Double-Beta Decay Searches in 2012 (and beyond)

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What is double beta decay (DBD)?

The 2-neutrino DBD ($2\nu\beta\beta$) 
[Goepert-Mayer, 1935]

$$A^ZX \rightarrow A^{Z+2}Y + 2e^- + 2\bar{\nu}_e$$

- $\Delta L = 0$
- Allowed in SM
- Decay rate: slow (second order weak process) and $\sim Q^{11}_{\beta\beta}$
- Can be calculated:
  $$\left( T^{2\nu}_{1/2} \right)^{-1} = G_{2\nu}(Q_{\beta\beta}, Z) \times |M_{2\nu}|^2$$
- Has been measured:
  $$T^{2\nu}_{1/2} \simeq 10^{18} - 10^{21} \text{ yr}$$
- Not very interesting... but...
What is neutrinoless double beta decay (DBD) ?

The neutrinoless DBD (0$\nu\beta\beta$) [Furry, 1939]

$$^{A}ZX \rightarrow ^{A}Z_{+2} Y + 2e^-$$

- $\Delta L = 2$ !!!
- Forbidden in SM !!!
- Decay rate is :

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \times |M_{0\nu}|^2 \times \eta$$

Expected $T_{1/2}^{0\nu} >> T_{1/2}^{2\nu}$

- $\eta$ contains new physics !
  - Lepton number violation

Several mechanisms can be envisaged : massive Majorana neutrino exchange, Majoron emission, SUSY...
What is neutrinoless double beta decay (DBD)?

The neutrinoless DBD \((0\nu\beta\beta)\) [Furry, 1939]

\[ _Z^A X \longrightarrow _{Z+2}^A Y + 2e^- \]

- \(\Delta L = 2 \) !!!
- Forbidden in SM !!!
- Decay rate is:

\[ (T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \times |M_{0\nu}|^2 \times \eta \]

Expected \(T_{1/2}^{0\nu} \gg T_{1/2}^{2\nu}\)

- \(\eta\) contains new physics!
  - Lepton number violation
  - Effective light Majorana neutrino mass \(< m_\nu \neq 0\)

The only natural \(W^- W^-\) collider available!
The game: counting decays...

Example: a DBD experiment using $^{76}\text{Ge}$ (ala HM)

- $G_{0\nu}(Q, Z) = 0.623 \times 10^{-14} \text{ y}^{-1}$ ($Q_{\beta\beta} = 2039$ keV)
- $M_{0\nu} \simeq [3 - 6]$ (dimensionless) \rightarrow Large theor. uncertainty!
- $T_{1/2}^{0\nu} \simeq 2 \times 10^{25} \text{ y}$ (HM) $\sim m_{\nu} \simeq [0.25 - 0.5]$ eV

Running an ideal experiment with $t=5 \text{ y}$, $M=10$ kg of $^{76}\text{Ge}$, $\varepsilon=100\%$ efficiency (exposure $M \times t=50 \text{ kg.y}$):

$$N_{\text{decay}}^{0\nu} = \frac{N_{A} M \varepsilon t \log 2}{A} \frac{T_{1/2}^{0\nu}}{T_{1/2}^{0\nu}}$$

This gives: $N_{\text{decay}}^{0\nu} \simeq 14$ expected decays

- But typical natural radioactivity ($^{232}\text{Th, } ^{238}\text{U...}$) is $\simeq 1\text{-}100$ Bq/kg:

$$N_{\text{decay}}^{\text{radioactivity}} = a \times t \times M$$

and gives: $N_{\text{decay}}^{\text{radioactivity}} \simeq [1 - 100] \times 10^{9}$ nasty decays !!!
Radioactivity background is the enemy!

