Present and Future of Double Beta Decay experiments

(aimed to know still unknown neutrino properties)
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Why so many efforts (and money) are needed?

\[ 0\nu\beta\beta \rightarrow 7 \text{ out of } 9 \text{ parameters of neutrino mass matrix!} \]

A. Smolnikov, International workshop “Prospects of Particle Physics”, Valdai, January 27 – February 1, 2014
Majorana vs. Dirac, effective mass, hierarchy, CP phases

Observation of 0νββ is the only known way to determine nature of neutrino (Dirac or Majorana)

Ton scale experiments are required to resolve neutrino-mass hierarchies

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

- Contains complex CP-violating Majorana phases
- Cancellations possible!

In order to discriminate normal from inverted hierarchy, an experiment with sensitivity down to 10 meV is needed!
\( 0\nu\beta\beta \) decay rate

**Light neutrino exchange**

\[
\frac{1}{\tau} = G(Q, Z) \cdot |M_{nucl}|^2 \cdot \langle m_{\beta\beta}\rangle^2
\]

- **Phase space factor** \((\sim Q_{\beta\beta}^5)\)

- **Nuclear matrix element**

- **Effective Majorana neutrino mass**

\[
Q = E_{e1} + E_{e2} - 2m_e
\]

\[
\langle m_{\beta\beta}\rangle = |\sum_j m_j U_{ej}^2| = m_1 |U_{e1}|^2.
\]

\(U_{ei}\) (complex) neutrino mixing matrix

\(\alpha_{1,2}\) - complex CP-violating Majorana phases

**The effective mass**
9 physical parameters in neutrino mass matrix $m_ν$

- $θ_{12}$ and $m_{2}^2 - m_{1}^2$
- $θ_{23}$ and $|m_{3}^2 - m_{2}^2|$
- $θ_{13}$ (or $|U_{e3}|$)
- $m_1$, $m_2$, $m_3$
- $\text{sgn} \ (m_{3}^2 - m_{2}^2)$
- Dirac phase $δ$
- Majorana phases $α$ and $β$ (or $α1$ and $α2$, or $φ1$ and $φ2$, or . . .)


\[
\mathcal{L} = \frac{1}{2} ν^T m_ν ν \quad \text{with} \quad m_ν = U \ diag(m_1, m_2, m_3) U^T
\]

where

\[
U = \begin{pmatrix}
    c_{12} & c_{13} & s_{12} c_{13} & s_{13} e^{-iδ} \\
    -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{iδ} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{iδ} & c_{23} c_{13} \\
    s_{12} s_{23} - c_{12} c_{23} s_{13} e^{iδ} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{iδ} & s_{23} c_{13}
\end{pmatrix}
\]

with $P = \ diag(e^{iα}, e^{iβ}, 1)$

(only show up in Lepton Number Violating processes, if neutrinos are Majorana)

⇒ 3 angles, 3 phases, 3 masses
### Which mass ordering with which life-time?

| Method | \( \Sigma \) | \( m_\beta \) | \( |m_{ee}| \) |
|--------|-----------------|-----------------|-----------------|
| NH     | \( \sqrt{\Delta m^2_A} \) | \( \sqrt{\Delta m^2_\odot + |U_{e3}|^2 \Delta m^2_A} \) | \( \sqrt{\Delta m^2_\odot + |U_{e3}|^2 \sqrt{\Delta m^2_A} e^{2i(\alpha-\beta)}} \) |
|        | \( \simeq 0.05 \text{ eV} \) | \( \simeq 0.01 \text{ eV} \) | \( \simeq 0.003 \text{ eV} \Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{28-29} \text{ yrs} \) |
| IH     | \( 2\sqrt{\Delta m^2_A} \) | \( \sqrt{\Delta m^2_A} \) | \( \sqrt{\Delta m^2_A} \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha} \) |
|        | \( \simeq 0.1 \text{ eV} \) | \( \simeq 0.05 \text{ eV} \) | \( \simeq 0.03 \text{ eV} \Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{26-27} \text{ yrs} \) |
| QD     | \( 3m_0 \) | \( m_0 \) | \( m_0 \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha} \) |
|        | \( \gtrsim 0.1 \text{ eV} \Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{25-26} \text{ yrs} \) |

### \(\nu - \text{mass Sensitivity}\)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurie</td>
<td>2.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Cosmology</td>
<td>1</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>0(\nu\beta\beta)</td>
<td>0.3</td>
<td>0.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Goal of the next generation experiments

- Isotope mass
  - ~ 10 kg (200 – 400kg $^{136}$Xe)
  - ~ 100 kg
  - ~ 1000 kg

- Required background level in the ROI
  - 100 – 1000 cts/yr/ton
  - 1 – 10 cts/yr/ton
  - 0.1 – 1 cts/yr/ton

- Lower $<m_{ee}>$ is given by (for light $\nu$ exchange):

  \[
  \langle m_{ee} \rangle_{IH} \approx \sqrt{m_3^2 + \Delta m_A^2 \cdot \cos(\theta_{12})^2 \cdot \cos(\theta_{13})^2} - \sqrt{m_3^2 + \Delta_{sol}^2 + \Delta m_A^2 \cdot \sin(\theta_{12})^2 \cdot \cos(\theta_{13})^2} - m_3 \sin(\delta_{13})^2
  \]

  \[
  \approx (1 - 2\sin(\theta_{13})^2) \sqrt{\Delta m_A^2}
  \]

  \[
  \approx (0.364^{+0.032}_{-0.030})(49 \pm 1.2) \text{ meV}
  \]

  \[
  = 17.8^{+1.6}_{-1.9} \text{ meV}
  \]
Neutrinoless double beta decay

\((A,Z) \rightarrow (A,Z+2) + 2\, e^-\)

Discovery implies \(\Delta L=2\) and Majorana neutrino

Process:
Light neutrino exchange
(V+A) current
Majoron emission
SUSY


\[\frac{T_1}{2} = F(Q^{bb}, Z) \left| M \right|^2 \]

Phase space factor
Nuclear matrix element

\[\langle m_\nu \rangle, \langle \lambda \rangle, \langle \eta \rangle\]

\[\langle g_M \rangle\]

\[\lambda'_{111}, \lambda'_{113}, \lambda'_{131}, \ldots\]

Nuclear matrix element

\[\frac{T_1}{2}\] depends on

Coupling between Majoron and neutrinos

Electron energy sum

Arbitrary unit

\[\left| U_{e1} \right|^2 + \left| U_{e2} \right|^2 + \left| U_{e3} \right|^2\]
Senjanovic, Keung, 1983; Senjanovic et al., 1011.3522; 1103.1627
Does Dirac neutrinos mean there is no Lepton Number Violation?

neutrinos are Dirac particles, and Lepton Number violated by 4 units!

⇒ observable: **neutrinoless quadruple beta decay** \((A, Z) \rightarrow (A, Z + 4) + 4 \, e^-\)

*Heeck, Rodejohann., Eur.Phys.Lett. 103*
## Neutrinoless Quadruple Beta Decay

<table>
<thead>
<tr>
<th>Decay</th>
<th>( Q_{0\nu 4\beta} )</th>
<th>Other decays ( T_{1/2} )</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{96}\text{Zr} \rightarrow ^{96}\text{Ru} )</td>
<td>0.629</td>
<td>( T_{1/2}^{2\nu 2\beta} \approx 2 \times 10^{19} )</td>
<td>2.8</td>
</tr>
<tr>
<td>(^{136}\text{Xe} \rightarrow ^{136}\text{Ce} )</td>
<td>0.044</td>
<td>( T_{1/2}^{2\nu 2\beta} \approx 2 \times 10^{21} )</td>
<td>8.9</td>
</tr>
<tr>
<td>(^{150}\text{Nd} \rightarrow ^{150}\text{Gd} )</td>
<td>2.079</td>
<td>( T_{1/2}^{2\nu 2\beta} \approx 7 \times 10^{18} )</td>
<td>5.6</td>
</tr>
</tbody>
</table>

### \( Q_{0\nu 4\text{EC}} \)

<table>
<thead>
<tr>
<th>Decay</th>
<th>( Q_{0\nu 4\text{EC}} )</th>
<th>Other decays</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{124}\text{Xe} \rightarrow ^{124}\text{Sn} )</td>
<td>0.577</td>
<td>—</td>
<td>0.095</td>
</tr>
<tr>
<td>(^{130}\text{Ba} \rightarrow ^{130}\text{Te} )</td>
<td>0.090</td>
<td>( T_{1/2}^{2\nu 2\text{EC}} \approx 10^{21} )</td>
<td>0.106</td>
</tr>
<tr>
<td>(^{148}\text{Gd} \rightarrow ^{148}\text{Nd} )</td>
<td>1.138</td>
<td>( T_{1/2}^{\alpha} \approx 75 )</td>
<td>—</td>
</tr>
<tr>
<td>(^{154}\text{Dy} \rightarrow ^{154}\text{Sm} )</td>
<td>2.063</td>
<td>( T_{1/2}^{\alpha} \approx 3 \times 10^6 )</td>
<td>—</td>
</tr>
</tbody>
</table>

### \( Q_{0\nu 3\text{EC}\beta^+} \)

<table>
<thead>
<tr>
<th>Decay</th>
<th>( Q_{0\nu 3\text{EC}\beta^+} )</th>
<th>Other decays</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{148}\text{Gd} \rightarrow ^{148}\text{Nd} )</td>
<td>0.116</td>
<td>( T_{1/2}^{\alpha} \approx 75 )</td>
<td>—</td>
</tr>
<tr>
<td>(^{154}\text{Dy} \rightarrow ^{154}\text{Sm} )</td>
<td>1.041</td>
<td>( T_{1/2}^{\alpha} \approx 3 \times 10^6 )</td>
<td>—</td>
</tr>
</tbody>
</table>

### \( Q_{0\nu 2\text{EC}\beta^+} \)

<table>
<thead>
<tr>
<th>Decay</th>
<th>( Q_{0\nu 2\text{EC}\beta^+} )</th>
<th>Other decays</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{154}\text{Dy} \rightarrow ^{154}\text{Sm} )</td>
<td>0.019</td>
<td>( T_{1/2}^{\alpha} \approx 3 \times 10^6 )</td>
<td>—</td>
</tr>
</tbody>
</table>

**Lifetime estimate gives:**

\[
\frac{T^{0\nu 4\beta}_{1/2}}{T^{2\nu 2\beta}_{1/2}} \approx \left( \frac{Q_{0\nu 2\beta}}{Q_{0\nu 4\beta}} \right)^{11} \left( \frac{\Lambda^4}{q^{12}G_F^4} \right) \approx 10^{46} \left( \frac{\Lambda}{\text{TeV}} \right)^4
\]

*Heeck, Rodejohann., Eur.Phys.Lett. 103*
Sterile Neutrinos:
the usual plot for double beta decay
gets completely turned around!

Barry, W.R., Zhang, JHEP 1107; Giunti et al., PRD 87; Girardi, Meroni, Petcov, 1308.5802
What we should observe in experiments?

