The EXO-200 Detector

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Frontier Detectors for Frontier Physics

11th Pisa meeting on advanced detectors

24-30 May 2009
Double Beta Decay ...

- Rare nuclear transition between same mass nuclei
  - Energetically allowed for even-even nuclei

\[
\beta\beta_{2\nu} : \quad (Z, A) \rightarrow (Z + 2, A) + e^- + \bar{\nu}_1 + e^- + \bar{\nu}_2
\]

\[
\left[ T_{1/2}^{2\nu} (0^+ \rightarrow 0^+) \right]^{-1} = G^{2\nu} (Q_{\beta\beta}, Z) |M^{2\nu}|^2
\]

Allowed in SM and already observed!

\[
\beta\beta_{0\nu} : \quad (Z, A) \rightarrow (Z + 2, A) + e^- + e^-
\]

\[
\Delta L = 2 \quad (Z, A) \rightarrow (Z + 2, A) + e^- + e^- + \chi
\]

Neutrinos are Majorana particles!

\[
\nu \equiv \bar{\nu} \quad m_\nu \neq 0
\]

\[
\left[ T_{1/2}^{0\nu} (0^+ \rightarrow 0^+) \right]^{-1} = G^{0\nu} (Q_{\beta\beta}, Z) |M^{0\nu}|^2 \left\langle m_{\beta\beta} \right\rangle^2
\]

\[
\left\langle m_{\beta\beta} \right\rangle^2 = \left| \sum_k m_k U_{ek}^2 \right|
\]
... and its Role in Neutrino Physics

Double beta decay experiments are part of a massive effort to determine the nature and properties of neutrinos!

\[
\langle m_\beta \rangle < 2\text{eV} \quad \text{Beta Decay Endpoint}
\]

\[
\Delta m_{23}^2 = (2.4_{-0.5}^{+0.6}) \times 10^{-3}\text{eV}
\]

\[
\Sigma = \sum_k m_k = 92.5\text{eV} \times (\Omega_v h^2)
\]

\[
\theta_{23} \approx 45^\circ \quad \text{Neutrino Oscillations}
\]

\[
\theta_{13} < 7^\circ \quad \text{Reactor and Beam}
\]

\[
\theta_{12} \approx 34^\circ \quad \text{Solar and Reactor}
\]

\[
\Delta m_{12}^2 = (8.0_{-0.3}^{+0.4}) \times 10^{-5}\text{eV}
\]

\[
\langle m_{\beta\beta} \rangle < 0.7\text{eV}
\]
Effective neutrino mass as a function of the smallest neutrino mass for various scenarios

**Experimental Requirements**

- **Large Mass:** at least 100 kg of source isotope
  - Scanning the quasi degenerate region
  - Ton scale for the inverted hierarchy region
  - Enrichment helps minimizing volume and improves source purity

- **Very Low Background:** 1 count per ton per year range
  - Survey, selection and purification of materials and components
  - Cleanroom assembly and detector operation
  - Deep underground installation and muon veto required

- **Very Good Energy Resolution:** in the 1% range
  - Limits the allowed double beta decay background
  - Increases signal to radioactive background ratio

- **And ...**
  - Large $Q_{\beta\beta}$ to have the signal out of the region densely populated by radioactive background for natural chains
  - Tagging the daughter isotope would eliminate most radioactive background or event topology and advanced kinematics details
EXO Project & EXO-200 Phase

- EXO project searches for double beta decay using $^{136}$Xe
  - Ton scale implementation either as liquid or gas phase TPC
  - Relatively large Q value and straightforward enrichment technique
  - $^{136}$Ba daughter tagging either in-situ or in external RF cage

\[
\langle m_{\beta\beta} \rangle \propto \left( \frac{1}{N_t} \right)^{1/4} \quad \text{No Background!} \quad \langle m_{\beta\beta} \rangle \propto \sqrt[4]{\frac{1}{N_t}}
\]

- EXO-200 is the first phase using 200 kg of 80% enriched Xe
  - Major R&D effort precursory to the ton-scale experiment
  - Exploration of the quasi-degenerate region with $^{136}$Xe
  - Allowed double beta decay never observed in xenon!
  - No tagging but massive progress for radioactive background reduction and energy resolution improvement (easily scalable to future detectors)
EXO Collaboration