**Background sources...**

- Natural radioactivity energy scale: 1-5 MeV $\approx Q_{\beta\beta}$
- $^{232}$Th, $^{238}$U, $^{235}$U chains: plenty of $\alpha$, $\beta$ and $\gamma$ emitters
- Special mention for $^{226}$Ra ($T_{1/2}=1800$ y) and $^{222}$Rn (gas, $T_{1/2}=3.8$ days) and ($\beta/\alpha$) decay products
- Very special mention for $^{214}$Bi ($Q_{\beta}=3.2$ MeV) and $^{208}$Tl ($Q_{\beta}=5$ MeV, $E_{\gamma}=2.614$ MeV)
- Fission neutrons from surrounding rocks $\sim (n,\gamma)$ reactions ($>3$ MeV)
- Also cosmic muons:
  - spallation and thus unstable cosmogenic isotopes
  - bremsstrahlung $\sim$ high-energy $\gamma \sim e^-, e^+$
- Possible artificial radioactive contaminants may also be a problem.
- $2\nu\beta\beta$ decays (ultimate background in some cases).
Recipe for a DBD experiment

How to make it?

- Collect a large mass of some enriched isotope(s) as the DBD source (≳ 100 mol)
- Purify this DBD source with some radiochemistry processes (for example removing Radium to break the U decay chain)
- Select ultra-low radioactivity materials to build the $\beta\beta$ detector ($1\mu$Bq/kg – 1mBq/kg, remove Radon from gas)
- Bury the experimental setup deep underground ($\gtrsim$1000 m.w.e, protection against cosmic rays)
- Shield against environmental radioactivity ($n, \gamma, \mu, {}^{222}\text{Rn}$)
- Invent some technique(s) to discriminate $0\nu\beta\beta$ signal from background(s)
Recipe for a DBD experiment

How to make it?

- Collect a large mass of some enriched isotope(s) as the DBD source ($\gtrsim 100$ mol)
- Purify this DBD source with some radiochemistry processes (for example removing Radium to break the U decay chain)
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- Shield against environmental radioactivity ($n$, $\gamma$, $\mu$, $^{222}$Rn)
- Invent some technique(s) to discriminate $0\nu\beta\beta$ signal from background(s)
- Switch on the detector, seat down and wait... wait... wait...
Recipe for a DBD experiment

Experimental questions

- What isotopes to be used for DBD search?
- What technology to discover/invalidate $0\nu\beta\beta$ process?
- How to improve the radiopurity of the experimental setup and background rejection performance?
- How does it cost in terms of time, effort, money...hope?
- How does it scale for a future larger experiment with improved sensitivity?
- Does a best experimental approach exist?
Isotopes of experimental interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$Q_{\beta\beta}$ [keV]</th>
<th>Nat. abund. (enr.) [%]</th>
<th>$G_{0\nu} \big( \tilde{G}_{0\nu}^{76} \big)$ $[10^{-14} \ (y^{-1})]^a$</th>
<th>$M_{0\nu}^a$</th>
<th>$T_{1/2, \text{exp}}^{2\nu}$ $[10^{19} \ (y)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>4270</td>
<td>0.187 ($73^b$)</td>
<td>6.35 (16.15)</td>
<td>0.85 – 2.37</td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>2039</td>
<td>7.83 (86$^c$)</td>
<td>0.623 (1)</td>
<td>2.81 – 7.24</td>
<td>155$^f$</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>2995</td>
<td>8.73 (97$^b$)</td>
<td>2.70 (4)</td>
<td>2.64 – 6.46</td>
<td></td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>3350</td>
<td>2.8 (57$^b$)</td>
<td>5.63 (7.1)</td>
<td>1.56 – 5.65</td>
<td>0.716$^e$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>3034</td>
<td>9.63 (99$^b$)</td>
<td>4.36 (5.3)</td>
<td>3.103 – 7.77</td>
<td></td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>2802</td>
<td>7.49 (93$^b$)</td>
<td>4.62 (4.8)</td>
<td>2.51 – 4.72</td>
<td>2.88$^e$</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>2527</td>
<td>34.08 (90$^b$)</td>
<td>4.09 (3.8)</td>
<td>2.65 – 5.50</td>
<td>70$^e$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>2480</td>
<td>8.857 (80$^d$)</td>
<td>4.31 (3.9)</td>
<td>1.71 – 4.2</td>
<td>211$^g$</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>3367</td>
<td>5.6 (91$^b$)</td>
<td>19.2 (15.6)</td>
<td>1.71 – 3.7</td>
<td></td>
</tr>
</tbody>
</table>