2νββ

Neutrino accompanied Double-Beta Decay:

0νββ

Neutrinoless Double-Beta Decay:

Light neutrino exchange

\[ \Delta L = 0 \]

\[ \Delta L = 2 \]
What we can observe in experiments?

Decay to Excited States

\((A, Z) \rightarrow (A, Z+2) + 2\ e^- + 1,2\ \gamma\)

1 or 2 additional \(\gamma\)-rays

Identification of daughter nucleus:

\(Xe \rightarrow Ba^{++} + 2\ e^-\)
\[ T_{1/2}^{2\nu EC/EC} \left( ^{106}Cd \right) > 4.2 \cdot 10^{20} \, \text{yr} \, (90\%) \]

\[ ^{124}_{54}Xe \xrightarrow{2e_k} ^{124}_{52}\text{Te}^{\ast\ast} + 2\nu (2.865(7)\, \text{MeV}) \]

\[ T_{1/2}^{2\nu 2K} (\text{g.s.} \rightarrow \text{g.s.}) \geq 4.67 \cdot 10^{20} \, \text{yr} \, (90\% \, \text{C.L.}) \]
The experimental challenge

Experiment observes \( N^0 = \ln 2 \frac{N_A}{A} a \cdot \epsilon \cdot M t / T_{1/2} \)

sensitivity on \( T_{1/2} \propto \epsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}} \)

Experimental approach:

→ reduce background \( b \), improve resolution \( \Delta E \), increase exposure \( (M \cdot T) \),

<table>
<thead>
<tr>
<th>( \epsilon )</th>
<th>detection efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>isotopic abundance</td>
</tr>
<tr>
<td>( M )</td>
<td>active target mass</td>
</tr>
<tr>
<td>( T )</td>
<td>measuring time</td>
</tr>
<tr>
<td>( b )</td>
<td>background rate (cts/(keV kg yr))</td>
</tr>
<tr>
<td>( \Delta E )</td>
<td>energy resolution</td>
</tr>
</tbody>
</table>
Calorimeter

- Ge diode $\varepsilon, \Delta E$, $^{76}\text{Ge}$
- Bolometers $\varepsilon, \Delta E$, $^{130}\text{Te}, ^{82}\text{Se}, ^{100}\text{Mo}$
- Liquid Xe $\varepsilon, M, (N_{\text{bckd}})$, $^{136}\text{Xe}$
- Scintillator $\varepsilon, M$, $^{136}\text{Xe}, ^{48}\text{Ca}, ^{150}\text{Nd}, ^{100}\text{Mo}$
- KamLAND-Zen, CANDLES, SNO+, Borexino, CdWO4, AMoRE

Tracker

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

Multilevel

- TGV -2, TGV -3
Recent results of $T_{1/2}^{2\nu\beta\beta}$

$$T_{1/2}^{2\nu\beta\beta} = (10^{18} - 10^{21})\text{y}$$

<table>
<thead>
<tr>
<th>Izotope</th>
<th>$T_{1/2}^{2\nu\beta\beta}$</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>$[7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (sys)}] \times 10^{18} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$[9.6 \pm 0.1 \text{ (stat)} \pm 1.0 \text{ (sys)}] \times 10^{19} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$[2.88 \pm 0.04 \text{ (stat)} \pm 0.16 \text{ (sys)}] \times 10^{19} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$[7.0 \pm 0.9 \text{ (stat)} \pm 0.9 \text{ (sys)}] \times 10^{20} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>$[9.11 + 0.25 - 0.22 \text{ (stat)} \pm 0.63 \text{ (sys)}] \times 10^{18} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>$[2.35 \pm 0.14 \text{ (stat)} \pm 0.16 \text{ (sys)}] \times 10^{19} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>$[4.4 + 0.5 - 0.4 \text{ (stat)} \pm 0.4 \text{ (sys)}] \times 10^{19} \text{ y}$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$[1.84 + 0.09 - 0.08 \text{ (stat)} + 0.11 - 0.06 \text{ (sys)}] \times 10^{21} \text{ y}$</td>
<td>GERDA-I</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$[2.30 \pm 0.02 \text{ (stat)} \pm 0.12 \text{ (syst)}] \times 10^{21} \text{ y}$</td>
<td>KamLand-Zen</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$[2.23 \pm 0.017 \text{ (stat)} \pm 0.22 \text{ (syst)}] \times 10^{21} \text{ y}$</td>
<td>EXO-200</td>
</tr>
</tbody>
</table>
Choice of the best isotope - 2νββ spectrum is always background for 0νββ

<table>
<thead>
<tr>
<th>isotope</th>
<th>$G^{0\nu}$ [$10^{-14}$ yr]</th>
<th>$Q_{\beta\beta}$ [keV]</th>
<th>nat. ab. [%]</th>
<th>$T_{1/2}^{2\nu}$ [10$^{20}$ y]</th>
<th>experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>6.3</td>
<td>4273.7</td>
<td>0.187</td>
<td>0.44</td>
<td>CANDLES</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>0.63</td>
<td>2039.1</td>
<td>7.8</td>
<td>15</td>
<td>GERDA, Majorana Demonstr.</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.7</td>
<td>2995.5</td>
<td>9.2</td>
<td>0.92</td>
<td>SuperNEMO, Lucifer</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>4.4</td>
<td>3035.0</td>
<td>9.6</td>
<td>0.07</td>
<td>MOON, AMoRe</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>4.6</td>
<td>2809.1</td>
<td>7.6</td>
<td>0.29</td>
<td>Cobra</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>4.1</td>
<td>2530.3</td>
<td>34.5</td>
<td>9.1</td>
<td>CUORE</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>4.3</td>
<td>2457.8</td>
<td>8.9</td>
<td>21</td>
<td>EXO, Next, Kamland-Zen</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>19.2</td>
<td>3367.3</td>
<td>5.6</td>
<td>0.08</td>
<td>SNO+, DCBA/MTD</td>
</tr>
</tbody>
</table>

*Highlighted** values indicate the isotope 82Se and 100Mo are the best choices.
Choice of the best isotope?

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu}_0 \left| M^{0\nu}_0 \right|^2 \left( \frac{\langle m_\nu \rangle}{m_e} \right)^2
\]

\[ G^{0\nu} \propto (Q_{\beta\beta}^5, Z) \]

Choice of the best isotope?

\[ Q = E_{e1} + E_{e2} - 2m_e \]

Transition energy \( Q_{\beta\beta} \)

**Other sources of background:**

- Muons (underground labs)
- \( \gamma \) from \((n,\gamma)\) reactions, \( \mu \) bremsstrahlung
- Muon spallation products
- \( \alpha \) emitters from bulk or surface contaminations for calorimeters
- \( \beta\beta(2\nu) \) if modest energy resolution

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( G^{0\nu} [10^{-14} \text{y}] )</th>
<th>( Q [\text{keV}] )</th>
<th>nat. abund. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{48}\text{Ca} )</td>
<td>6.3</td>
<td>4273.7</td>
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<td>( ^{76}\text{Ge} )</td>
<td>0.63</td>
<td>2039.1</td>
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</tr>
<tr>
<td>( ^{82}\text{Se} )</td>
<td>2.7</td>
<td>2995.5</td>
<td>9.2</td>
</tr>
<tr>
<td>( ^{100}\text{Mo} )</td>
<td>4.4</td>
<td>3035.0</td>
<td>9.6</td>
</tr>
<tr>
<td>( ^{130}\text{Te} )</td>
<td>4.1</td>
<td>2530.3</td>
<td>34.5</td>
</tr>
<tr>
<td>( ^{136}\text{Xe} )</td>
<td>4.3</td>
<td>2461.9</td>
<td>8.9</td>
</tr>
<tr>
<td>( ^{150}\text{Nd} )</td>
<td>19.2</td>
<td>3367.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Nuclear matrix elements

\[
(T_{1/2}^{0v})^{-1} = G^{0v}(Q, Z) |M^{0v}|^2 \langle m_{ee} \rangle^2
\]

Is \( M \) decreasing with \( A^{-2/3} \) (IBM-2, QRPA) or constant with \( A \) (SM)?

S. Schöner, NME WS, LNGS Nov. 2011
Nuclear matrix elements

Comparison of isotopes: Is there a super-DBD-isotope?

\[ (T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) M^{0\nu} \left( \langle m_{ee} \rangle^2 \right) \]

\[
\text{QRPA} \\
\text{(Simkovic et al. PRC 77, 2008)}
\]

Ratio to \(^{76}\text{Ge}\)

\[
\begin{array}{ccccccc}
\text{Ratio to } ^{76}\text{Ge} & ^{76}\text{Ge} & ^{82}\text{Se} & ^{100}\text{Mo} & ^{116}\text{Cd} & ^{130}\text{Te} & ^{136}\text{Xe} \\
\hline
0 & 1 & 2 & 3 & 4 & 5 & 6 \\
\end{array}
\]

(Q)RPA

Simkovic et al. PRC77 2008

Figure adopted from Robertson

\sim \text{ factor 4}

Expected 0\nu\beta\beta rates per mass vary within a factor \sim 4!
Nuclear matrix elements for $m = 50$ meV:

- QRPA (Simkovic et al., PRC 77, 2008):
  9 cts/(ton year)

- IBM2 (Barea and Iachello, PRC 79, 2009):
  13 cts/(ton year)

- SM (Caurier et al., PRL 100, 2008):
  2 cts/(ton year)
Conclusion of general consideration

No favorite isotope / experimental techniques

Several experiments using different isotopes and methods are needed
Presently used isotopes

- $^{116}$Cd
  - COBRA
  - CdWO$_4$

- $^{76}$Ge
  - GERDA
  - MAJORANA

- $^{82}$Se
  - SuperNEMO
  - LUCIFER

- $^{136}$Xe
  - KamLAND-Zen
  - EXO
  - NEXT

- $^{100}$Mo
  - ZnMoO$_4$
  - AMoRE

- $^{130}$Te
  - CUORE

- $^{48}$Ca
  - CANDLES
  - SuperNEMO
  - AMoRE

- $^{150}$Nd
  - SNO+
  - Borexino

A dream?
Kilograms of enriched Nd-150
– dream or close to reality?

To: Director of the JINR (Dubna)
V.A. Matveev

By October 2014 it is planned to build the prototype of separation cascade and produce on it the sample contained 0.5 kg of Nd-150 enriched to more than 80%. This sample will be presented to the SuperNEMO collaboration for tests.
Industrial production of Nd-150 can be started at the beginning of 2016.

