification and dynamics of single $\text{Ba}^+$ in ion traps well studied (1)
- 493 nm, 650 nm lasers cycle trapped ion electronic states
- LIF $\sim 10^7$ photons/sec/ion into $4\pi$

$^{136}\text{Ba}^+$ level structure

Single trapped Ba\(^{+}\) in a gas-filled 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
Ba\(^+\)/Ba\(^{++}\) single ion sources being developed

- Use recoils from a very thin \(\alpha\) emitter \(^{148}\text{Gd}\) to dislodge Ba atoms from a carefully designed layer of BaF\(_2\) (arXiv:1008.3422, accepted for publication in Rev. Sci. Instr.)
- A fraction of the Ba emitted is Ba\(^+\)
- Multiple sources under development
Ba transport & tagging by Resonant Ionization Spectroscopy

• Ba+ or Ba++ is electrostatically attracted (from LXe) onto a clean substrate (Si works well)
• Substrate is removed into vacuum
• 1064 nm YAG laser pulse desorbs Ba
• ~ 1us later a pair of laser pulses of appropriate freq. re-ionize Ba+
• Current testing uses stationary substrate and Ba is deposited over time using the Gd-driven source (104-105 ions deposited)
TOF spectrum (data) from RIS test

- Background already very small
- Efficiency > $10^{-3}$ (deposit $10^5$, wait hrs., get > 100 out)
- This gives us a signal to tune on
Next step: do it one ion at a time

- High efficiency (~80%) ion optics (both injection and extraction)
- “Top hat” YAG beam (lower background)
- Only Ti and Si construction (lower background)
- Possibly no ion trap required
- Many other Ba tagging fronts, but no time here
Full EXO GXe TPC R&D in progress

Goal: Test tracking, $\Delta E/E$, electronics, ionization + scintillation readout, Ba tagging interface in 1-10 bar GXe

- 10 bar GXe cylindrical TPC
- 1 MeV $e^-$ source
- Segmented readout (tracking) on both ends
- Electroluminescent gap + CsI photocathode for both charge and scintillation readout
- Replaceable endcaps for alternate charge/light readout technologies, Ba tagging interface

• Field cage length: 780 mm
• Field cage diameter: 535 mm
Coupling a quadrupole trap to a TPC

- Ion transport, stopping, through quadrupoles well known to heavy-ion nucl. phys.
- Eventual goal is to test full pipeline efficiency for single ion extraction, ID
Full EXO conceptual design

• LXe core
  – Liquid Xenon ($^{136}$Xe)
    • Fiducial Mass = 10 Tonnes (overall geometry almost independent of fiducial mass)
    • Volume = 3,400 liters
    • Temperature = 165K
  – Cu vessel for LXe
    • Single vessel, 170cm x 160cm x 170cm
    • 3 equally sized internal chambers

• TPC – Time Projection Chamber
  – Central Cathode in each chamber
    • Max drift distance = 25cm
  – Ionization and scintillation readout
  – Coincidence measurement by identifying Ba$^{++}$ Daughter
Full EXO conceptual design with shielding and infrastructure

- Because of conveyance system constraints at DUSEL, the EXO design must be made from smaller components (that fit inside the #6 Winze) and assembled underground.

EXO support bldg.

EXO detector

#6 Winze
5.4 Tonnes Capacity

1,000+ Tonnes Material
Full EXO TPC installation

- **Outer Cryo**
  - 19.1mm Ti
  - 10 Tonnes

- **Inner Cryo**
  - 6.35mm Ti
  - 2 Tonnes

- **HFE**
  - 70 Tonnes

- **TPC**
  - LXe/Cu
  - 10+9 Tonnes

- **Ba^{++} Tagging**
  - 10 Tonnes

- **Lead Shield**
  - 0.5m Pb
  - 430 Tonnes

- **Inner Tank**
  - 0.25m HDPE
  - 60 Tonnes
  - 320 m$^3$ H$_2$O
  - 320 Tonnes

- **Outer Tank**
  - 12.7mm SS
  - 110 Tonnes
  - 2,200 m$^3$ H$_2$O
  - 2,175 Tonnes

**Total Mass = ~711 Tonnes (not including H$_2$O)**
EXO Majorana mass $<m_{\beta\beta}>$ sensitivity

Assumptions
1. $^{136}$Xe, 80% enrichment
2. Intrinsic low backgrounds & Ba tagging eliminate all radioactive backgrounds
3. Energy resolution used to separate $0\nu\beta\beta$ from $2\nu\beta\beta$ modes (select $0\nu$ events in +/- $2\sigma$ interval around 2.458 MeV endpoint)
4. $2\nu\beta\beta (T_{1/2} > 1\times10^{22}$ yr, Bernabei et al.)

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<th>$2\nu\beta\beta$ background [events]</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]</th>
<th>Neutrino majorana mass [meV]</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conservative</td>
<td>1</td>
<td>70</td>
<td>5</td>
<td>1.6 (3)</td>
<td>0.5 (~1)</td>
<td>2.0x10$^{27}$</td>
<td>19 (1)</td>
</tr>
<tr>
<td>Aggressive</td>
<td>10</td>
<td>70</td>
<td>10</td>
<td>1.0 (4)</td>
<td>0.7 (~1)</td>
<td>4.1x10$^{28}$</td>
<td>4.3 (1)</td>
</tr>
</tbody>
</table>

(3) $\sigma_E/E = 1.6\%$ obtained in EXO R&D, Conti et al., Phys. Rev. B 68 (2003) 054201
(4) $\sigma_E/E = 1.0\%$ considered aggressive but realistic guess with large light collection
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