Neutrinoless Double-Beta Decay

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• Neutrinoless double-beta decay ($0\nu\beta\beta$) 
  Historical background & Motivation

• Neutrino masses

• Overview of ($2\nu\beta\beta$ & $0\nu\beta\beta$) detection techniques

• Detector examples & Recent Results

• Future “Ton Scale” experiments

• Summary/Outlook
Historical background and motivation

- 1930: Pauli suggests a “neutrino” which accompanies the electron in the $\beta$-decay
- 1932: Chadwick's discovery of the “neutron”
- 1934: Fermi's incorporation of both in his theory of the $\beta$ decay

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

$\beta$ decay: $(Z,A) \rightarrow (Z+1, A) + e^- + \bar{\nu}_e$

e.g. $^{198}\text{Au}_{79} \rightarrow ^{198}\text{Hg}_{80} + e^- + \bar{\nu}_e$
1935: M. Goppert-Meyer describes “double $\beta$ disintegration”

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

$2\nu\beta\beta$ decay: $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$

compatible with standard model
In some isotopes simultaneous decay of two neutrons into two protons possible

\[ T_{1/2} (2\nu\beta\beta) = (10^{18} - 10^{21}) \text{ year} \]

Age of the Universe: \( \sim 10^{10} \) years!
1937: Majorana suggests that $\nu_e = \bar{\nu}_e$

$0\nu\beta\beta$ decay: $(Z,A) \rightarrow (Z+2,A) + 2e^-$

not compatible with standard model

$\Delta L = 2$

$\rightarrow m_\nu > 0$

1937 Giulio Racah points out that Majorana's theory can be tested
How to address the problem experimentally?

Neutrino and anti-neutrino seem distinguishable, since they produce different final states.
1955 Ray Davis in concludes that $\nu_e$ distinct from $\bar{\nu}_e$
using anti-neutrinos from reactor

$$\bar{\nu}_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \quad \times$$  Anti-neutrinos from reactor

$$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \quad \checkmark$$  Neutrinos from the sun

Introduce Lepton Number 'L' to distinguish between neutrino and anti-neutrino

Allows to define allowed reactions

<table>
<thead>
<tr>
<th>Lepton</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^-</td>
<td>+1</td>
</tr>
<tr>
<td>e^+</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>+1</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>-1</td>
</tr>
</tbody>
</table>

$$\Sigma L_{\text{IN}} = \Sigma L_{\text{OUT}}$$
• 1957 discovery of parity violation in weak interactions and two component neutrino

• Since parity violation labels the neutrinos to be left-handed, no lepton number needed anymore

• Observations could be explained with neutrino helicity

Majorana nature of neutrinos not excluded yet
We know neutrinos have mass!

Our first hints of physics beyond Standard Model

Further hints

• Gravity
• Dark Matter
• Dark Energy
• Matter-antimatter asymmetry
- Solar $\nu$
- Reactor $\nu$
- Atmospheric $\nu$
- Accelerator $\nu$

**Neutrino Masses**

![Diagram showing normal and inverted neutrino mass eigenstates with solar and atmospheric oscillation parameters.](image)
To reach inverted hierarchy region we need sensitivities of:

$0\nu\beta\beta$: $T_{1/2} \sim 10^{27} - 10^{28}$ years

$2\nu\beta\beta$: $T_{1/2} \sim 10^{19} - 10^{21}$ years

IH = Inverted Hierarchy

NH = Normal Hierarchy
Overview of detection techniques

Signal signature

(A,Z) -> (A,Z+2) + 2e- +2 ν_e

2νββ

0νββ

Q-value
Overview of detection techniques

\[ \frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}^{(Q,Z)} |M_{0\nu}|^2 <m_\nu^2 > \]

- Phase space factor
- Nuclear matrix element
- Effective neutrino mass can be inferred from halflife measurements

Halflifes are determined by:

- Phase space factor
- Nuclear matrix elements
- Effective neutrino mass can be inferred from halflife measurements
Detector Sensitivity

\[ T_{1/2}(0\nu\beta\beta) = a \cdot \varepsilon \cdot \sqrt{M \cdot T / B \cdot dE} \]