$Q$: below 2.6 MeV $\gamma$-line ($^{208}\text{Tl}$), below 3.2 MeV $Q$-value ($^{214}\text{Bi}$)

$\tilde{G}_{0\nu}^{76} = (G_{0\nu}/A)$ then normalized to the value for $^{76}\text{Ge}$

$M_{0\nu}$: small theor. value or difficult to compute...

$^a$ from PRD 83, 113010 (2011)

$^b$ achieved in NEMO-3, $^c$ achieved in HM, $^d$ achieved in EXO-200

$^e$ from NEMO3 (see TAUP 2011), $^f$ from HM, $^g$ from EXO-200 (arXiv-1108.4193)
Measuring the electron energy sum spectrum \( Q_{\beta\beta} \)

- Use a Calorimeter:
  measurement of the energy sum of both electrons emitted in \( \beta\beta \) processes

![Diagram showing a Calorimeter scope with \( \beta\beta \) source and \( \beta\beta \) decay points, indicating energy sum \( E_1 + E_2 \).]

- New Physics!

\[ \frac{dN}{dE} \]

- Indices:
  - \( 2\nu\beta\beta \)
  - \( 0\nu\beta\beta_X \)
  - \( 0\nu\beta\beta \)

\( Q_{\beta\beta} \)

Counts/keV/kg/y: typical \( B \sim 0.1 \pm 0.001 \) counts/keV/kg/y

- Particle identification (\( \gamma, e^- , e^+ , \alpha \ldots \))
Measuring the electron energy sum spectrum @ $Q_{\beta\beta}$

- **Use a Calorimeter**: measurement of the energy sum of both electrons emitted in $\beta\beta$ processes.
- A critical criterion for signal/background discrimination in the $Q_{\beta\beta}$ ROI.
Measuring the electron energy sum spectrum @ $Q_{\beta\beta}$

- Use a **Calorimeter**: measurement of the energy sum of both electrons emitted in $\beta\beta$ processes
- A critical criterion for signal/background discrimination in the $Q_{\beta\beta}$ ROI
- High energy resolution is a must
Measuring the electron energy sum spectrum @ $Q_{\beta\beta}$

- **Use a Calorimeter**: measurement of the energy sum of both electrons emitted in $\beta\beta$ processes
- A critical criterion for signal/background discrimination in the $Q_{\beta\beta}$ ROI
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- Introducing the background index: typical $B \sim 0.1 - 0.001$ counts/keV/kg/y
Measuring the electron energy sum spectrum @ $Q_{\beta\beta}$

- Use a **Calorimeter**: measurement of the energy sum of both electrons emitted in $\beta\beta$ processes
- A critical criterion for signal/background discrimination in the $Q_{\beta\beta}$ ROI
- High energy resolution is a must
- Introducing the **background index**: typical $B \sim 0.1 - 0.001$ counts/keV/kg/y
- Additional criteria: particle identification ($\gamma$, $e^-$, $e^+$, $\alpha$...)

