The Search for Neutrinoless Double Beta-Decay

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OUTLINE:

• Motivation: Neutrinos and their (unknown) properties
  • Neutrinoless Double-Beta-Decay
  • Experimental considerations and approaches
    • Past 0νββ experiments
    • The next generation(s) of 0νββ-experiment
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Motivation: Neutrinos and their (un)known Properties:

Know about neutrinos:
- 2nd most abundant known particles in observable universe
- They love to oscillate
- Some neutrinos must have mass
- They are generators for Nobel prizes

Unknown about neutrinos:
- Is the neutrino a Majorana or Dirac particle (BAU, SeeSaw)?
- Absolute mass scale?
- Mass hierarchy?
- Majorana-CP/Dirac phases?
- Admixture of $\nu_e$ in $m_{\nu_3}$?
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![Diagram of neutrino mass spectrum with Majorana and Dirac representations.](image)
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DIRAC $\nu \neq \overline{\nu}$

Majorana $\nu = \overline{\nu}$
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Neutrinoless Double Beta-Decay:

Neutrino accompanied Double-Beta Decay:

\[ n \xrightarrow{W^-} W^- \bar{\nu}_e e^- p \]

\[ n \xrightarrow{W^-} W^- \bar{\nu}_e e^- p \]

Neutrinoless Double-Beta Decay:

\[ n \xrightarrow{W^-} W^- \bar{\nu}_e = \nu_e e^- p \]

\[ n \xrightarrow{W^-} W^- \bar{\nu}_e \neq \nu_r e^- p \]

Neutrinoless mode of double beta decay can only occur if:

- Neutrino is a Majorana particle
- Neutrino is massive (chirality flip required)

\[ \frac{1}{\tau} = G(Q,Z) |M_{\text{nucl}}|^2 <m_{ee}>^2 \]

Decay rate factor Matrix Effective Majorana Neutrino mass
Neutrinoless Double Beta-Decay:

- $2\nu\beta\beta$-decay is allowed (observed) weak process:
  - Initial state nucleus bound stronger than intermediate, but less then final
  - Can occur for even-even nuclei
  - $\sim 35$ isotopes decay via $2\nu\beta\beta$.

$^{76}\text{Ge} \rightarrow ^{76}\text{As} + e^- + \nu_e$

$^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- + 2\nu_e$

$Q = 2039$ keV

$T_{1/2}^{2\nu\beta\beta} \sim 10^{10}$ • age of the universe

$E$
Neutrinoless Double Beta-Decay:

Neutrinoless double-beta-decay probes the effective Majorana-neutrino mass: \[ <m_{ee}> = \sum_i |U_{ei}|^2 \Delta m_{32}^2 i \beta m_i \]

Detection of > 10 meV Majorana neutrino required to distinguish between normal, inverted and degenerate hierarchy.

\[ \Delta m_{32} < 0 \text{ eV} \]

\[ \Delta m_{32} > 0 \text{ eV} \]


90% CL (1 dof)

90% CL
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Signature: Sharp peak at Q-value of the decay

2 neutrinos escape the detector undetected: Continuous spectrum

Total energy of decay is deposited within detector: sharp peak

Expected half-life: $T_{1/2}^{0
\nu\beta\beta} \lesssim 10^{15} \cdot \text{age of the universe}$

Be aware: There are many sources producing mono-energetic peaks!
$ightarrow$ Need more than one isotope!
Experimental considerations and approaches

Figure of merit for a LIMIT sensitivity:

\[ T_{1/2} \propto M_{\text{nucl}} \sqrt{\frac{m}{b \delta E}} t \]

<table>
<thead>
<tr>
<th>( M_{\text{nucl}} )</th>
<th>Nuclear matrix element</th>
<th>Select Isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>background rate of the experiment</td>
<td>Minimize and select material</td>
</tr>
<tr>
<td>( a )</td>
<td>abundance of isotope under consideration (&lt; 1.0)</td>
<td>Use isotope with high natural abundance or enrich material</td>
</tr>
<tr>
<td>( m )</td>
<td>active target mass of the experiment</td>
<td>Increase target mass</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>signal detection efficiency (&lt;1.0)</td>
<td></td>
</tr>
<tr>
<td>( \delta E )</td>
<td>Energy resolution</td>
<td>Use high resolution spectroscopy</td>
</tr>
<tr>
<td>( t )</td>
<td>Measuring time (&lt; 20y)</td>
<td></td>
</tr>
</tbody>
</table>

\( b > 0 : \ T_{1/2} \propto M_{\text{nucl}} a \varepsilon \sqrt{\frac{m}{b \delta E}} t \)

\( b = 0 : \ T_{1/2} \propto M_{\text{nucl}} a \varepsilon m t \)

→ Experimental approach: Improve EXPOSURE and BACKGROUND
Experimental considerations and approaches

two main experimental possibilities:

- **Semiconductor detectors, Phonon detection**
  - Source = Detector
  - (Calorimetry)
  - + High detection efficiency
  - + Large target mass possible
  - + Very good energy resolution
  - + Reconstruction of event topologies
  - - Restricted number of isotopes
  - → Improve on topology reconstruction

- **Foils between Scintillation detectors, Gas TPCs**
  - Source ≠ Detektor
  - + Very good position resolution
  - → reconstruction of event topologies
  - → Except for $2\nu\beta\beta$: zero background
  - + No restriction on isotopes.
  - - Energy resolution → Background from $2\nu\beta\beta$-decay
  - - Difficult to obtain large masses
  - → Improve on energy resolution
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Past $0\nu\beta\beta$ experiments

Most sensitive $0\nu\beta\beta$ experiments so far: HPGe based

Heidelberg-Moscow Experiment:

IGEX Experiment:

11.5 kg of enriched Ge detectors
71.7 kg yrs of data
0.11 Counts/(kg keV y) around 2040 keV
$T_{1/2} \geq 1.9 \times 10^{25}$ years (90% C.L.)

6.8 kg of enriched Ge detectors
8.5 kg yrs of data
0.17 Counts/(kg keV y) around 2040 keV
$T_{1/2} \geq 1.6 \times 10^{25}$ years (90% C.L.)
Past 0νββ experiments

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Heidelberg-Moscow Experiment:

11.5 kg of enriched Ge detectors
71.7 kg yrs of data
0.11 Counts/(kg keV y) around 2040 keV
\(T_{1/2} \geq 1.9 \times 10^{25} \text{ years (90\% C.L.)}\)

Subgroup of HdMo:
Claim: \(T_{1/2} = 2.23 \times 10^{25} \text{ years}\)

IGEX Experiment:

6.8 kg of enriched Ge detectors
8.5 kg yrs of data
0.17 Counts/(kg keV y) around 2040 keV
\(T_{1/2} \geq 1.6 \times 10^{25} \text{ years (90\% C.L.)}\)

K-K and K, Mod.


## Past $0\nu\beta\beta$ experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Underground Laboratory</th>
<th>Isotope</th>
<th>Technology</th>
<th>$T_{1/2} \ [10^{24} \text{ y}]$</th>
<th>$&lt;m_{ee}&gt; \ [eV]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elegant VI</td>
<td>Oto (Japan)</td>
<td>$^{48}\text{Ca}$</td>
<td>Scintillator $\text{CaF}_2$</td>
<td>$&gt; 0.095$</td>
<td>&lt; 7.2 - 44.7</td>
</tr>
<tr>
<td>Heidelberg-Moscow</td>
<td>Gran Sasso (Italy)</td>
<td>$^{76}\text{Ge}$</td>
<td>HPGe</td>
<td>$&gt;19$</td>
<td>&lt; 0.35 - 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>evidence:</strong></td>
<td>22.3 $^{4.4}_{-3.1}$</td>
<td>0.28 $^{0.17}_{-0.11}$</td>
</tr>
<tr>
<td>IGEX</td>
<td>Canfranc (Italy)</td>
<td>$^{76}\text{Ge}$</td>
<td>HPGe</td>
<td>$&gt; 16$</td>
<td>&lt; 0.3 - 1.5</td>
</tr>
<tr>
<td>NEMO-III</td>
<td>Frejus (France)</td>
<td>$^{82}\text{Se}$</td>
<td>Foils btw.</td>
<td>$&gt; 0.14$</td>
<td>&lt; 1.7 - 4.9</td>
</tr>
<tr>
<td>NEMO-III</td>
<td></td>
<td>$^{100}\text{Mo}$</td>
<td>tracker</td>
<td>$&gt;1.1$</td>
<td>&lt; 0.45 - 0.93</td>
</tr>
<tr>
<td>CdWO$_4$ scintillator</td>
<td>Solotvina (Ukrain)</td>
<td>$^{116}\text{Cd}$</td>
<td>Scintillator</td>
<td>$&gt; 0.17$</td>
<td>&lt; 1.5 - 1.7</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>Gran Sasso</td>
<td>$^{130}\text{Te}$</td>
<td>Phonons</td>
<td>$&gt; 2.8$</td>
<td>&lt; 0.3 – 0.7</td>
</tr>
</tbody>
</table>

**Disclaimer:** List represents only a few past experiments and is incomplete…
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The next generation(s) of 0νββ experiments

CUORE

Low temperature bolometer using TeO₂ crystals. 
Te has 33.4% nat. abundance of ¹³⁰Te → no enrichment

New cryostat with improved radiopurity (to be delivered 2011). Will house up to 988 TeO₂ crystals → 200kg of ¹³⁰Te

100 crystals already at LNGS

b = 0.01 cts/ (kg y keV )

Plan: Start measurements in 2013

CUORE0: use Cuoricino cryostat with first improved CUORE tower:
52 TeO₂ crystals 750g each → ~11 kg of ¹³⁰Te
Commissioning in 2011
The next generation(s) of 0νββ experiments
Enriched Xenon Observatory: EXO

Liquid Xe TPC:
Measure scintillation light and ionization.