Deputy Director General,
Head of the separation department S.I. Belyantcev
JSC "ECP"
# Overview of past/current/near future $0\nu\beta\beta$ experiments

<table>
<thead>
<tr>
<th>Name</th>
<th>Nucleus</th>
<th>Mass [kg]</th>
<th>Method</th>
<th>Location</th>
<th>Time</th>
<th>$T_{1/2}$ limits (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Past/Recent experiments</strong></td>
<td></td>
<td></td>
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<tr>
<td>Heidelberg-Moscow</td>
<td>$^{76}\text{Ge}$</td>
<td>11</td>
<td>ionization</td>
<td>LNGS</td>
<td>-2003</td>
<td>1.9 $10^25$ / (1.2 $10^25$)</td>
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<tr>
<td>IGEX</td>
<td>$^{76}\text{Ge}$</td>
<td>6</td>
<td>ionization</td>
<td>Canfranc</td>
<td>-2000</td>
<td>1.6 $10^25$</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>$^{130}\text{Te}$</td>
<td>11</td>
<td>bolometer</td>
<td>LNGS</td>
<td>-2008</td>
<td>2.8 $10^24$</td>
</tr>
<tr>
<td>NEMO-3</td>
<td>$^{100}\text{Mo}/^{82}\text{Se}$</td>
<td>7/1</td>
<td>track./calor.</td>
<td>Modane</td>
<td>-2011</td>
<td>1.0 $10^24$</td>
</tr>
<tr>
<td><strong>Current experiments (funded, under construction or running)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GERDA I/II</td>
<td>$^{76}\text{Ge}$</td>
<td>15/35</td>
<td>ionization</td>
<td>LNGS</td>
<td>2013/14</td>
<td>2.1 $10^25$</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}\text{Ge}$</td>
<td>30</td>
<td>ionization</td>
<td>SURF</td>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>EXO200</td>
<td>$^{136}\text{Xe}$</td>
<td>200</td>
<td>liquid TPC</td>
<td>WIPP</td>
<td>2012</td>
<td>1.6 $10^25$</td>
</tr>
<tr>
<td>Cuore0/Cuore</td>
<td>$^{130}\text{Te}$</td>
<td>10/200</td>
<td>bolometer</td>
<td>LNGS</td>
<td>2013/15</td>
<td>1.9 $10^25$</td>
</tr>
<tr>
<td>Kamland-Zen</td>
<td>$^{136}\text{Xe}$</td>
<td>400</td>
<td>bolometer</td>
<td>Kamioka</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{130}\text{Te}$</td>
<td>800</td>
<td>LS</td>
<td>Sudbury</td>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>NEXT-100</td>
<td>$^{136}\text{Xe}$</td>
<td>100</td>
<td>gas TPC</td>
<td>Canfranc</td>
<td>2015</td>
<td></td>
</tr>
<tr>
<td><strong>SuperNemo dem.</strong></td>
<td>$^{82}\text{Se} / ^{150}\text{Nd}$</td>
<td>7</td>
<td>track./calor.</td>
<td>Modane</td>
<td>2015</td>
<td>6.6 $10^24$</td>
</tr>
</tbody>
</table>

*adopted from B.Schwingenheuer, PACT 2013*
Past Ge-76 experiments

Heidelberg-Moscow

IGEX

Disclaimer:
Next slides represent only the past Ge-76 experiments for comparison with the recent results of the Ge-76 and Xe-136 experiments.
HPGe detectors fabricated from germanium enriched in $^{76}$Ge isotope (up to 86 %) are simultaneously the $\beta\beta$ decay sources and the $4\pi$ detectors.

**The advantages** of such type experiments are due to:
1) the excellent energy resolution (4 кэВ at 2 MeV),
2) the high purity of Ge crystals (very low intrinsic background),
3) and the high signal detection efficiency (close to 100%).

**Disadvantages:**
1) not the highest $\beta\beta$–transition energy for $^{76}$Ge: $Q_{\beta\beta}=2039$ keV (in comparison with the more promising isotopes, such as Mo-100, Nd-150, Ca-48)
2) only one characteristic of $\beta\beta$ decay - sum energy of two electrons – is possible to detect.
Heidelberg-Moscow

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.)


IGEX

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.)

Aalseth et al.,
Heidelberg-Moscow
(H.V. Klapdor-Kleingrothaus et al.)

53.9 kg y (35.5 kg y): $T_{1/2}^{0ν} > 1.3 \times 10^{25}$ yr (1.9 $\times 10^{25}$ yr)
(90% C.L.)

IGEX
(Aalseth et al.)

8.8 kg y: $T_{1/2}^{0ν} > 1.6 \times 10^{25}$ yr (90% C.L.)
Claim of signal
by part (small) of Hd-M collaboration

N.B. Half-life $T_{1/2}^{0\nu} = 2.23 \times 10^{25}$ yr $T_{1/2}^{0\nu}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006)) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with $\varepsilon_{psd} = 1$ (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- $\varepsilon_{fep} = 1$ (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: $\varepsilon_{fep} = 0.9$)

2.23 x 0.6 x 0.9 = 1.19 !!!

- claimed significance of $4.2 \sigma$
- disputed in literature,
  see e.g. Strumia+Vissani
  Nucl Phys B726 (2005)
Current experiments
(running, first results)

GERDA Phase I
EXO200
Kamland-Zen
The main conceptual design of the GERDA experiment is to operate with “naked” HPGe detectors (enriched in Ge-76) submerged in high purity liquid argon supplemented by a water shield.

Water tank instrumented with PMTs: Shielding, Cherenkov muon-veto

Clean room: Detector handling

Lock system: Detector insertion

Liquid Ar cryostat: Shielding, cooling of detectors

Cu shield

Phase I detector array

Located at LNGS, Italy

3400 m w.e.
Expected sensitivity of the GERDA experiment

Phase I: \(\sim 18 \text{ kg of } ^{76}\text{Ge} \)
Phase II: \(\sim 40 \text{ kg of } ^{76}\text{Ge} \)

KDKC claim:

Phase I
Phase II
Phase III

GERDA phase I:
background 0.01 cts / (kg \cdot keV \cdot y)

\(\uparrow\) to scrutinize KKDC result within 1 year

GERDA phase II:
background 1 cts / (ton \cdot keV \cdot y)

\(\uparrow\) to cover the degenerate neutrino mass hierarchy \(< m_{\text{ee}} > < 0.08 - 0.29 \text{ eV} \)

Phase III:
GERDA – MAJORANA collaboration
background 0.1 cts / (ton \cdot keV \cdot y)

\(\uparrow\) to cover the inverted neutrino mass hierarchy \(< m_{\text{ee}} > \sim 10 \text{ meV} \)
Construction of the GERDA set up
started in 2007
in Gran Sasso National Laboratory (LNGS), Italy.
Installation of the “nested type” assembly
completed in 2010
in the deep underground facility at 3400 m w.e.

• End of 2009: Cryostat was filled with 95 t of liquid argon.
Summer 2010: Water tank was filled with 565 t of ultrapure water.
* June 2010: Start of commissioning runs with 3 natGe detectors

November 2011 – May 2013: Phase I physics data taking

Phase I detectors
8 enriched HPGe detectors
(in total ~ 18 kg of 76Ge)
from HdM and IGEX experiments,
6 natural HPGe detectors
(in total ~ 16 kg of NatGe)
from the Genius T-F will be deployed.
All detectors reprocessed optimized for LAr. Energy resolution in LAr:
~2.5 keV (FWHM) @1.3 MeV
+ 5 enriched BeGe detectors
(in total ~ 4 kg of 76Ge) – from July 2012

Phase II detectors
the new 30 BeGe detectors (~ 20 kg of 76Ge) made from enriched in 76Ge material will be added.
In total: ~ 40 kg of 76Ge + 16 kg of NatGe

Installation of the “nested type” assembly completed in 2010 in the deep underground facility at 3400 m w.e.
The GERDA Phase I semi-coaxial enriched in Ge-76 and natural Ge detectors.

Three strings with the GERDA Phase I semi-coaxial detectors.
Phase II (and Phase I-b) detectors - BEGe

- **p-type germanium**
  - 81 mm diameter
  - 32 mm height
  - 878 g mass

- **Contact**
  - p⁺ contact
  - n⁺ contact

**Performance**

- **FWHM @ 59.5 keV**: 0.49 keV
- **FWHM @ 1.33 MeV**: 1.59 keV

**Spectrum**

- Single-site (0νββ-like)
  - Amplitude [a.u.]
  - Time after trigger [ns]

- Multi-site (bgd: γ FE peak)
  - Amplitude [a.u.]
  - Time after trigger [ns]

**DEP**

- 90%
- 0νββ-like
- γ-bgd: 11%

**Data**

- ²²⁸Th all events
- after PSD cut

**Graphs**

- Energy [keV]
  - Number of counts
  - 5500
  - 5000
  - 4500
  - 4000
  - 3500
  - 3000
  - 2500
  - 2000
  - 1500
  - 1000
  - 500
  - 0

- 1560 1580 1600 1620 1640

**Images**

- Detector module
- Energy distribution
- Timing characteristics

**Notes**

- GERDA logo
- Phase II (and Phase I-b) detectors
- p-type germanium details
- Performance metrics
- Spectrum graphs
- DEP calculations
- Data analysis

From July 2012 - 5 enrGe BEGe detectors (R&D for Phase II)

Detector array assembly for GERDA Phase I:

3 + 1 strings:
- 8 enrGe coaxial detectors (2 not considered in the analysis)
- 3 natGe coaxial detectors
- 5 enrGe BEGe detectors

*enrGe mass for physics analysis: 14.6 kg (coaxial) + 3.6 kg (BEGe)*
Phase I Data taking

**9 November 2011:** Start of Phase I
All 8 \textit{enrGe} + 3 \textit{natGe} coaxial detectors deployed in GERDA
(2 \textit{enrGe} detectors are not used for analysis due to high leakage current)

**7 July 2012:** Insert 5 \textit{enrGe BEGe} detectors (2 \textit{natGe} detectors were removed)

**9 November 2011 – 21 May 2013:**
558.6 days,
-> exposure:
Enriched Ge-76 detectors:
21.612 kg*yr,
Natural Ge detectors:
6.192 kg*yr
The first 5.04 kg yr of data collected in Phase I of the experiment have been analyzed. The observed spectrum in the energy range between 600 and 1800 keV is dominated by $2\nu\beta\beta$ decay of $^{76}\text{Ge}$.