**0νββ source**
Isotopically enriched

**Detector**
High detection efficiency (e.g. source=detector)
Good energy resolution
Low-background

**Experiment**
Long exposure times
Large source mass

\( a = \) isotopic abundance of source
\( \varepsilon = \) detection efficiency
\( M = \) total mass
\( T = \) exposure time
\( B = \) background in 0\nu\beta\beta ROI
\( dE = \) energy resolution
Overview of detection techniques

Half lives of $2\nu\beta\beta$ are $O(10^{21})$ years

1 Mole of source isotope produces ~ 1 decay/day !

<table>
<thead>
<tr>
<th>Half Life [years]</th>
<th>Signal [counts/tonne-year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{25}$</td>
<td>500</td>
</tr>
<tr>
<td>$5 \cdot 10^{26}$</td>
<td>10</td>
</tr>
<tr>
<td>$10^{27}$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{28}$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$T_{1/2} = a \cdot \varepsilon \cdot \sqrt{M \cdot T / B \cdot dE}$  
Background limited

$T_{1/2} = a \cdot \varepsilon \cdot M \cdot T$  
Background free

$0\nu\beta\beta$ & $2\nu\beta\beta$ detector technology challenging due to rare events
Potential Backgrounds

- Primordial, natural radioactivity in detector components: U, Th, K

- Backgrounds from cosmogenic activation while material is above ground (ββ- isotope or shield specific)

- Backgrounds from the surrounding environment:
  - external γ, (α,n), (n,α), Rn,

- μ-induced backgrounds generated at depth

- 2 neutrino double beta decay (irreducible, E resolution dependent)

- Neutrino backgrounds (negligible)
Overview of detection techniques

Reduce Background (passive)
- Ultra pure materials
- Shielding
- Deep underground

Discriminate Background (active)
- Energy resolution
- Event topology
- Fiducial cuts
- Pulse shape discrimination
- Particle identification

Further issues
- Unknown gamma transitions
- Nuclear matrix elements not accurately known
- Different isotopes require different technologies
- 2-v background different in each case
Overview of detection techniques

Ionization

Tracking&Cal:
SuperNEMO

Crystals
GERDA
Majorana

TPC:
EXO
NEXT

Scintillation

Liquid:
KamLAND ZEN
SNO+

Phonons

Bolometer:
Cuore

CUPID (Lucifer)
• There are 35 naturally occurring isotopes that can undergo a $\beta\beta$ decay.

• Only twelve isotopes have been experimentally observed undergoing $2\nu\beta\beta$:

  48Ca, 76Ge, 82Se, 96Zr, 100Mo, 116Cd, 128Te, 130Te, 130Ba, 136Xe, 150Nd, and 238U

• How do you choose your isotope?
Choice of isotopes

- Higher Q-value
  = less background

- Higher nat. abundance
  = better cost efficiency

Optimal isotope:
upper, right corner
Overview of detection techniques

![Graph showing m(ν) limit with data points for different isotopes (76Ge, 136Xe, 130Te, 100Mo) over time (1960-2030). The graph includes a reference to NME: RQRPA, Phys.Rev.C 79, 055501 (2009).]
Detector examples & Recent Results

EXO-200, 1600 m.w.e.  
WIPP, NM

CUORE, 3500 m.w.e  
LNGS, Gran Sasso

GERDA, 3500 m.w.e  
LNGS, Gran Sasso

NEMO-3/ SuperNEMO, 4800 m.w.e.  
LSM, Modane

and ~20 more .....
• EXO – 200 searches for the $0\nu\beta\beta$ decay in $\text{Xe}^{136}$

• Q-value: 2.458 MeV

• Location at WIPP (Waste Isolation Pilot Plant), NM

• EXO-200 drift: 655 m deep, ca. 1600 m.w.e.