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EXO-200 Detector

- Liquid xenon TPC with two cylindrical drift volumes
  - Charge collection using 114 by 114 wire planes (at 60° pitch)
  - Scintillation light readout using 37 groups of 7 bare LAAPD (Large Area Avalanche Photodiodes) at both end caps
- High purity copper cryostat with external refrigeration-based cooling

~ 115 kg fiducial mass
Successful Enrichment Program

200 kg of 80% enriched Xe delivered in 2003!
Used mass-separating centrifuges in Russia
The other isotopes can be returned to provider!
Radio-Purity Survey

• Large effort to determine the residual radioactive contamination of the materials employed for the construction of EXO-200 detector
  - Mass spectrometry (MS)
  - Neutron activation analysis (NAA)
    • Very sensitive but expensive, potential background from main elements
  - **Alpha counting** (evaluation of the $^{210}\text{Pb}$ concentration in the shield lead)
  - **Glow discharge MS (GD-MS), inductively coupled plasma MS (ICP-MS)**
    • ICP-MS has better sensitivity when pre-concentration procedures are employed but the samples have to be soluble in acids (preferably HNO$_3$)
  - **Direct gamma counting**
    • Large mass samples and long duration exposures are necessary

• Published database of characterized materials

• Detailed Monte Carlo simulation of expected background
Improving the Energy Resolution

Strong anti-correlation between ionization and scintillation signals in liquid xenon has been observed!

\[ \frac{\Delta E}{E} = 1.4\% @ Q_{\beta\beta} = 2479\text{keV} \]

- 570keV
- 207\text{Bi}: \gamma's
EXO-200 Detector
EXO-200 Chamber

Ultra low radioactivity copper!
Shielded surface transport and storage
Only 1.5 mm thickness to reduce mass
PLC-based real-time pressure control
e-beam welded components
TIG welding for the final assembly
Charge and Light Readout

Photo-etched phosphor-bronze cathode
Induction & charge collection wire grids
259 LAAPD (37 groups of 7) per plane
- 1.6 cm active diameter
- very clean and low mass
- QE > 1 @ 174 nm
- gain 100× to 150× @ ~ 1500V
Radial Teflon UV light reflectors
Chamber Assembly
Cryostat and Cooling System

Refrigeration based cooling (3 × 1500 W PolyCold units)
4.2 tons of high purity heat transfer fluid (3M HFE-7000)
Serves also as inner shield!
WIPP Installation
Experimental Area

Waste Isolation Pilot Plant, Carlsbad, New Mexico
~ 1600 m.w.e. (muon flux reduction by ~ 10×)

Large and wide remote experimental area available!
20× muon induced background reduction (99.7% detection efficiency)

Extensive Monte Carlo simulations to optimize the veto configuration!
Expected Performance

• Very low radioactive background
  – Careful selection of materials, optimized custom design
  – Manufacturing, handling and installation in cleanrooms

• Very good energy resolution
  \[ \frac{S}{B} = \frac{m_e}{7Q_{\beta\beta}} \left( \frac{E}{\Delta E} \right)^6 \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}} \]

Chamber underground installation in August 2009
Physics runs starting in 2010, 2 years run time!

\[ T_{1/2}^{2\nu} > 1.2 \times 10^{24} \text{ yr at 90\% C.L.} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</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} ) (yr, 90% CL)</th>
<th>Majorana mass (meV)</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>6.4 \times 10^{25}</td>
<td>133</td>
</tr>
</tbody>
</table>

2) Caurier et. al., arXiv:0709.2137v1
Ba$^+$ Tagging

- Ba$^{++} \rightarrow$ Ba$^+$ conversion expected
  - Ionization potentials:
    - Xe$^+$ = 12.13 eV vs. Ba$^+$ = 5.21 eV
    - Xe$^{++}$ = 21.21 eV vs. Ba$^{++}$ = 10.00 eV
    - $E_G$ = 9.22 +/- 0.01 eV
    - 9.28 to 9.49 eV range
  - Use of additives for gas based detectors

RF cage with low pressure buffer gas
Conclusion

• EXO-200 detector soon operational!
• The largest neutrino-less double beta decay detector!
• Successful large scale xenon enrichment proven!