Neutrinoless Double Beta Decay

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The New, the Rare and the Beautiful
07. January 2010
Overview

1. Neutrino Physics & Double Beta Decay
2. Principle of Experiments
3. Status of Double Beta Decay Measurements
4. Present & Future
5. Summary
We know

- Neutrinos have a mass
- Mass difference between eigenstates

The 3 big questions

- Absolute mass scale
- Mass hierarchy
- Majorana vs. Dirac
**Double Beta Decay**

### $2\nu\beta\beta$

- $(Z, A) \rightarrow (Z + 2, A) + 2e^- + 2\bar{\nu}_e$
- $\Delta L = 0$
- $|T_{1/2}^{2\nu}|^{-1} = G^{2\nu}(Q_{\beta\beta}, Z) M_{2\nu}^2 \sim |10^{20} \text{ y}|^{-1}$

### $0\nu\beta\beta$

- $(Z, A) \rightarrow (Z + 2, A) + 2e^-$
- $\Delta L = 2$
- $|T_{1/2}^{0\nu}|^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) M_{0\nu}^2 \langle m_{\beta\beta}^2 \rangle \sim |10^{25} \text{ y}|^{-1}$
- $\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$
**Nuclear Matrix Elements**

Three different methods for calculation:

**Nuclear Shell Model (SM)** Uses Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels.

**Quasi-Particle Random Phase Approximation (QRPA)** Uses 3 parameters accounting for pairing, particle-particle and particle-hole interactions.

**Interacting Boson Model (IBM)** Bosons can interact through 1- and 2-body interactions giving rise to bosonic wave functions.

- QRPA and IBM (coincidentally?) in agreement
- SM a factor of 2 lower
What do we measure?

Requirements

We measure

$$T_{1/2}^{0\nu} \propto \langle m_{\beta\beta} \rangle^{-2} \propto \text{const} \sqrt{\frac{M \times t}{\Delta E \times B}}$$

To get the best possible measurements we need

- High mass $M$ and/or long time $t$ (exposure)
- Excellent energy resolution $\Delta E$
- Minimal background $B$
Measuring the energy of both electrons

- \(2\nu\beta\beta\): Continuous energy spectrum
- \(0\nu\beta\beta\): Sharp peak at Q value of decay
  \[ Q = E_{\text{mother}} - E_{\text{daughter}} - 2m_e \]
- Schechter & Valle (1982): Measuring \(0\nu\beta\beta \Rightarrow \nu\) Majorana particle
How do we measure?

General Principal

Source = Detector

- High masses possible
- High efficiency for the detection of both electrons
- Good energy resolution
- No angular correlation of electrons measurable

Source ≠ Detector

- Topology of events can be used for background suppression
- Angular correlation and energy of single electrons measurable
- Many isotopes as possible sources
- Small masses
- Low efficiency
- Worse energy resolution
Heidelberg-Moscow Experiment

The Claim

- 5 HPGe crystals with 71.7 kg y
- Peak at Q value:
  \[ T_{1/2}^{0\nu} = 1.2 \times 10^{25} \text{y} \quad (4\sigma) \]
  \[ \langle m_{\beta\beta} \rangle = 0.44 \text{eV} \]
- Problem: Confidence depends on background model and energy region selected for analysis
  \[ \Rightarrow \text{New experiments with higher sensitivity needed} \]
### Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Q-Value [keV]</th>
<th>Half-life [y]</th>
<th>$\langle m_\nu \rangle$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4271</td>
<td>$&gt; 9.5 \times 10^{21}$</td>
<td>$&lt; 8.3$</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>$&gt; 1.9 \times 10^{25}$</td>
<td>$&lt; 0.35$</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2995</td>
<td>$&gt; 3.6 \times 10^{23}$</td>
<td>$0.9 - 1.61$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3034</td>
<td>$&gt; 1.1 \times 10^{24}$</td>
<td>$0.45 - 0.9$</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2805</td>
<td>$&gt; 7.0 \times 10^{22}$</td>
<td>$&lt; 2.6$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2528</td>
<td>$&gt; 3.0 \times 10^{24}$</td>
<td>$0.2 - 0.7$</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2476</td>
<td>$&gt; 4.4 \times 10^{23}$</td>
<td>$1.8 - 5.2$</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3367</td>
<td>$&gt; 1.2 \times 10^{21}$</td>
<td>$&lt; 3.0$</td>
</tr>
</tbody>
</table>
### Experiments
Past, Present and Future