**First $2\nu\beta\beta$ half-life results**

**Binned maximum likelihood**

**Parameters:**
- Active detector masses (6+1) *nuisance parameter*
- Fraction enrichment in $^{76}\text{Ge}$ (6) *nuisance parameter*
- Background contributions (3×6) *nuisance parameter*
- $T^{2\nu}_{1/2}$ common to all the detectors (1)

**Derive $T^{2\nu}_{1/2}$ after the fit integrating over nuisance parameters**

$2\nu\beta\beta$ (80%)  $^{42}\text{K}$ (14%)  
$^{214}\text{Bi}$ (4%)  $^{40}\text{K}$ (2%)

\[
T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08 \text{ fit}})^{+0.11}_{-0.06 \text{ syst}} \cdot 10^{21} \text{ yr}
\]

**Signal to background: 4:1**

*The GERDA collaboration*  
*J. Phys. G 40 (2013) 035110*
Intensities of Gamma-peaks in comparison with Hd-M experiment
### Intensities of Gamma-peaks in comparison with Hd-M experiment

The Gerda experiment for the search of $0\nu\beta\beta$ decay in $^{76}$Ge, *Eur. Phys. J. C (2013) 73:2330*

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy [keV]</th>
<th>nat Ge (3.17 kg·yr)</th>
<th>enr Ge (6.10 kg·yr)</th>
<th>HDM (71.7 kg·yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>tot/bck [cts]</td>
<td>rate [cts/(kg·yr)]</td>
<td>rate [cts/(kg·yr)]</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>1460.8</td>
<td>85 / 15</td>
<td>$21.7^{+3.4}_{-3.0}$</td>
<td></td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1173.2</td>
<td>43 / 38</td>
<td>&lt; 5.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1332.3</td>
<td>&lt; 3.8</td>
<td></td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>661.6</td>
<td>46 / 62</td>
<td>&lt; 3.2</td>
<td></td>
</tr>
<tr>
<td>$^{228}$Ac</td>
<td>910.8</td>
<td>54 / 38</td>
<td>$5.1^{+2.8}_{-2.9}$</td>
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</tr>
<tr>
<td>$^{208}$Tl</td>
<td>583.2</td>
<td>9 / 5</td>
<td>$2.1^{+1.1}_{-1.1}$</td>
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<td>$^{214}$Pb</td>
<td>352</td>
<td>740 / 630</td>
<td>$34.1^{+12.4}_{-11.0}$</td>
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<tr>
<td>$^{214}$Bi</td>
<td>609.3</td>
<td>99 / 51</td>
<td>$15.1^{+3.9}_{-3.9}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1120.3</td>
<td>$8.4^{+3.5}_{-3.3}$</td>
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<td>1764.5</td>
<td>$5.4^{+1.9}_{-1.5}$</td>
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<tr>
<td></td>
<td></td>
<td>2204.2</td>
<td>$0.8^{+0.8}_{-0.7}$</td>
<td></td>
</tr>
</tbody>
</table>

| Rate HDM/coaxial | 13 | 11 >48 |

*The table provides a comparison of gamma-peak intensities and detection rates between natural Ge (nat Ge), enriched Ge (enr Ge), and HDM (HdM) experiments for various isotopes.*
0νββ blinded data of GERDA Phase I

1. Data after January 2012 is blinded in ± 20 keV region around Qββ

   -> To avoid tuning the analysis towards signal or no-signal outcome.

2. All data processing, quality cuts and statistical analysis methods are being fixed.

   -> Paper with background model and analysis parameters published on arXiv prior to final unblinding:

   The background in the neutrinoless double beta decay experiment GERDA submitted to EPJC; on arXiv:1306.5084
Background spectra of GERDA Phase I

2νββ result
arXiv:1212.3210

\[ T_{1/2}^{2ν} = (1.84^{+0.14}_{-0.08}) \times 10^{21} \text{ yr} \]

backgd. paper
arXiv:1306.5084
to appear in EPJ C
Unblinding of the GERDA Phase-I 0νββ data

GERDA has unblinded the data after 1.5 years of data taking (558.6 days) on 14 June 2013 at the GERDA Collaboration Meeting in Dubna.

This happened after developing a model for the background and several methods of PSD for BEGe and semi-coaxial detectors.
Region of Interest

expected bg from interpolation:
- 5.1 events w/o PSD
- 2.5 events with PSD
expected bg from interpolation:
- 5.1 events w/o PSD
- 2.5 events with PSD

observed:
- 7 events w/o PSD
- 3 events with PSD
profile likelihood (PL) fit:

\[ \text{signal} = a \times \text{flat background} + b \times \text{line} \]

- best fit: \( N^{0\nu} = 0 \); upper limit: \( N^{0\nu} < 3.5 \) (90\% CL)
- half life limit \( T_{1/2}(0\nu\beta\beta) > 2.1 \times 10^{25} \) yr (90\% C.L.)
KK-claim: $T_{1/2}(0\nu\beta\beta) = 1.19 \times 10^{25}$ yr

Stronger 2006 claim has known error: 100% PSD efficiency assumed ➔ realistic efficiency = no improvement

GERDA:
- much lower BI
- no unknown nuclear lines
- flat background in ROI

GERDA upper limit from PL fit:
< 3.5 events (90% CL)
KK claim strongly disfavoured (Bayes factor $2 \times 10^{-4}$)

Combine: GERDA phase I + HdM + IGEX
➔ PL fit to combined data
➔ backgrounds = free parameters
➔ Best fit for $N^{0\nu} = 0$
➔ $T_{1/2}(0\nu\beta\beta) > 3.0 \times 10^{25}$ yr (90% CL)
3 new limits on $T_{1/2}$ in 2012/13

$T_{1/2}(^{136}\text{Xe}) > 1.6 \times 10^{25}$ y  
$T_{1/2}(^{136}\text{Xe}) > 1.9 \times 10^{25}$ y  
$T_{1/2}(^{76}\text{Ge}) > 2.1 \times 10^{25}$

How to compare? Who is better?
How to compare? Who is better?

Xe-limit is stronger than Ge-limit when:

\[ T_{\text{Xe}} > T_{\text{Ge}} \frac{G_{\text{Ge}}}{G_{\text{Xe}}} \left| \frac{M_{\text{Ge}}}{M_{\text{Xe}}} \right|^2 \text{ yrs} \]

<table>
<thead>
<tr>
<th>Method</th>
<th>(M_{0\nu}(^{76}\text{Ge}))</th>
<th>(M_{0\nu}(^{136}\text{Xe}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDF(U)</td>
<td>4.60</td>
<td>4.20</td>
</tr>
<tr>
<td>ISM(U)</td>
<td>2.81</td>
<td>2.19</td>
</tr>
<tr>
<td>IBM-2</td>
<td>5.42</td>
<td>3.33</td>
</tr>
<tr>
<td>pnQRPA(U)</td>
<td>5.18</td>
<td>3.16</td>
</tr>
<tr>
<td>SRQRPA-B</td>
<td>5.82</td>
<td>3.36</td>
</tr>
<tr>
<td>SRQRPA-A</td>
<td>4.75</td>
<td>2.29</td>
</tr>
<tr>
<td>QRPA-B</td>
<td>5.57</td>
<td>2.46</td>
</tr>
<tr>
<td>QRPA-A</td>
<td>5.16</td>
<td>2.18</td>
</tr>
<tr>
<td>SkM-HFB-QRPA</td>
<td>5.00</td>
<td>1.80</td>
</tr>
</tbody>
</table>

(Bhupal Dev, Goswami, Mitra, W.Rodejohann., PRD 88)

small QRPA-NME for Xe! (Mustonen, Engel, 1301.6997)

\( \leftrightarrow \) small overlap in initial and final mean fields
# Xe vs. Ge

| NME               | Limit on $|m_{ee}|$ (eV) | $^{76}$Ge | KLZ | $^{136}$Xe |
|-------------------|-----------------------|----------|-----|------------|
|                   |                       | GERDA    | comb| comb       |
| EDF(U)            | 0.32                  | 0.27     | 0.15| 0.11       |
| ISM(U)            | 0.52                  | 0.44     | 0.28| 0.21       |
| IBM-2             | 0.27                  | 0.23     | 0.19| 0.14       |
| pnQRPA(U)         | 0.28                  | 0.24     | 0.20| 0.15       |
| SRQRPA-B          | 0.25                  | 0.21     | 0.18| 0.14       |
| SRQRPA-A          | 0.31                  | 0.26     | 0.27| 0.20       |
| QRPA-A            | 0.28                  | 0.24     | 0.29| 0.21       |
| SkM-HFB-QRPA      | 0.29                  | 0.24     | 0.33| 0.25       |

Bhupal Dev, Goswami, Mitra, W.R., PRD 88
EXO 200, Kamland-Zen and GERDA Phase I vs KK claim

**H1:** signal with $T_{1/2}^{0v} = 1.19 \times 10^{25}$ yr

**H0:** background only

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$P(H_1)/P(H_0)$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>0.024</td>
<td>Model independent</td>
</tr>
<tr>
<td>GERDA +HdM+IGEX</td>
<td>0.0002</td>
<td>Model independent</td>
</tr>
<tr>
<td>KamLAND-Zen*</td>
<td>0.40</td>
<td>Model dependent: NME, leading term</td>
</tr>
<tr>
<td>EXO-200*</td>
<td>0.23</td>
<td>Model dependent: NME, leading term</td>
</tr>
<tr>
<td>GERDA+KLZ*+EXO*</td>
<td>0.002</td>
<td>Model dependent: NME, leading term</td>
</tr>
</tbody>
</table>

*: with conservative NME ratio $M_{0v}(^{136}\text{Xe})/M_{0v}(^{76}\text{Ge}) \approx 0.4$ from:

Left-right symmetry. Who is better?

Xe vs. Ge

Barry, W.R., JHEP 1309

Barry, Rodejohann., JHEP 1309)
Search for double beta decay of Ge-76 on excited level $0_1^+$ and $2_1^+$ of daughter nuclei Se-76.

Fig. 1. Lowest energy levels of $^{76}$Se which can be populated in the double beta-decay of $^{76}$Ge. The energies of the excited states and of the de-excitation $\gamma$-rays are given in keV [21].
Future experiment
(under construction or funded)

GERDA Phase II
Majorana demonstrator
Super NEMO demonstrator
Cuore 0 / Cuore
Kamland-Zen 1000
nEXO
GERDA - Majorana
TGV-3
CANDLES – data taking
GERDA Phase-II

Phase I finished → currently preparing Phase II

+ 2x detector mass (~20 kg BEGe + 15 kg semi-coax)
+ liquid argon instrumentation to veto background
+ new readout electronics + detector suspension

→ better energy resolution & pulse shape discrimination, lower background (factor 10)
→ collect ~ 100 kg yr exposure sensitivity ~ $1.4 \times 10^{26}$ yr (90% C.L.)
Phase II detectors - BEGe

- Whole production chain from $^\text{en}_\text{rGeO}_2$ to BEGe diode organized by GERDA and tested with $^\text{de}_p\text{Ge}$ (JINST 8 P04018 2013)

- Total gain 30 BEGe detectors with 20.5 kg (58% yield)

- Detector characterization in HADES underground facility, Belgium

- Exposure to cosmic rays reduced as much as possible:
  - Transport in shielded container
  - Storage and testing underground

Adopted from: B. Lehnert., Talk at RICAP 13 conf., Rome, 23 May 2013
R&D for GERDA Phases II and III

LArGe test facility + BEGe detectors

The LArGe set up was assembled at LNGS in 2010 and operates with naked Ge detectors immersed in 1.4 tons of LAr served as scintillation veto. Efficiency of the LAr scintillation veto and pulse shape discrimination (PSD) of signals from the BEGe detector inside the LArGe were tested and optimized. It was shown that the internal background from Th-228 suppressed in LArGe by factor 5000 after applying LAr veto and PSD.