• Dual Time Projection Chamber with LXe enriched to 80.6% $\text{Xe}^{136}$
• Read Scintillation and Ionization signals
• Scintillation light measured with APDs
• Charge Collection (U) wires
• Shielding/Induction (V) wires
• Event topology used for Single-site and Multi-site event discrimination
• Anti-correlation between scint & ionization used to improve energy resolution

Detector examples & Recent Results

EXO-200
- Background well understood
- Profile Likelihood Analysis
- No evidence for $0\nu\beta\beta$ in Xe$^{136}$
- Current half life limit: $1.1 \times 10^{25}$ years, 90% CL
- Majorana neutrino mass: $(190 – 450)$ meV
Detector examples & Recent Reults

- cleanroom, lock & lowering system
- watertank & μ veto
- Ge-detector array
- LAr cryostat

HALL A
• Strings of Ge detectors immersed in LAr
• Enrichment up to 86% $^{76}$Ge possible
• Q-value: 2.039 MeV
• Detector = Source: very good detection efficiency: $\varepsilon \sim 100\%$
• Very good energy resolution: $< 0.2\%$ @ 2.6 MeV
• High-purity germanium $\rightarrow$ low intrinsic background
• Detector technology well established and developed (since $\sim$1960)
GERDA - Phase I finished

- Exposure 21.6 kg x year
- Background: \((11 \pm 2) \times 10^{-3} \text{ cts/(keV kg year)}\)
- \(T_{1/2} > 2.1 \times 10^{25} \text{ years (90\% CL)}\)

GERDA-Phase II, commissioned in Dec 2015

- 30 new Broad Energy Ge (BEGe) detectors
- Active mass 35.8 kg of enriched Ge
- Background reduction to \(~10^{-3} \text{ cts/(keV kg year)}\)

Goal

- Exposure of 100 kg years
- Improve limit on \(T_{1/2} \sim 10^{26} \text{ years}\)
Recent Highlights

• The EXO, GERDA and KamLAND-Zen double beta decay detectors have essentially ruled out a long-standing claim for observation of the neutrinoless decay mode in $^{76}\text{Ge}$ (HdM).

• The CUORE Collaboration has brought the world's largest-volume dilution refrigerator to base temperature (6mK), a major step towards a ton-scale bolometric experiment.

• The MAJORANA DEMONSTRATOR Collaboration has reported record Cu purity from its underground electroforming campaign, and expects to achieve the ultra-low backgrounds specified. Commissioning runs with more than 10 kg of highly enriched $^{76}\text{Ge}$ are beginning in the SURF laboratory.

• The SNO+ experiment has demonstrated the stable suspension of isotopes in the scintillator Linear Alkyl Benzene, another path toward a ton-scale
## Detector examples & Recent Results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Exposure (kg year)</th>
<th>Sensitivity $10^{25}$ yr</th>
<th>$T_{1/2} \times 10^{25}$ yr 90%CL</th>
<th>$&lt;m_\nu&gt;$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge$^{76}$</td>
<td>GERDA I</td>
<td>21.6</td>
<td>2.4</td>
<td>&gt;2.1</td>
<td>200-400</td>
</tr>
<tr>
<td>Xe$^{136}$</td>
<td>EXO-200</td>
<td>100</td>
<td>1.9</td>
<td>&gt;1.1</td>
<td>190-450</td>
</tr>
<tr>
<td>Xe$^{136}$</td>
<td>KamlandZen</td>
<td>504</td>
<td>4.9</td>
<td>&gt;11</td>
<td>60-161</td>
</tr>
<tr>
<td>Te$^{130}$</td>
<td>CUORE</td>
<td>19.75</td>
<td>0.29</td>
<td>0.4</td>
<td>270-760</td>
</tr>
</tbody>
</table>
Goal of current and future efforts - test inverted hierarchy parameter space with tonne scale experiments

$^{76}\text{Ge}$:
- Large Scale Ge, O(tonne) HPGE crystals (GERDA & MAJORANA)

$^{82}\text{Se}$:
- SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale

$^{136}\text{Xe}$:
- KamLANDZen — $^{136}\text{Xe}$ in scintillator (several upgrades planned)
- NEXO - Liquid TPC, 5 tonne of $^{136}\text{Xe}$
- NEXT - High pressure gas TPC, tonne scale LZ (dark matter), liquid TPC, 7 tonne
Future “Ton Scale” experiments

Isotope Mass

- 10-100 kg
- 1-10 ton

Current Bound

Current generation

Next generation

Background

- 10-100 cts/yr/ton
- 0.1-1 cts/yr/ton
• $0\nu\beta\beta$ physics is the most sensitive probe of lepton number violation.