<table>
<thead>
<tr>
<th>Name</th>
<th>Isotope</th>
<th>Mass</th>
<th>Method</th>
<th>Location</th>
<th>Time Line</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operational &amp; Recently completed experiments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CUORICINO</td>
<td>$^{130}\text{Te}$</td>
<td>12 kg</td>
<td>bolometric</td>
<td>LNGS</td>
<td>2003-2008</td>
</tr>
<tr>
<td>NEMO-3</td>
<td>$^{100}\text{Mo}/^{82}\text{Se}$</td>
<td>6.9/0.9 kg</td>
<td>tracko-calor</td>
<td>LSM</td>
<td>until 2010</td>
</tr>
<tr>
<td><strong>Construction funding</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}\text{Te}$</td>
<td>200 kg</td>
<td>bolometric</td>
<td>LNGS</td>
<td>2012</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$^{136}\text{Xe}$</td>
<td>160 kg</td>
<td>liquid TPC</td>
<td>WIPP</td>
<td>2009 (comiss.)</td>
</tr>
<tr>
<td>GERDA I&amp;II</td>
<td>$^{76}\text{Ge}$</td>
<td>35 kg</td>
<td>ionization</td>
<td>LNGS</td>
<td>2009 (comiss.)</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{150}\text{Nd}$</td>
<td>56 kg</td>
<td>scintillation</td>
<td>SNOlab</td>
<td>2011</td>
</tr>
<tr>
<td><strong>Substantial R&amp;D funding / prototyping</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CANDLES</td>
<td>$^{48}\text{Ca}$</td>
<td>0.35 kg</td>
<td>scintillation</td>
<td>Kamioka</td>
<td>2009</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}\text{Ge}$</td>
<td>26 kg</td>
<td>ionization</td>
<td>SUSL</td>
<td>2012</td>
</tr>
<tr>
<td>NEXT</td>
<td>$^{136}\text{Xe}$</td>
<td>80 kg</td>
<td>gas TPC</td>
<td>Canfranc</td>
<td>2013</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}\text{Se}$ or $^{150}\text{Nd}$</td>
<td>100 kg</td>
<td>tracko-calor</td>
<td>LSM</td>
<td>2012 (first mod.)</td>
</tr>
</tbody>
</table>
CUORICINO
Source = Detector

Location  LNGS
Isotope    40.7 kg of TeO₂
Bolometer  Cysts cooled down to \( \sim \) 8 mK to measure temperature increase proportional to energy deposition of the event
Energy resolution  FWHM \( \sim \) 8-10 keV
Status     Data from 2003–2008
**CUORICINO**

**Results**

- **Exposure**: 11.83 kg y of $^{130}$Te
- **Background level**: $0.18 \pm 0.02$ cts/(keV kg y)
- **Half-life**: $T_{1/2} > 2.94 \times 10^{24}$ y
- **Majorana mass**: $m_{ee} < 0.19 - 0.68$ eV
- **Follow-up experiment**: CUORE with 200 kg of $^{130}$Te

Arnaboldi et al. 2008
**NEMO-3**

Source ≠ Detector

<table>
<thead>
<tr>
<th>Location</th>
<th>Frejus Underground Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
<td>10 kg of different isotopes, mainly $^{100}$Mo</td>
</tr>
<tr>
<td>Tracking</td>
<td>Drift wire chamber operating in Geiger mode (6180 cells)</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>1940 plastic scintillators coupled to low radioactivity PMTs</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>8% FWHM @ 3 MeV</td>
</tr>
<tr>
<td>Status</td>
<td>Data collection started 2003</td>
</tr>
</tbody>
</table>

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NEMO-3

Results until end of 2008

$^{100}$Mo

<table>
<thead>
<tr>
<th>Exposure</th>
<th>26.6 kg y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>$T_{1/2} &gt; 1.1 \times 10^{24}$ y</td>
</tr>
<tr>
<td>Majorana mass</td>
<td>$m_{ee} &lt; 0.45 - 0.93$ eV</td>
</tr>
</tbody>
</table>

$^{82}$Se

<table>
<thead>
<tr>
<th>Exposure</th>
<th>3.6 kg y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>$T_{1/2} &gt; 3.6 \times 10^{23}$ y</td>
</tr>
<tr>
<td>Majorana mass</td>
<td>$m_{ee} &lt; 0.89 - 1.61$ eV</td>
</tr>
</tbody>
</table>

Follow-up experiment  SuperNEMO with 100 kg of $^{82}$Se or $^{150}$Nd

Mauger, Taup 2009
The GERmanium Detector Array (GERDA)

### Overview

<table>
<thead>
<tr>
<th>Location</th>
<th>LNGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
<td>17.8 kg (Phase I) and $\sim$40 kg (Phase II) of $^{76}$Ge</td>
</tr>
<tr>
<td>Ionization</td>
<td>Naked high purity semiconductor diodes placed in liquid argon</td>
</tr>
<tr>
<td>Status</td>
<td>Commissioning</td>
</tr>
</tbody>
</table>

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## GERDA
Goals & Status

### Phase I goals
- **Exposure**: 15 kg y
- **Background**: $10^{-2}$ cts/(keV kg y)
- **Half-life**: $T_{1/2} > 2.2 \times 10^{25}$
- **Majorana mass**: $m_{ee} < 0.27$ eV

### Phase II goals
- **Exposure**: 100 kg y
- **Background**: $10^{-3}$ cts/(keV kg y)
- **Half-life**: $T_{1/2} > 15 \times 10^{25}$
- **Majorana mass**: $m_{ee} < 0.11$ eV

### Status
- **Most parts installed**
- **Liquid argon filled**
- **Operating first detector in a couple of weeks**
Observing $0\nu\beta\beta$ would answer the questions about the absolute mass scale, the hierarchy and the nature of neutrinos.

$2\nu\beta\beta$ measured in more than 10 isotopes.

Experiments use different isotopes and techniques.

So far just upper limits on $m_{ee}$ and a claim but no evidence for $0\nu\beta\beta$.

Promising experiments start data taking this year!