First results obtained with LArGe + BEGe successfully demonstrate possibility of considerable background reduction for GERDA Phase II and III by using LAr scintillation veto + BeGe PSD.
Phase II: LAr Scintillation Veto

- Experimental prove of principle in R&D facility LArGe (LNGS)
- Investigation of different design principles for GERDA with tuned MC simulations:
  - PMT arrays on top and bottom
  - Fiber shroud with SiPM readout
  - SiPMs inside mini shroud (if deployed)

- Combination of designs is approved
MAJORANA demonstrator: under construction → data taking

- ~ 30 kg $^{enr}$Ge + ~ 10 kg $^{nat}$Ge detectors, in two cryostats
- Ultrapure materials; copper that has been electroformed and machined underground
- Compact passive and active shields
- At the 4850-foot level of SURF, Lead, SD
- Construction scheduled for completion in 2015

GERDA + MAJORANA cooperation agreement:
- open exchange of knowledge & technologies (e.g. MaGe, R&D)
- intention to merge for ton-scale experiment
→ best techniques developed & tested in GERDA and MAJORANA
NEMO 3

Tracking detector: drift chambers (6180 Geiger cells)
\[ \sigma_t = 5 \text{ mm}, \sigma_z = 1 \text{ cm (vertex)} \]
Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

Identification \( e^-, e^+, \gamma, \alpha \)
Very high efficiency for background rejection

Background level @ \( Q_{\beta\beta} [2.8 - 3.2 \text{ MeV}] : 1.2 \times 10^{-3} \text{ cts}/\text{keV/kg/y} \)

Multi-isotope (7 measured at the same time)

Running at Modane underground laboratory (2003 - 2011)

Unique feature
Measurement of all kinematic parameters:
individual energies and angular distribution

\[ E_1 + E_2 = 2088 \text{ keV} \]
\[ \Delta t = 0.22 \text{ ns} \]
\[ (\Delta \text{vertex})_t = 2.1 \text{ mm} \]

Measurement of 7 isotopes \( \beta\beta(2\nu) \) half-lives
Excited states, Majoron limits for \( \beta\beta(0\nu) \)

[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

\[ ^{100}\text{Mo} \quad T_{1/2} (\beta\beta0\nu) > 1.0 \times 10^{24} \text{ y (90\% C.L.)} \]
\[ <m_\nu > < 0.31–0.79 \text{ eV} \]
# The SuperNEMO experiment

## SuperNEMO design

<table>
<thead>
<tr>
<th>NEMO3</th>
<th>SuperNEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>isotope</strong></td>
<td>$^{82}\text{Se}$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>or $^{48}\text{Ca}$ or $^{150}\text{Nd}$</td>
</tr>
<tr>
<td><strong>isotope mass</strong></td>
<td>100kg</td>
</tr>
<tr>
<td><strong>efficiency</strong></td>
<td>30%</td>
</tr>
<tr>
<td><strong>internal contaminations</strong></td>
<td>$^{208}\text{Tl} : \leq 2\mu\text{Bq/kg}$</td>
</tr>
<tr>
<td>in the $\beta\beta$ foils</td>
<td>$^{214}\text{Bi} : \leq 10\mu\text{Bq/kg}$</td>
</tr>
<tr>
<td>$\text{Rn} : 5\text{ mBq/m}^3$</td>
<td>$\text{Rn} : \leq 0.15\text{ mBq/m}^3$</td>
</tr>
<tr>
<td><strong>$T^{0\nu}_{1/2} \gtrsim 1 \times 10^{24}\text{yr}$</strong></td>
<td>$T^{0\nu}_{1/2} \gtrsim 1 \times 10^{26}\text{yr}$</td>
</tr>
<tr>
<td>$\langle m_\nu \rangle &lt; (0.3 - 0.9)\text{ eV}$</td>
<td>$\langle m_\nu \rangle &lt; (0.04 - 0.11)\text{ eV}$</td>
</tr>
<tr>
<td><strong>$7\text{kg}$</strong></td>
<td><strong>$100\text{kg}$</strong></td>
</tr>
<tr>
<td><strong>18%</strong></td>
<td><strong>30%</strong></td>
</tr>
<tr>
<td>$^{208}\text{Tl} : \approx 100\mu\text{Bq/kg}$</td>
<td><strong>$T^{0\nu}_{1/2} \gtrsim 1 \times 10^{24}\text{yr}$</strong></td>
</tr>
<tr>
<td>$^{214}\text{Bi} : &lt; 300\mu\text{Bq/kg}$</td>
<td>$\langle m_\nu \rangle &lt; (0.3 - 0.9)\text{ eV}$</td>
</tr>
<tr>
<td>$\text{Rn} : 5\text{ mBq/m}^3$</td>
<td><strong>$T^{0\nu}_{1/2} \gtrsim 1 \times 10^{26}\text{yr}$</strong></td>
</tr>
<tr>
<td><strong>$8% @ 3\text{MeV}$</strong></td>
<td>$\langle m_\nu \rangle &lt; (0.04 - 0.11)\text{ eV}$</td>
</tr>
</tbody>
</table>
SuperNEMO

A module

20 modules

<table>
<thead>
<tr>
<th></th>
<th>Demonstrator module</th>
<th>20 Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source : $^{82}$Se</td>
<td>7 kg</td>
<td>100 kg</td>
</tr>
<tr>
<td>Drift chambers for tracking</td>
<td>2 0000</td>
<td>40 000</td>
</tr>
<tr>
<td>Electron calorimeter</td>
<td>500</td>
<td>10 000</td>
</tr>
<tr>
<td>$\gamma$ veto (up and down)</td>
<td>100</td>
<td>2 000</td>
</tr>
<tr>
<td>$T_{1/2}$ sensitivity (No background)</td>
<td>$6.6 \times 10^{24}$ y</td>
<td>$1.0 \times 10^{26}$ y</td>
</tr>
<tr>
<td>&lt;$m_e$&gt; sensitivity</td>
<td>200 – 400 meV</td>
<td>40 – 100 meV</td>
</tr>
</tbody>
</table>
Objective: to reach the background level for 100 kg
to perform a no background experiment with 7 kg isotope of $^{82}\text{Se}$ in 2 yr

Source
$^{214}\text{Bi} < 10 \mu\text{Bq/kg}$
(NEMO3 100 $\mu\text{Bq/kg}$)
$^{208}\text{Tl} < 2 \mu\text{Bq/kg}$
(NEMO3 100 $\mu\text{Bq/kg}$)

Calorimeter
$\Delta E/E < 4\%$ @ 3 MeV
(NEMO3 8.6% at 3MeV)

Tracker
3.7 m long (NEMO3 2.7 m)
$\sigma_t = 5 \text{ mm}, \sigma_z = 1 \text{ cm}$
Radon < 0.15 mBq/m$^3$
(NEMO3 5 mBq/m$^3$)
Wiring robot

Global efficiency: 30% (NEMO3 8%)
- Construction started in the laboratories
- Installation and commissioning (2013 – 2014) @ Modane Underground Laboratory
- Data taking in 2014
- No background expected
- Sensitivity after 2 years: $T_{1/2} > 6.6 \times 10^{24}$ y and $<m_\nu> < 0.2 - 0.4$ eV
And many other experimental R&D efforts, such as

**Lucifer** – phonons and scintillation

**COBRA** – pixelized CdZnTe semiconductor detector,

**SuperNEMO** – full scale, SNO+, Moon, DCBA, NEXT,.....

<table>
<thead>
<tr>
<th>R&amp;D funding, proto-typing, proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CandlesIII</td>
</tr>
<tr>
<td>MOON</td>
</tr>
<tr>
<td>DCBA</td>
</tr>
<tr>
<td>Cobra</td>
</tr>
<tr>
<td>SuperNEMO</td>
</tr>
<tr>
<td>XMASS</td>
</tr>
<tr>
<td>Lucifer</td>
</tr>
<tr>
<td>Amore</td>
</tr>
<tr>
<td>nEXO</td>
</tr>
</tbody>
</table>

**Source** (4 kg yr$^{-1}$) [Evolving volumes / 3000 channels] and calorimeter

- Modular (4 kg) enriched in $^{136}$Xe
- 100 kg: 20 modules - 40,000 channels for 8B; 12,000/50,000 channels for $^{136}$Xe PMT

---

Super NEMO  \hspace{0.5cm} COBRA  \hspace{0.5cm} NEXT  \hspace{0.5cm} LUCIFER  \hspace{0.5cm} SNO+  \hspace{0.5cm} MAJORANA
Nearest Future

GERDA-II: preparation in progress from 2013, data taking from 2014

Super NEMO demonstrator: installation in progress from 2013, data taking from 2015

EXO-200: started 2011, current run stopped June 2013, factor 3.6 more data in hand compared to publication → new result soon, hardware: currently installing radon reducer for air + new electronics

Kamland-Zen: started data taking in 2011, large bkg @ 2.5 MeV from $^{110m}$Ag (on balloon / activation of Xe), filtration + purifications in 2012, fire in 2012 → stop operation for ~ 9 months,

currently scintillator purification → expect factor 1/100 for $^{110m}$Ag bkg, restart in Nov 2013, options: new mini-balloon & 600 kg more Xe, stop latest in May 2016 for vessel inspection

NEXT-100: test detectors show extrapolated FWHM ~ 0.8% @ $Q_{\beta\beta}$ & good tracking, commissioning expected 2016, 10 kg proto-type in 2014

SNO+: changed to $^{nat}$Te loading of scintillator (0.8-1.3 ton of $^{130}$Te), currently filling water, introduction of Te end 2014 / start 2015

Majorana Demonstrator: 2 cryostats with ~30 kg $^{enr}$Ge diodes & 10 kg $^{nat}$Ge in 2014

Cuore: 1 tower (out of 19) in Cuoricino cryostat (Cuore0) → $\alpha$ surf. bkg reduction 1/6 assembly in 2014, data taking 2015
Summary

$0\nu\beta\beta$ experimental strategy during the next decade

Controversy S. Schönert, NME WS, LNGS Nov. 2011
CONCLUSION

New generation of the 0νββ experiments has a good chance to penetrate deeper in understanding of the neutrino properties.
Extra slides
Pulse shape discrimination for coaxial detectors

3 independent PSD methods:
- likelihood classification
- PSD selection based on pulse asymmetry
- neural network analysis (ANN) ➔ training with calibration data

SSE library: DEP peak of $^{208}\text{Tl} \rightarrow$ gamma at $1592 \pm 1$ keV

MSE library: FAP (Full Absorption Peak) of $^{212}\text{Bi}$ at $1620$ keV
Pulse shape discrimination A/E for BEGe

- Cutting in A/E → rejects background like MSEs
- $\varepsilon_{\text{PSD}} = 0.92 \pm 0.02$ → ca. 85% of background events at $Q_{\beta\beta}$ rejected
Classification of (0νββ) signal-like (SSE) or background-like (MSE, p+) events

Weighting potential for coax and BEGe detectors are different

Current pulses of simulated SSE signals

Coax

BEGe
PSD discrimination parameter: \( A/E \)
\[ T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \varepsilon \]
\[ \varepsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd} \]

- $N_A$: Avogadro number
- $\mathcal{E}$: exposure
- $\varepsilon$: exposure averaged efficiency
- $m_{enr}$: molar mass of enriched Ge
- $N^{0\nu}$: signal counts / limit