• A $0\nu\beta\beta$ discovery would prove the Majorana or Dirac nature of neutrinos and indicate physics beyond the Standard Model.

• Half-life limits of $10^{25}-10^{26}$ years are currently probed, but no discovery claimed yet.

• Scalability of detector technology will push the limits further down. New results expected in few years.

• Covering the inverted hierarchy with $10\text{meV}$ sensitivities is within reach.

Many thanks to my colleagues from the EXO-200 collaboration who contributed with slides and comments.
Backup slides
Future “Ton Scale” experiments

Discovery level, inverted hierarchy

- $^{76}$Ge (87% enr.)
- $^{136}$Xe (90% enr.)
- $^{130}$Te (nat.)

$T_{1/2}$ vs. Exposure [ton-years]

$10^3$ to $10^30$ scales

$IO m_{\beta\beta}^{min}$ ranges

- Background free
- 0.1 counts/ROI-t-y
- 1.0 count/ROI-t-y
- 10 counts/ROI-t-y

J. Detwiler
# Ongoing upgrades and their projections

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Mass [kg] (Total / FV)</th>
<th>Bckg [counts/y t] in ROI</th>
<th>FWHM in ROI [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge$^{76}$</td>
<td>GERDA II</td>
<td>35/27</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ge$^{76}$</td>
<td>Majorana demonstrator</td>
<td>30/24</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Xe$^{136}$</td>
<td>NEXT100</td>
<td>100/80</td>
<td>9</td>
<td>17</td>
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<tr>
<td>Te$^{130}$</td>
<td>CUORE</td>
<td>600/206</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Te$^{130}$</td>
<td>SNO+</td>
<td>2340/160</td>
<td>45 per t (Te)</td>
<td>240</td>
</tr>
<tr>
<td>Collaboration</td>
<td>Isotope</td>
<td>Technique</td>
<td>mass (0νββ isotope)</td>
<td>Status</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------</td>
<td>-----------------------------------------------</td>
<td>---------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>CANDLES</td>
<td>Ca-48</td>
<td>305 kg CaF$_2$ crystals - liq. scint.</td>
<td>0.3 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>CARVEL</td>
<td>Ca-48</td>
<td>$^{48}$CaWO$_4$ crystal scint.</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>GERDA I</td>
<td>Ge-76</td>
<td>Ge diodes in LAr</td>
<td>15 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>II</td>
<td>Ge-76</td>
<td>Point contact Ge in LAr</td>
<td>30-35 kg</td>
<td>Commissioning</td>
</tr>
<tr>
<td>MAJORANA DEMONSTRATOR</td>
<td>Ge-76</td>
<td>Point contact Ge</td>
<td>30 kg</td>
<td>Commissioning</td>
</tr>
<tr>
<td>Ton Scale Ge</td>
<td>Ge-76</td>
<td>Point contact</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>NEMO3</td>
<td>Mo-100</td>
<td>Foils with tracking</td>
<td>6.9 kg</td>
<td>Complete</td>
</tr>
<tr>
<td></td>
<td>Se-82</td>
<td></td>
<td>0.9 kg</td>
<td></td>
</tr>
<tr>
<td>SuperNEMO Demonstrator</td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>7 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>100 kg</td>
<td>R&amp;D</td>
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<td>LUCIFER</td>
<td>Se-82</td>
<td>ZnSe scint. bolometer</td>
<td>18 kg</td>
<td>R&amp;D</td>
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<td>AMoRE</td>
<td>Mo-100</td>
<td>CaMoO$_4$ scint. bolometer</td>
<td>50 kg</td>
<td>R&amp;D</td>
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<tr>
<td>MOON</td>
<td>Mo-100</td>
<td>Mo sheets</td>
<td>200 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>COBRA</td>
<td>Cd-116</td>