![Diagram showing electron energy spectrum with $Q_{\beta\beta}$ and $E_1 + E_2$ axes]
Experimental half-life sensitivity

- Background-free (lower limit):

\[ T_{1/2}^{0\nu} \gtrsim \frac{N_A \ln 2}{n_\sigma} \left( \frac{a \times \varepsilon}{A} \right) M \times t \]

- Background limited (lower limit):

\[ T_{1/2}^{0\nu} \gtrsim \frac{N_A \ln 2}{n_\sigma} \left( \frac{a \times \varepsilon}{A} \right) \sqrt{\frac{M \times t}{B \times \Delta E}} \]

where:
- \( n_\sigma \) the number of standard deviations at desired CL,
- \( a \) the isotopical abundance,
- \( M \) the mass of the source,
- \( t \) the measuring time,
- \( \varepsilon \) the efficiency,
- \( \Delta E \) the energy resolution at peak position (ROI),
- \( B \) the background index in the ROI (counts/keV/kg/y).

\[ \langle m_\nu \rangle \sim (M \times t)^{1/4} \]

\[ \langle m_\nu \rangle \sim (M \times t)^{1/2} \]

\[ B = 0.001 \text{ counts/keV/kg/y} \]

\[ B = 0.01 \text{ counts/keV/kg/y} \]
Experimental approaches

**Calorimeter**
- Detector = DBD source
- Excellent $\Delta E/E$
- Large efficiency
- Compact
- Address only one DBD isotope ($^{76}$Ge, $^{130}$Te...)
- Limited particle identification
- Techniques: Semiconductor, Bolometer, (Liquid-)Scintillator ($^{136}$Xe, $^{150}$Nd)

**Tracker**
- Detector $\neq$ DBD source
- Limited $\Delta E/E$
- Limited efficiency
- Not so compact
- Isotope flexibility ($^{100}$Mo, $^{82}$Se, $^{150}$Nd, $^{48}$Ca...)
- Particle identification and event topology
- Probe $\neq$ mechanisms
- Techniques: Drift chamber, TPC
### Experimental approaches

#### Calorimeter
- Detector = DBD source
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#### Hybrid
- Elements (best) of both
- Gaseous (Xe) TPC
- Pixelated calorimeter (CdZnTe)
It there a "best" technique for DBD?

- Each technique has its own problems in terms of source enrichment, source purification and, last but definitively not the least, background(s).

### Diagram

- **Small**
  - Liquid scintillator
  - Liquid Xe
  - Ionisation/Bolometer
  - Isotope mass

- **Large**
  - SNO+ (>100 kg $^{150}$Nd)
  - B(ROI) ≈ 10’s
  - EXO (80 kg $^{136}$Xe)
  - B(ROI) ≈ several

- **Background**
  - GERDA
    - 30 kg $^{76}$Ge
    - B(ROI) ≈ 5
  - Tracker/Calo.
    - SuperNEMO
      - 7 kg $^{82}$Se
      - B(ROI) < 1
  - Gas Xe TPC?

- **High**
- **Low**

**A selection of experiments**

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Experimental approaches

It there a “best” technique for DBD?

- Each technique has its own problems in terms of source enrichment, source purification and, last but definitively not the least, background(s).
- None is zero-background experiment (but some could pretend to be...)

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<th>Source</th>
<th>Background</th>
</tr>
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<tbody>
<tr>
<td>Large</td>
<td>Liquid scintillator</td>
<td>High</td>
</tr>
<tr>
<td>Large</td>
<td>Liquid Xe</td>
<td>Background</td>
</tr>
<tr>
<td>Large</td>
<td>Gas Xe TPC?</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td>Ionisation/Bolometer</td>
<td>Large</td>
</tr>
<tr>
<td>Small</td>
<td>Tracker/Calo.</td>
<td>Small</td>
</tr>
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- SNO+ (>100 kg $^{150}$Nd) B(ROI) $\sim$ 10’s
- EXO (80 kg $^{136}$Xe) B(ROI) $\sim$ several
- GERDA (30 kg $^{76}$Ge) B(ROI) $\sim$ 5
- SuperNEMO (7 kg $^{82}$Se) B(ROI) < 1

**A selection of experiments**
Experimental approaches

It there a “best” technique for DBD?