<table>
<thead>
<tr>
<th>Data set</th>
<th>Exposure (kg yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden-coax</td>
<td>17.9</td>
</tr>
<tr>
<td>Silver-coax</td>
<td>1.3</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- $f_{76}$: enrichment fraction
- $f_{av}$: fraction of active detector volume
- $\varepsilon_{fep}$: full energy peak efficiency for $0\nu\beta\beta$
- $\varepsilon_{psd}$: signal acceptance

<table>
<thead>
<tr>
<th></th>
<th>$&lt;f_{76}&gt;$</th>
<th>$&lt;f_{av}&gt;$</th>
<th>$&lt;\varepsilon_{fep}&gt;$</th>
<th>$&lt;\varepsilon_{psd}&gt;$</th>
<th>$&lt;\varepsilon&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coax</td>
<td>0.86</td>
<td>0.87</td>
<td>0.92</td>
<td>0.90 $\pm0.05/-0.09$</td>
<td>0.619 $\pm0.044/-0.070$</td>
</tr>
<tr>
<td>BEGe</td>
<td>0.88</td>
<td>0.92</td>
<td>0.90</td>
<td>0.92 $\pm0.02$</td>
<td>0.663 $\pm0.022$</td>
</tr>
</tbody>
</table>
Expectation for claimed $T_{1/2}^{0v} = 1.19 \times 10^{25}$ yr (Phys. Lett. B 586 198 (2004)):

5.9±1.4 signal over 2.0±0.3 bgd in ±2σ energy window to be compared with 3 cts (0 in ±1σ)

**H1**: claimed signal: 5.9±1.4  
**H0**: background only

**Bayes factor**: $P(H1)/P(H0) = 0.024$

**p-value from profile likelihood**  
$P(N=0 = 0 | H1) = 0.01$ (0.006 if $1/T$ unconstrained)

⇒ Claim refuted with high probability
Bayes factor: $P(H1)/P(H0) = 2 \times 10^{-4}$ strongly disfavors claim

Comparison is independent of NME and of physical mechanism which generates $0\nu\beta\beta$
**H1**: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

**H0**: background only

<table>
<thead>
<tr>
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<th>Isotope</th>
<th>$P(H_1)/P(H_0)$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>0.024</td>
<td>Model independent</td>
</tr>
<tr>
<td>GERDA +HdM+IGEX</td>
<td>$^{76}$Ge</td>
<td>0.0002</td>
<td>Model independent</td>
</tr>
</tbody>
</table>

NME from:

Ge combined: $<m_{ee}> < 0.2 - 0.4$
**H1:** signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

**H0:** background only

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</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>0.0002</td>
</tr>
<tr>
<td>KamLAND-Zen*</td>
<td>$^{136}$Xe</td>
<td>0.40</td>
</tr>
<tr>
<td>EXO-200*</td>
<td>$^{136}$Xe</td>
<td>0.23</td>
</tr>
<tr>
<td>GERDA+KLZ* + EXO*</td>
<td>$^{76}$Ge + $^{136}$Xe</td>
<td>0.002</td>
</tr>
</tbody>
</table>

*: with conservative NME ratio $M_{0\nu}(^{136}$Xe$)/M_{0\nu}(^{76}$Ge$) \approx 0.4$ from:


S. Schönert (TUM): First GERDA results results on $0\nu\beta\beta$ decay search - LNGS, July 16, 2013
• GERDA Phase I design goals reached:
  • Background index after PSD: 0.01 cts / (keV kg yr)
  • Exposure 21.6 kg yr

• No 0νββ-signal observed at Q_{ββ} = 2039 keV; best fit: N^{0ν}=0
  • Background-only hypothesis H_0 strongly favored
  • Claim strongly disfavored (independent of NME and of leading term)

• Bayes Factor / p-value:
  
  GERDA: \quad 10^{-2}
  GERDA+IGEX+HdM: \quad 10^{-4}

• Limit on half-life:
  
  GERDA: \quad T_{1/2}^{0ν} > 2.1\times10^{25} \text{ yr (90\% C.L.)}
  GERDA+IGEX+HdM: \quad T_{1/2}^{0ν} > 3.0\times10^{25} \text{ yr (90\% C.L.) (<m_{ee}> < 0.2-0.4)}

• Results reached after only 21.6 kg yr exposure because of unprecedented low background: bgd counts in ±2σ after analysis cuts:
  
  0.01 cts / (mol yr) (cf. EXO: 0.07, KL: 0.67)
## Majoron models

### Lepton number violating

<table>
<thead>
<tr>
<th>Model</th>
<th>Mode</th>
<th>Goldstone boson</th>
<th>$L$</th>
<th>$n$</th>
<th>Matrix element</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB</td>
<td>$\chi$</td>
<td>no</td>
<td>0</td>
<td>1</td>
<td>$M_F - M_{GT}$</td>
</tr>
<tr>
<td>IC</td>
<td>$\chi$</td>
<td>yes</td>
<td>0</td>
<td>1</td>
<td>$M_F - M_{GT}$</td>
</tr>
<tr>
<td>ID</td>
<td>$\chi\chi$</td>
<td>no</td>
<td>0</td>
<td>3</td>
<td>$M_{Fw^2} - M_{GTw^2}$</td>
</tr>
<tr>
<td>IE</td>
<td>$\chi\chi$</td>
<td>yes</td>
<td>0</td>
<td>3</td>
<td>$M_{Fw^2} - M_{GTw^2}$</td>
</tr>
<tr>
<td>IF (bulk)</td>
<td>$\chi$</td>
<td>bulk field</td>
<td>0</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

### Lepton number conserving

<table>
<thead>
<tr>
<th>Model</th>
<th>Mode</th>
<th>Goldstone boson</th>
<th>$L$</th>
<th>$n$</th>
<th>Matrix element</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIB</td>
<td>$\chi$</td>
<td>no</td>
<td>-2</td>
<td>1</td>
<td>$M_F - M_{GT}$</td>
</tr>
<tr>
<td>IIC</td>
<td>$\chi$</td>
<td>yes</td>
<td>-2</td>
<td>3</td>
<td>$M_{CR}$</td>
</tr>
<tr>
<td>IID</td>
<td>$\chi\chi$</td>
<td>no</td>
<td>-1</td>
<td>3</td>
<td>$M_{Fw^2} - M_{GTw^2}$</td>
</tr>
<tr>
<td>IIE</td>
<td>$\chi\chi$</td>
<td>yes</td>
<td>-1</td>
<td>7</td>
<td>$M_{Fw^2} - M_{GTw^2}$</td>
</tr>
<tr>
<td>IIF</td>
<td>$\chi$</td>
<td>gauge boson</td>
<td>-2</td>
<td>3</td>
<td>$M_{CR}$</td>
</tr>
</tbody>
</table>
χ0 predicted by several theories (extensions of SM, SUSY, ...)
Can be massless Goldstone boson, massless or light boson, with or without leptonic charge, ....
Emission of 2χ0 possible
Recent years: 3-flavor analysis
small $\theta_{13}$, favorable mass splitting & **high precision**

Atmospheric

- Chooz, Palo Verde

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

**Majorana phases**
not observable in oscillations but important for $0\nu\beta\beta$
Insert (known) Neutrino Data

\[ U = \begin{pmatrix} 
    c_{12} & c_{13} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & s_{13}e^{i\alpha} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta})e^{i\alpha} \\
    s_{13}e^{i\beta} & s_{23}c_{13}e^{i(\beta+\delta)} \\
    s_{23}c_{13}e^{i(\beta+\delta)} & c_{23}c_{13}e^{i(\beta+\delta)} 
\end{pmatrix} \]
Insert (known) Neutrino Data

\( \nu_\mu \quad \nu_\tau \quad \nu_3 \)

\( \nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_2 \)

\( \nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_2 \)

\( \nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_3 \)

atm

sun

normal ordering

inverted ordering
Future Prospects continued

KamLAND-Zen initial 112 days
\[ \langle m_{\beta\beta} \rangle < 0.26 \sim 0.54 \text{ eV} \] @90% C.L.

KamLAND-Zen ~100 days more data

- KamLAND-Zen after purification aiming at 100 times BG reduction
- KamLAND-Zen 700+kg with cleaner mini-balloon
- KamLAND2-Zen with brighter LS and light collector
  \[ \sigma_E(2.6\text{MeV}) \sim 2.5\% \]
- Super-KamLAND-Zen
- also precise anti-neutrino physics

R&D for imaging device to discriminate \( \beta / \gamma \)

R&D for higher Xe concentration

various possibilities as a low radioactive background environment
Five neutrino parameters are now measured in the solar, atmospheric and reactor neutrino experiments.

\[
\Delta m_{21}^2 = 7.59^{+0.20}_{-0.18} \times 10^{-5} \text{ eV}^2, \quad \Delta m_{31}^2 = 2.45^{+0.09}_{-0.09} \times 10^{-3} \text{ eV}^2 \text{ (NH)}, \\
\sin^2 \theta_{12} = 0.312^{+0.017}_{-0.015}, \quad \sin^2 \theta_{23} = 0.51^{+0.06}_{-0.06} \text{ (NH)}, \quad \sin^2 \theta_{13} = 0.023^{+0.004}_{-0.004},
\]
Which mass ordering with which life-time?

|     | $\Sigma$ | $m_\beta$ | $|m_{ee}|$ |
|-----|----------|-----------|-----------|
| NH  | $\sqrt{\Delta m_A^2}$ | $\sqrt{\Delta m_\odot^2 + |U_{e3}|^2 \Delta m_A^2}$ | $\sqrt{\Delta m_\odot^2 + |U_{e3}|^2 \sqrt{\Delta m_A^2} e^{2i(\alpha-\beta)}}$ |
|     | $\simeq 0.05$ eV | $\simeq 0.01$ eV | $\sim 0.003$ eV $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{28-29}$ yrs |
| IH  | $2\sqrt{\Delta m_A^2}$ | $\sqrt{\Delta m_A^2}$ | $\sqrt{\Delta m_A^2} \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha}$ |
|     | $\simeq 0.1$ eV | $\simeq 0.05$ eV | $\sim 0.03$ eV $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{26-27}$ yrs |
| QD  | $3m_0$ | $m_0$ | $m_0 \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha}$ |
|     | $\gtrsim 0.1$ eV | $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{25-26}$ yrs |
enriched detectors, 6.10 kg × yr

40 keV blinded window
(energy resolution at $Q_{\beta\beta}$: 4.5 keV (FWHM))
Kinematic determination of $m(\nu_e)$

$$\frac{d\Gamma}{dE} = C \ p(E + m_e)(E_0 - E) \sqrt{(E_0 - E)^2 - m^2_{\nu_e}} \ F(Z + 1, E) \ \Theta(E_0 - E - m_{\nu_e}) \ S(E)$$

$$C = \frac{G_F^2}{2 \pi^3} \cos^2\theta_C \ |M|^2$$

(modified by final states, recoil corrections, radiative corrections, ...)