<td>CdZnTe detectors</td>
<td>10 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>183 kg</td>
<td></td>
</tr>
<tr>
<td>CUORICINO</td>
<td>Te-130</td>
<td>TeO$_2$ Bolometer</td>
<td>10 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>Te-130</td>
<td>TeO$_2$ Bolometer</td>
<td>11 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>CUORE</td>
<td>Te-130</td>
<td>TeO$_2$ Bolometer</td>
<td>206 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>CUPID</td>
<td>Te-130</td>
<td>TeO$_2$ Bolometer &amp; scint.</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SNO+</td>
<td>Te-130</td>
<td>0.3% nat Te suspended in scint.</td>
<td>~ tonne</td>
<td>Construction</td>
</tr>
<tr>
<td>KamLAND-ZEN</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>360 kg</td>
<td>Operating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7% in liquid scint.</td>
<td>800 kg</td>
<td>Upgrade</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>80 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>EXO200</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>160 kg</td>
<td>Operating*</td>
</tr>
<tr>
<td>nEXO</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>Nd foils &amp; tracking chambers</td>
<td>20 kg</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>
| Isotope | $0
\nu\beta\beta$ half life | Experiment | $<m>$ eV |
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>48-Ca</td>
<td>$&gt; 1.4 \times 10^{22}$ (90%CL)</td>
<td>ELEGANT-VI</td>
<td>&lt; 7 - 44</td>
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<tr>
<td>76-Ge</td>
<td>$&gt; 1.9 \times 10^{25}$ (90%CL)</td>
<td>Heidelberg-Moscow</td>
<td>&lt; 0.35</td>
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<tr>
<td>76-Ge</td>
<td>$2.3 \times 10^{25}$ (90%CL)</td>
<td>Subset of HM coll.</td>
<td>0.32 +/- 0.03</td>
</tr>
<tr>
<td>76-Ge</td>
<td>$&gt; 2.1 \times 10^{25}$ (90%CL)</td>
<td>GERDA†</td>
<td>&lt; 0.2 – 0.4</td>
</tr>
<tr>
<td>82-Se</td>
<td>$&gt; 2.1 \times 10^{23}$ (90%CL)</td>
<td>NEMO-3</td>
<td>&lt;1.2 – 3.2</td>
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<tr>
<td>100-Mo</td>
<td>$&gt; 5.8 \times 10^{23}$ (90%CL)</td>
<td>NEMO-3</td>
<td>&lt; 0.6 – 2.7</td>
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<tr>
<td>116-Cd</td>
<td>$&gt; 1.7 \times 10^{23}$ (90%CL)</td>
<td>Solotvino</td>
<td>&lt; 1.7</td>
</tr>
<tr>
<td>130-Te</td>
<td>$&gt; 2.8 \times 10^{24}$ (90%CL)</td>
<td>Cuoricino</td>
<td>&lt; 0.41 – 0.98</td>
</tr>
<tr>
<td>136-Xe</td>
<td>$&gt; 1.9 \times 10^{25}$ (90%CL)</td>
<td>KamLAND-Zen</td>
<td>&lt; 0.12 – 0.25</td>
</tr>
<tr>
<td>136-Xe</td>
<td>$&gt; 1.6 \times 10^{25}$ (90%CL)</td>
<td>EXO-200</td>
<td>&lt; 0.14 – 0.38</td>
</tr>
<tr>
<td>150-Nd</td>
<td>$&gt; 1.1 \times 10^{24}$ (90%CL)</td>
<td>NEMO-3</td>
<td>&lt; 0.33-0.62</td>
</tr>
</tbody>
</table>
Neutrino Oscillations

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

\[ |\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} |\nu_i(0)\rangle \]

with \( E_i = m_i c^2 \)

\[ P_{\alpha \rightarrow \beta} \sim \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) \]

\( v_\alpha \) = mass eigenstates

\( v_i \) = flavour eigenstates

\( U \) = Lepton mixing matrix

\( L \) = Travel distance

Neutrino oscillations = non-zero neutrino mass
Super-K: atmospheric $\nu_\mu$ oscillation

SNO: solar $\nu_e$ flavor oscillation

K2K: accelerator $\nu_\mu$ oscillation

KamLAND: reactor $\nu_e$ disappearance and oscillation