- Each technique has its own problems in terms of source enrichment, source purification and, last but definitely not the least, background(s)
- None is zero-background experiment (but some could pretend to be…)
- Each realizes a kind of compromise

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<tr>
<td>Gas Xe TPC?</td>
<td>SuperNEMO 7 kg $^{82}$Se B(ROI) &lt; 1</td>
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<td>Ionisation/Bolometer</td>
<td>Tracker/Calo.</td>
<td>GERDA 30 kg $^{76}$Ge B(ROI) $\sim$ 5</td>
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A selection of experiments
Experimental approaches

It there a “best” technique for DBD?

- Each technique has its own problems in terms of source enrichment, source purification and, last but definitively not the least, background(s)
- None is zero-background experiment (but some could pretend to be...)
- Each realizes a kind of compromise
- Some approaches exist to get the best available...

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- SNO+ (>100 kg $^{150}$Nd) $B(ROI)$ sim 10’s
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- SuperNEMO $7 \text{ kg }^{82}\text{Se}$ $B(ROI) < 1$
- A selection of experiments
Where we are now!

- ~1990-2000: HM experiment ($^{76}$Ge)

- 2000-2010: $\simeq 10$ kg
  - Cuoricino ($^{130}$Te, 2008)
  - NEMO3 ($^{100}$Mo, 2011)

- 2011+: New generation experiments
  - $\simeq 10$-100 kg
    - EXO200 ($^{136}$Xe)
    - Kamland-ZEN ($^{136}$Xe)

- → 2015: Start to investigate IH region
- Beyond 2015: cover IH?
  - $\simeq 100$-1000 kg

\[ \langle m_{\nu} \rangle (\text{eV}) \]

\[ \Delta m_{23}^2 > 0 \]

\[ \Delta m_{23}^2 < 0 \]

Normal (NH)

Inverted hierarchy (IH)

Quasi-degenerate

disfavoured by $0\nu\beta\beta$

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[Strumia & Vissani, hep-ph/0606054]
Where we are now!

- ~1990-2000: HM experiment ($^{76}$Ge)
- ~2000-2010: $\simeq 10$ kg
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  - NEMO3 ($^{100}$Mo, 2011)

$\Delta m^2_{23} < 0$  
$\Delta m^2_{23} > 0$

Lightest neutrino mass (eV)

[Normal (NH)]

90% CL (1 dof)

[Inverse hierarchy (IH)]

[HM Cuoricino NEMO3]

Disfavoured by 0$\nu$ββ

[Strumia & Vissani, hep-ph/0606054]
Where we are now!

- **~1990-2000**: HM experiment ($^{76}$Ge)
  - **~2000-2010**: ≃10 kg
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- **~2011+**: New generation experiments
  - ≃10-100 kg
  - First stimulating results:
    - EXO200 ($^{136}$Xe)
    - Kamland-ZEN ($^{136}$Xe)

![Graph showing neutrino mass and mixing](image)

[Strumia & Vissani, hep-ph/0606054]
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- **→2015**: Start to investigate IH region

\[ \Delta m_{23}^2 < 0 \] (Inverted hierarchy (IH))
\[ \Delta m_{23}^2 > 0 \] (Normal (NH))

90 % CL (1 dof)

[Strumia & Vissani, hep-ph/0606054]
Where we are now!