→ Energy resolution: 1.6%@2479keV

Drift time of electrons and position on grid gives Information on decay position

200 kg of Xenon enriched in 80% with 136Xe

70% fiducial volume

→ 112 kg 136Xe target mass

Expect 20 events/year in RoI
Commissioning is starting:
Cryostat filled, ramping up voltage.
First results expected 2011.
The next generation(s) of $0\nu\beta\beta$ experiments
The Majorana project

HPGe detectors operated in ultra low background cryostat.
Copper for cryostat specially electroplated

Detectors with very good PSA capabilities (point contact/BEGe detectors) to recognize background

20 kg target mass in the form of enriched HP$^{76}\text{Ge}$ detectors

Commissioning of first cryostat expected for 2012
The next generation(s) of $0\nu\beta\beta$ experiments

The GErmanium Detector Array - GERDA

Clean-room

Lock system

Water tank (steel)

Muon veto ($\bar{\chi}$)

Cryostat (steel + Cu)

Liquid argon

Detector array
The next generation(s) of 0νββ experiments

First phase:

Use Heidelberg-Moscow and IGEX detectors.

Need 15 kg y with $10^{-2}$ cts/(kg y keV) to confirm or refute the HdMo claim.

Commissioning started June 2010

Second phase:

Use additional 35 kg of enriched germanium to produce detectors. Improve background to $10^{-3}$ cts/(kg y keV) by Pulse Shape Analysis or segmentation.

→ Proof of principle for ton scale experiment (GERDA and Majorana will merge)

Start expected 2012
The next generation(s) of $0\nu\beta\beta$ experiments

Main GERDA background: $^{42}\text{Ar}$

Distinct peak at 1525 keV

No other characteristic background peaks visible yet.

Background contributions due to $^{232}\text{Th}$, $^{238}\text{U}$
(90\%C.L. upper limit):

$< 1.2 \times 10^{-2}$ Counts/(kg y keV)

(Background level of HdMo and IGEX experiments. Dominated by $^{42}\text{Ar}$ background)

Presently commissioning is ongoing to understand and reduce the $^{42}\text{Ar}$ background. Ions are long lived in LAr and can be drifted!
The next generation(s) of $0\nu\beta\beta$ experiments

Experiments starting data taking soon:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Target Mass</th>
<th>Technology</th>
<th>FWHM</th>
<th>Exp. Sens. [meV]</th>
<th>Start</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA I</td>
<td>$^{76}\text{Ge}$</td>
<td>18 kg</td>
<td>HPGe</td>
<td>0.2%</td>
<td>220 (-) 500</td>
<td>2011</td>
</tr>
<tr>
<td>GERDA II</td>
<td>$^{76}\text{Ge}$</td>
<td>40 kg</td>
<td>HPGe</td>
<td>0.2%</td>
<td>90 (-) 200</td>
<td>2012</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}\text{Ge}$</td>
<td>(~20) kg</td>
<td>HPGe</td>
<td>0.2%</td>
<td></td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 kg</td>
<td></td>
<td></td>
<td></td>
<td>2014</td>
</tr>
<tr>
<td>CUORE0</td>
<td>$^{130}\text{Te}$</td>
<td>10 kg</td>
<td>$^{130}\text{TeO}_2$ bolometer</td>
<td>0.25%</td>
<td>168 (-) 391</td>
<td>2011</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{136}\text{Xe}$</td>
<td>200 kg</td>
<td></td>
<td></td>
<td>41 (-) 96</td>
<td>2013</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}\text{Xe}$</td>
<td>100 kg</td>
<td>LXe TPC</td>
<td>1.6%</td>
<td>130 (-) 190</td>
<td>2011</td>
</tr>
</tbody>
</table>

Many other experimental R&D efforts that can not be discussed in detail:

- SNO+ - Doped liquid scintillator
- NEXT – High pressure gas TPC
- Lucifer – phonons and scintillation
- COBRA – pixelized CdZnTe semiconductor detector,
- Candles, Moon, DCBA, …..
- SuperNEMO – Foils between tracking detectors,
CONCLUSIONS:

- Observation of $0\nu\beta\beta$ is the only known way to determine nature of neutrino (Dirac or Majorana)
- Part of Heidelberg-Moscow collaboration claims evidence for observation
- Need independent confirmation with same and different isotope
- First next generation experiments are being commissioned. Results expected next year.
- Ton scale experiments are required to disentangle neutrino-mass hierarchies