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

Suitable $\beta$ emitters:

**Tritium**
- $E_0 = 18.6 \text{ keV}, T_{1/2} = 12.3 \text{ a}$
- $S(E) = 1$ (super-allowed)

**Rhenium**
- $E_0 = 2.47 \text{ keV}, T_{1/2} = 43.2 \text{ Gy}$

alternative approach:

**Holmium** (EC decay)
- $Q_{EC} \approx 2.5 \text{ keV}, T_{1/2} = 4570 \text{ y}$
- 41 kg TeO₂, active mass ~ 11 kg,
- avg FWHM = 7.5 keV at 2527 keV
- stopped June 2008
- total statistics 19.75 kg y

Astropart. Phys 34 (2011) 822  $T_{1/2}^{0\nu} > 2.8 \cdot 10^{24}$ y (90% CL)

60Co sum peak
2505 keV
~ 3 FWHM from DBD Q-value

130Te
$\beta \beta (0\nu)$

$\langle m_{ee} \rangle < 0.3-0.7$ eV
not sensitive enough to check Heidelberg-Moscow claim
EXO 200

Probing the $0\nu\beta\beta$ of $^{136}\text{Xe}$, $Q = 2458$ keV

$\sim 100$ kg of $^{136}\text{Xe}$

- Using $\sim 110$ kg of 80.6% enriched Xe in the isotope 136
- Two TPC modules separated by a common cathode.
- LAAPD arrays for light measurement.
- Two planes of 38 collection wire triplets (U-wires).
- Two planes of 38 induction wire triplets (V-wires).
- Wire planes crossing at 60° for stereoscopic informations.

Combining Ionization and Scintillation

Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)


Use projection onto a rotated axis to determine event energy

Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)

Rotation angle chosen to optimize energy resolution at 2615 keV
Zoomed around $0\nu\beta\beta$ region of interest (ROI)

**Exposure:** 35 kg yr (120.7 days)

- No signal observed
- Background in ROI: $(1.5 \pm 0.1) \times 10^{-3} \text{ kg}^{-1} \text{ yr}^{-1} \text{ keV}^{-1}$ in $\pm 1\sigma$ ROI

- Profile likelihood study to extract limits for $T_{1/2}^{0\nu\beta\beta}$

$$T_{1/2}^{0\nu\beta\beta} (^{136}\text{Xe}) > 1.6 \times 10^{25} \text{ yr (90\% C.L.)}$$

[arXiv:1205.5608]
KamLAND - Zen

- Zero Neutrino double beta decay search

Good features of using KamLAND
- running detector
  - relatively low cost and quick start
- huge and clean (1200m³, U: 3.5x10⁻¹⁸ g/g, Th: 5.2x10⁻¹⁷)
  - negligible external gamma
  - (Xe and mini-balloon need to be clean)
- Xe-LS can be purified, mini-balloon replaceable if necessary, with relatively low cost
  - highly scalable (up to several tons of Xe)
- No escape or invisible energy from β, γ
  - BG identification relatively easy
- anti-neutrino observation continues
  - geo-neutrino w/o Japanese reactors

Disadvantages toward an ultimate sensitivity
- relatively poor energy resolution
  - tolerable thanks to slow 2ν2β and low BG
- no β/γ discrimination so far
- delicate balloon film
- limited LS composition (for density matching)
**MC simulation**

**Real experiment**

---

**Simulated Energy Spectrum at KamLAND**

Signal / Bkg ~ 2/1
new 2νββ T_{1/2} ~ 1/1

---

100 days on surface, 300 days in the mine

---

**110mAg fits well**
Radioactive Impurities

- Cesium is from Fukushima-I reactor fallout. It is not very serious for $0\nu2\beta$ search. It doesn’t leach out, fortunately.
- $^{214}$Bi on the mini-balloon is limiting the fiducial volume.
- $^{208}$Tl is not serious. It appears far above $0\nu2\beta$ peak.

What is the peak around 2.6MeV?
The EXO-200 Detector

- HV FILTER AND FEEDTHROUGH
- VETO PANELS
- High purity Heat transfer fluid HFE7000 > 50 cm
- DOUBLE-WALLED CRYOSTAT 25 mm ea
- LXe VESSEL 1.37 mm
- LEAD SHIELDING > 25 cm
- VETO PANELS

FRONT END ELECTRONICS
VACUUM PUMPS
Maximum likelihood fit

- Trigger fully efficient above 700 keV
- Low background run livetime: \textbf{120.7 days}
- Active mass: \textbf{98.5 kg LXe (79.4 kg}^{136} \text{LXe)}
- Exposure: \textbf{32.5 kg\cdot yr}
- Total dead time (vetos): 8.6%
- Various background PDFs fitted along with $2νββ$ and $0νββ$ PDFs

$T_{1/2}^{2νββ} (^{136} \text{Xe}) = (2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys}) \cdot 10^{21} \text{ yr}$

(In agreement with previously reported value by EXO-200 and KamLAND-ZEN collaborations)
Construction started in the laboratories

Installation and commissioning (2013 – 2014) @ Modane Underground Laboratory

Data taking in 2014

No background expected

Sensitivity after 2 years: $T_{1/2} > 6.6 \times 10^{24}$ y and $\langle m_\nu \rangle < 0.2 - 0.4$ eV
Good features of using KamLAND

- running detector
  → relatively low cost and quick start

- huge and clean (1200m³, U: 3.5x10⁻¹⁸ g/g, Th: 5.2x10⁻¹⁷)
  → negligible external gamma
  (Xe and mini-balloon need to be clean)

- Xe-LS can be purified, mini-balloon replaceable if necessary, with relatively low cost
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Disadvantages toward an ultimate sensitivity

- relatively poor energy resolution
tolerable thanks to slow 2ν2β and low BG

- no β/γ discrimination so far

- delicate balloon film

- limited LS composition (for density matching)
MC simulation

Real experiment

Signal / Bkg ∼ 2/1
new 2νββ T_{1/2}: ∼ 1/1

100 days on surface, 300 days in the mine
Radioactive Impurities

- Cesium is from Fukushima-I reactor fallout. It is not very serious for $0\nu2\beta$ search. It doesn’t leach out, fortunately.
- $^{214}\text{Bi}$ on the mini-balloon is limiting the fiducial volume.
- $^{208}\text{TI}$ is not serious. It appears far above $0\nu2\beta$ peak.

What is the peak around 2.6MeV?
Limit on the $0\nu 2\beta$ half life

 simultaneous fit and 90% CL upper limit for $0\nu 2\beta$ 

($\chi^2$ at 2.2~3.0MeV)

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$ 112days</th>
</tr>
</thead>
<tbody>
<tr>
<td>simul. fit</td>
<td>11.6</td>
</tr>
<tr>
<td>$0\nu + ^{110m}\text{Ag}$</td>
<td>13.1</td>
</tr>
<tr>
<td>$0\nu + ^{208}\text{Bi}$</td>
<td>22.7, △</td>
</tr>
<tr>
<td>$0\nu + ^{88}\text{Y}$</td>
<td>22.2, △</td>
</tr>
<tr>
<td>$0\nu + ^{60}\text{Co}$</td>
<td>82.9, ×</td>
</tr>
<tr>
<td>$0\nu$ only</td>
<td>85.0, ×</td>
</tr>
</tbody>
</table>

BG is likely to be $^{110m}\text{Ag}$

$T^{0\nu}_{1/2} > 5.7 \times 10^{24}$ years at 90% C.L. (78days)

factor 5 improvement from DAMA

$T^{0\nu}_{1/2} > 6.2 \times 10^{24}$ years (KL-Zen 112days)

(ref. current best is $16 \times 10^{24}$ years from EXO-200)

(R)QRPA (CCM SRC) 

$\langle m_{\beta\beta} \rangle < 0.26$~0.54 eV @90% C.L.
Measurement of the $2\nu2\beta$ half-life

**DAMA (2002)**

Liquid Xe scintillator

$T^\text{2v}\text{1/2} > 1.0 \times 10^{22}$ years at 90% CL


(factor 5 contradiction)

**EXO-200 (2011)**

Liquid Xe TPC + scintillator

$T^\text{2v}\text{1/2} = 2.11 \pm 0.04\text{(stat)} \pm 0.21\text{(syst)} \times 10^{21}$ years


(update)

$T^\text{2v}\text{1/2} = 2.23 \pm 0.017\text{(stat)} \pm 0.22\text{(syst)} \times 10^{21}$ years

arXiv:1205.5608

**KamLAND-Zen (2012)**

Xe loaded liquid scintillator

$T^\text{2v}\text{1/2} = 2.38 \pm 0.02\text{(stat)} \pm 0.14\text{(syst)} \times 10^{21}$ years


(update)

$T^\text{2v}\text{1/2} = 2.30 \pm 0.02\text{(stat)} \pm 0.12\text{(syst)} \times 10^{21}$ years

arXiv:1205.6372
Telescope Germanium Vertical (TGV-2)

32 HPGe planar detectors $\Phi 60$ mm $\times$ 6 mm
with sensitive volume: 20.4 cm$^2 \times$ 6 mm
Total sensitive volume: $\sim 400$ cm$^3$
Total mass of detectors: $\sim 3$ kg
Total area of samples: 330 cm$^2$
Total mass of sample(s): 10 ÷ 25 g
Total efficiency: 50 ÷ 70 %
E-resolution: 3 ÷ 4 keV @ $^{60}$Co
LE-threshold: 5 ÷ 6 keV
Double beta emitters:
16 samples ($\sim 50$ $\mu$m) of $^{106}$Cd (enrich.75%)
13.6 g $\sim 5.79 \times 10^{22}$ atoms of $^{106}$Cd
- Construction started in the laboratories
- Installation and commissioning (2013 – 2014) @ Modane Underground Laboratory
- Data taking in 2014
- No background expected
- Sensitivity after 2 years: $T_{1/2} > 6.6 \times 10^{24}$ y and $<m_{\nu}> < 0.2$ - 0.4 eV
$^{76}$Ge offers an excellent combination of capabilities & sensitivities. (Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)

- **40-kg of Ge detectors**
  - Up to 30-kg of 86% enriched $^{76}$Ge crystals required for science and background goals
  - Examine detector technology options focus on point-contact detectors for **DEMONSTRATOR**

- **Low-background Cryostats & Shield**
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto

- **Agreement to locate at 4850’ level at Sanford Lab**

- **Background Goal in the $0\nu\beta\beta$ peak ROI (4 keV at 2039 keV)**
  - $\sim 3$ count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)
Three Phases

- Prototype cryostat (2 strings, $^{\text{nat}}$Ge) **(End 2012)**
  
  $1^{\text{st}}$ order of $^{\text{enr}}$Ge (20 kg) on hand. $2^{\text{nd}}$ order in process. Refinement/processing facility in Oak Ridge (via NSF) has completed testing with $^{\text{nat}}$Ge.

- Cryostat 1 (3 strings $^{\text{enr}}$Ge & 4 strings $^{\text{nat}}$Ge) **(Fall 2013)**

- Cryostat 2 (up to 7 strings $^{\text{enr}}$Ge) **(Fall 2014)**
– Measurement started in June 2011!

CANDLES III(U.G.)