- **1990-2000**: HM experiment ($^{76}\text{Ge}$)
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- →2015: Start to investigate IH region
- Beyond 2015: cover IH?
  - ≈100-1000 kg

[Strumia & Vissani, hep-ph/0606054]
Next generation of experiments

Calorimeter

- Ge diode $\varepsilon, \Delta E$ 76Ge
- Bolometers $\varepsilon, \Delta E$ 130Te, 82Se, 100Mo
- Liquid Xe $\varepsilon, M, (N_{\text{Bckd}})$ 136Xe
- Scintillator $\varepsilon, M$ 136Xe, 82Se, 100Mo

Tracker

- Tracko-calo $N_{\text{Bckd}},$ isotopes 82Se (150Nd, 48Ca)
- Pixellized CdZnTe $\varepsilon, N_{\text{Bckd}}$ 116Cd
- TPC $\varepsilon, N_{\text{Bckd}}$ 136Xe, 150Nd

- GERDA
- MAJORANA
- CUORE
- LUCIFER
- ZnMo4
- EXO
- KamLAND-Zen CANDLES SNO+ Borexino CdWO4 AMoRE
- SuperNEMO
- COBRA
- MTD EXO-gas NEXT
GERDA – Calorimeter, $^{76}\text{Ge}$

- Bare detectors in liquid argon for effective background suppression
- Re-use HM & IGEX crystals
- Phase 1 data-taking: 18 kg $^{\text{enr}}\text{Ge}$
- Sensitivity to Klapdor claim soon
- $^{42}\text{Ar}/^{42}\text{K}$ problem now solved
- Phase 1: $B \sim 0.02$ counts/keV/kg/y
- Phase 2 target: $B \sim 10^{-3}$ counts/keV/kg/y
- See also the MAJORANA project
CUORE – Calorimeter, $^{130}\text{Te}$

- $^{nat}\text{Te}$ bolometer experiment
  ($^{130}\text{Te}$, 34% natural abundance)
- Te02 crystal: low heat capacity, high intrinsic radio-purity
- Operated at 8-10 mK
- 19 towers $\sim 200$ kg $^{130}\text{Te}$
- Background target:
  10-100 smaller than CUORICINO
  $B \sim 5 \times 10^{-2} - 5 \times 10^{-3}$ counts/keV/kg/y
- 2011-2018: $t=5$ year
  $<m_\nu> \approx 40-100$ meV

![CUORE Experiment Image]
SuperNEMO – Calorimeter+Tracker, $^{82}\text{Se}$

- Tracker/Calorimeter ala NEMO3 experiment
- Demonstrator module: 7 kg of $^{82}\text{Se}$ ($\times 2.5$ y)
- Prove $B \sim 10^{-4}$ counts/keV/kg/y
- Limit: $T_{1/2}^{0\nu} \sim 6.5 \times 10^{24}$ y
- Construction started, running 2015-2016 (LSM)
- Prove scalability for a full-scale 20 modules with:
  - 100 kg $\times$ 2016-2020
  - $T_{1/2}^{0\nu} \sim 10^{26}$ y, $<m_\nu> = 40$-100 meV
- R&D for $^{48}\text{Ca}$, $^{150}\text{Nd}$
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EXO-200 – Calorimeter, $^{136}$Xe

- Liquid-xenon TPC with ionisation & scintillation readout
- Fiducial mass of 79.4 kg of $^{136}$Xe for the $0\nu\beta\beta$ search.

$^{136}$Xe $2\nu\beta\beta$ measurement:

$$T_{1/2}^{2\nu\beta\beta} = 2.11 \pm 0.04\text{(stat.)} \pm 0.21\text{(syst.)} \times 10^{21}\text{ yr}$$

*Ackerman et al. (2011)*

1 event observed in 1σ ROI around $Q_{\beta\beta}$ vs. 4.1 background events expected.

33 kg.yr    $B \sim 0.0015$ cts/keV/kg/yr

$$T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{25}\text{ yr} \; @\; 90\% \text{ C.L.}$$

$$\langle m \rangle < 140 - 380 \text{ meV}$$

*Auger et al. (2012)*
KamLAND-ZEN – Calorimeter, $^{136}\text{Xe}$

- Several $0\nu\beta\beta$ isotopes compatible with LS.
- Large masses can be loaded.
- Reasonable energy resolution: $\sigma_E = 6.6\%/\sqrt{E}$ (MeV)

$^{136}\text{Xe}(2\nu\beta\beta)$, $Q(\beta\beta) = 2.5$ MeV

- $T^{2\nu}_{1/2} = 2.38 \pm 0.14 \times 10^{21}$ yr
- $T^{0\nu}_{1/2} > 5.7 \times 10^{24}$ yr @ 90% C.L.
- $\langle m_{\beta\beta} \rangle < (0.3 - 0.6)$ eV

- Currently background limited (Fukushima).
- Reduce backgrounds by factor 100, increase $^{136}\text{Xe}$ mass and use brighter scintillator.
  - target of $<m_e> \sim 20-40$ meV

Fall-out: $^{110m}\text{Ag}$, $^{208}\text{Bi}$ (?) produces $E \sim 2.6$ MeV
SNO+ – Calorimeter, $^{150}$Nd

- SNO detector filled with 800 tonnes of LS: Linear Alkyl-Benzene + 2g/litre PPO fluor.
- Broad physics program: solar/geo-ν; SN; 0νββ
- Major engineering challenges.
- Extremely stringent radiopurity requirements:
  - $< 10^{-17} \text{ g } ^{226}\text{Ra}/^{228}\text{Th per g scintillator}$.
  - $< 10^{-14} \text{ g } ^{226}\text{Ra}/^{228}\text{Th per g Nd}$
- Purification proof of principle: KamLAND/Borexino.

![Diagram of SNO+ detector with hold-down ropes and energy spectrum](image)

Optimal loading $\sim 0.3\%$

$M(\text{^{150}Nd}) \sim 135 \text{ kg}$

$\frac{\sigma(E)}{E} = 6 - 7\% \text{ @ } 1 \text{ MeV}$

Sensitivity:

- 3 years of data
- $\langle m \rangle \sim 100 \text{ meV}$
Summary [1]

- DBD physics is a major concern for particle physics:
  - Lepton number non conservation
  - Majorana neutrino
  - Neutrino mass, “exotic” weak coupling, SUSY

- Interplay with other $\nu$ mass measurements, hierarchy problem and oscillation experiments

- A new generation experiments (10-100kg) have started or will within few years:
  - We are entering the era of 100 kg scale DBD experiments
  - Different isotopes, techniques, mass and backgrounds
  - Lots of experimental efforts are done to improve, step by step, the sensitivity of DBD detectors
  - Some very interesting results are expected within a few years (GERDA, EXO, KAMLAND, SNO+, CUORE... SuperNEMO...)
  - We need a few years to make our mind about the best way(s), maybe 1-2 techniques remaining in the future (2020+)
  - In the meanwhile, some R&D programs with (promising) novel techniques has started (scintillating bolometers, tracker crystals, gas TPC...)
Summary [2]

After 10 years of aggressive statements about some future ton scale experiments and claims for efficient background reduction with existing technologies, the new generation experiments are now facing the real: background exists!
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However: DBD physics MUST be investigated (and supported) by the scientific community

Despite the background challenge it is [a kind of nightmare]

Despite funding issues [another kind of nightmare]

Despite maybe there are no chance to go further (IH, NH) but we still don't know

Thanks to the motivation of many skilled groups worldwide

Message for the newborn LIO: please consider carefully to join some DBD experimental program!

F. Mauger
LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France
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Thanks (for stolen slides and pictures)

- ...

Apologies and also best wishes for

- AMoRE ($^{100}$Mo)
- CANDLES ($^{48}$Ca)
- COBRA ($^{116}$Cd)
- DCBA ($^{100}$Mo/$^{150}$Nd)
- LUCIFER($^{82}$Se/$^{100}$Mo)
- MAJORANA ($^{76}$Ge)
- MOON ($^{100}$Mo)
- NEXT ($^{136}$Xe)
- XMASS ($^{136}$Xe)
- ZnMo4 ($^{100}$Mo), CdMo4 ($^{116}$Cd)