- CaF$_2$(pure)
  - $10^3$ cm$^3 \times 96$ crystals; 305 kg ($^{48}$Ca; 350 g)

- Liquid scintillator
  - two phase system
  - Purification system

- H$_2$O Buffer
  - passive shield

- PMTs
  - 17” PMT (× 14) : R7250
  - 13” PMT (× 48) : R8055
- **48Ca enrichment**
  - R&D for next CANDLES system
  - by using crown-ether
  - Under development
  - for a large amount of 48Ca

- **CANDLES IV & V**
  - 48Ca enrichment
  - Cooling system (≈0°C) for good energy resolution

- **Schedule**

<table>
<thead>
<tr>
<th>Year</th>
<th>CANDLES III</th>
<th>CANDLES IV &amp; V (scintillator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Measurement at Kamioka Lab.

<m_3> sensitivity 0.5 eV

48Ca enrichment

<m_3> sensitivity 50 meV

Construction of detector

. . . not funded yet
Kamland-Zen, 1000 kg

1st phase enriched Xe 400kg
R=1.7m balloon
V=20.5m³, S=36.3m²
LS : C₁₀H₂₂(81.8%)+PC(18%)
+PPO+Xe(~2.5wt%)
ρLS : 0.78kg/ℓ
high sensitivity with low cost

tank opening (2013 or 2015)

2nd phase enriched Xe 1000kg
R=2.3m balloon
V=51.3m³, S=66.7m²
improvement of energy resolution
(brighter LS, higher light concentrator)
CUORE program

Cryogenic Underground Observatory for Rare Events

Primary objective is to search for $0\nu\beta\beta$ decay in $^{130}\text{Te}$
CUORE construction started

988 TeO$_2$ 5x5x5 cm$^3$ crystals $\Rightarrow$ 741 kg TeO$_2$
$\Rightarrow$ 204 kg $^{130}$Te

Cryostat order placed

The COURE building in hall A of LNGS
Construction of the GERDA set up started in 2007 in Gran Sasso National Laboratory (LNGS), Italy. Installation of the “nested type” assembly completed in 2010 in the deep underground facility at 3400 m w.e.

- **End of 2009:** Cryostat was filled with 95 t of liquid argon.
- **Summer 2010:** Water tank was filled with 565 t of ultrapure water.
- **June 2010:** Start of commissioning runs with 3 natGe detectors

**November 2011:** Start of Phase I.
All 8 $^{76}$Ge + 3 NatGe detectors deployed in GERDA

**Phase I detectors**
- 8 enriched HPGe detectors (in total ~ 18 kg of $^{76}$Ge)
  from HdM and IGEX experiments,
- 3 natural HPGe detectors (in total ~ 7.6 kg of NatGe)
  from the Genius T-F

Soon: 5 BEGe from $^{76}$Ge will be implemented (June 2012)

**Phase II detectors**
the new BeGe detectors (~ 25 kg of $^{76}$Ge) made from enriched in $^{76}$Ge material will be added.
In total: about 40 kg of $^{76}$Ge
\[ \bar{\nu}_{e,R} = \bar{\nu}_e \frac{1}{2} (1 + \gamma_5) = \]

\[ \sum_{i=1}^{3} U_{ei}(\bar{\nu}_{i,h=1} + \frac{m_i}{E} \bar{\nu}_{i,h=-1}) \]

\[ \nu_{e,L} = \frac{1}{2} (1 - \gamma_5) \nu_e = \]

\[ \sum_{i=1}^{3} U_{ei}(\nu_{i,h=-1} + \frac{m_i}{E} \nu_{i,h=1}) \]

h = helicity
SRQRPA = self-consistent renormalized quasiparticle random
phase approx. (2), Phys Rev D83 (2011) 113015,
Phys Rev C79 (2009) 055501,
Phys Rev C83 (2011) 034320
GCM = generating coordinate method
pHFB = projected Hartree-Fock-Bogoliubov
Phys Rev C82 (2010) 064310
(1) for 76Ge: measurement of n+p occupancies, Phys Rev Lett
100 (2008) 112501, Phys Rev C79 (2009) 021301, lead to
15% increase for NSM and 20% decrease for QRPA
(2) scaled by 1.14 to compensate for different phase space
(3) scaled by 1.18 as estimate for calculation with UCOM
short range correlation instead of Jastrow

- 0ν NME in first approximation ~ A^{-1/3}
- q~100 MeV --> "neighboring n" decay
- NSM lower than other calculations
- NME vary by factor 2-3 for given A
<table>
<thead>
<tr>
<th>Phase</th>
<th>I</th>
<th>II</th>
<th>Ton Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure [kg · yr]</td>
<td>15</td>
<td>100</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>$B_g$ [counts/kg · keV · yr]</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Upper limit $m_{\beta\beta}$ [eV]</td>
<td>0.23-0.39</td>
<td>0.09-0.15</td>
<td>$\sim 0.05$</td>
</tr>
</tbody>
</table>

A. Smolnikov, P. Grabmayr

PRC 81 028502(2010)

Merge with Majorana
Radioactive Impurities

- Cesium is from Fukushima-I reactor fallout. It is not very serious for 0ν2β search. It doesn’t leach out, fortunately.
- $^{214}\text{Bi}$ on the mini-balloon is limiting the fiducial volume.
- $^{208}\text{Tl}$ is not serious. It appears far above 0ν2β peak.

What is the peak around 2.6MeV?
AMoRE

(Advanced Mo-based Rare process Experiment)

Collaboration (Korea, Russia, Ukraine, China, 11 institutions)

CaMoO$_4$ scintillators or bolometers
Enriched in $^{100}$Mo and depleted in $^{48}$Ca

1$^{st}$ stage: room temperature
6 kg $^{40}$Ca$^{100}$MoO$_4$, 5% FWHM
3 years, $6.0 \times 10^{24}$ y (90% CL)

2$^{nd}$ stage: Cryogenic technique
5 years, 100 kg $^{40}$Ca$^{100}$MoO$_4$
15 keV FWHM, Eff = 0.8
3 $\times$ $10^{26}$ years ~ 50 meV

Event Number

2$\nu$ $\beta\beta$ of $^{100}$Mo

0$\nu$ $\beta\beta$ of $^{100}$Mo
R&D funded (3.3 M€) by ERC, in the form of an advanced GRANT (03/2010→03/2015)

Scintillating bolometers to recognize the α-induced background thanks to the readout of the scintillation light

Array of 36÷44 enriched (95%) Zn^{82}Se crystals.

Expected background in the ROI (2995 keV) is $\sim 3\pm 6 \times 10^{-3}$ c/keV/kg/y

Energy resolution $\sim 10$ keV FWHM
The $\alpha$-induced background is recognized:

1) the decay time of the scintillating signal
2) the different scintillation yield between $\alpha$ and $\gamma/\beta$ particles (the "usual" light Vs Heat scatter plot)

R&D on light detectors
15 kg $^{82}$Se production
Enriched crystal growth
Detector assembling

LUCIFER will be located in CUORICINO (now CUORE-0) cryostat, once CUORE-0 will finish his data taking (2015)
\( ^{150} \text{Nd} \) salt dissolved in liquid scintillator

**\( \beta\beta \)-decay signal for 0.3 \% Nd-loaded scintillator**

- 2.4 live-years data simulated
- \(^{214}\text{Bi} \) tagged and removed with \(^{214}\text{Bi-Po} \)
- \(^{208}\text{Tl} \) constrained with \(^{212}\text{Bi-Po} \)
  - delayed coincidence
- \( t_{1/2} \) 3 min alpha tag of \(^{208}\text{Tl} \) rejects 90%

**Neutrino mass sensitivity for 0.3 \% Nd loading (44 kg of \(^{150}\text{Nd} \))**

  - NME values were used (includes deformation)
- radioactivity backgrounds at the levels achieved by Borexino
• Acrylic Vessel Hold Down Net installed
• New SNO+ Electronics and DAQ being tested (e.g. air fill runs)
• Water fill and detector commissioning starting mid-2012
• Scintillator purification and process systems installed: end of 2012
• Scintillator fill in early 2013 and data taking
• Addition of Nd to the scintillator soon thereafter

photo of SNO+ AV Hold Down Net installed
COBRA

Use large amount of CdZnTe Semiconductor Detectors

- Source = detector
- Focus on $^{116}$Cd
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Tracking/Pixelisation („Solid state TPC“)

Objective: Massive background reduction by particle identification

Current spectrum (black), 12.73 kg*days
Background at 2813 keV about 1 ct/keV/kg/yr

Currently ongoing upgrade:
- 64 detectors (in hand) 32 running at LNGS
- new DAQ
- Pulse shape information (done), rejection of surface events
- Improvement on shielding
- new location at LNGS (former HdMo cabin)
MTD (Magnetic Tracking Detector: temporary name) following of DCBA

Chamber cell: the same as DCBA-T3, Source plate: 80 m²/module
Thickness: 40 mg/cm², Source weight: 32 kg/module

Expected Energy Resolution 3.4% at $Q_{\beta\beta}$ for $^{150}$Nd

Multi-isotope $^{150}$Nd, $^{100}$Mo, $^{82}$Se
Several modules to reach $<m_\nu>$ 50 meV
NEXT Detection Concept

- Cylindrical single drift volume
- Scintillation signal for $t_0$
- Ionization signal for separated energy and tracking measurements
  - Converted into EL light
- Instrumented endcaps
  - PMTs on energy plane
  - SiPMs on tracking plane
- TPB coating: 170 → 430 nm light

NEXT strengths:
- Scalability to ton-scale relatively easy
- 0.5-1% FWHM energy resolution
- Tracking and dE/dx information for event topology
• Experience and results from prototypes
  • Testing ground for all foreseeable technical hurdles in NEXT-100
  • 0.5-1% FWHM energy resolution at $Q_{\beta\beta}$ demonstrated
  • Tracking and event topology studies underway
NEXT Sensitivity and Schedule

• NEXT-100 should be sensitive to effective Majorana masses as small as 100 meV after 5 years of operation
  • 90% CL, assuming 100 kg of xenon
  • half-life sensitivity: $6 \times 10^{25}$ years

• Main backgrounds expected to be gammas from $^{214}$Bi and $^{208}$Tl
  • $2 \times 10^{-7}$ background rejection factor
  • $8 \times 10^{-4}$ counts/(keV·kg·y) background rate
  • Based on detailed background model

Schedule:
2012: complete R&D, NEXT-100 design, radiopurity campaign
2013: NEXT-100 construction
2014: NEXT-100 commissioning with non-enriched xenon
2015: start physics run with enriched xenon
Search for $2\nu$EC/EC of $^{106}$Cd with pixel detectors

- Si pixel detectors in coincidence mode
- Thin foil of enriched isotope
- Signature = two hit pixels with X-rays of precise energy
- Good efficiency (comparable with TGV-2)
- Particle identification (alpha, electrons)
- Information about energy + position of registered X-ray
- Measurement at room temperature

Observable: $2\times$ 21keV X-rays from $^{106}$Pd daughter originated in the enriched Cd foil

Single-side events (SSE)

Double-side event (DSE)