1. Introduction
2. Basic facts about double beta decay
3. Detection techniques in double beta decay and main experiments
4. Future of double beta decay
Double beta decay

- **two-neutrinos double beta decay (2\(\nu\beta\beta\))**

  (Z-2, A) → (Z, A) + 2e\(^-\) + 2\(\nu\)\(_e\)  \((2\nu\beta^-\beta^-)\)  \(\text{observables: } 2\ e^-\)

  Z+2, A) → (Z, A) + 2e\(^+\) + 2\(\nu\)\(_e\)  \((2\nu\beta^+\beta^+)\)  \(\text{observables: } 2\ e^+, 4x511\ \text{keV } \gamma\)

  e\(^-\)(Z+2, A) → (Z, A) + e\(^+\) + 2\(\nu\)\(_e\)  \((2\nu\beta^+/EC)\)  \(\text{observables: } 1\ e^+, 2x511\ \text{keV } \gamma, \text{X-ray}\)

  2e\(^-\)(Z+2, A) → (Z, A) + 2\(\nu\)\(_e\) + 2X  \((2\nu\text{EC/EC})\)  \(\text{observables: } 2\ X\text{-rays}\)

- **neutrinoless double beta decay (0\(\nu\beta\beta\))**

  1. (Z-2, A) → (Z, A) + 2e\(^-\)  \((0\nu\beta^-\beta^-)\)

  2. (Z+2, A) → (Z, A) + 2e\(^+\)  \((0\nu\beta^+\beta^+)\)

  3. e\(^-\)(Z+2, A) → (Z, A) + e\(^+\)  \((0\nu\beta^+/EC)\)

  4. 2e\(^-\)(Z+2, A) → (Z, A)\(^*\) → (Z-2, A) + (\(\gamma\)) + 2X  \((0\nu\text{EC/EC})\)

**2\(\nu\beta\beta\)** - allowed process in the „Standard model“, process of the second order  \(T_{1/2} = 10^{18}-10^{24}\ \text{years}\)

**0\(\nu\beta\beta\)** - forbidden process in „Standard model“, violate lepton number conservation, effective mass and type of neutrino (Majorana, Dirac), existence of right-handed currents
2 possibilities for $2\nu\beta\beta$:

- if simple beta decay is energetically forbidden

$\beta^{-}\beta^{-}$

$\gamma$

- if “simple” beta decay is strongly suppressed by spin difference

There are 35 candidates for $2\beta$ decay, $W \sim Q^5(0\nu), W \sim Q^{11}(2\nu)$
Expected decay rate:

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

- Phase space integral
- Nuclear matrix element
- \( \langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right| \)
- Effective neutrino mass
- Elements of (complex) PMNS mixing matrix

Experimental signatures:
- peak at \( Q_{\beta\beta} = m(A,Z) - m(A,Z+2) - 2m_e \)
- two electrons from vertex

Discovery would imply:
- lepton number violation \( \Delta L = 2 \)
- \( \nu \)'s have Majorana character
- mass scale & hierarchy
- physics beyond the standard model
MEDEX workshop
(Matrix Elements for the Double-beta-decay EXperiments)

Organizing committee:
Osvaldo Civitarese (University of La Plata), Jouni Suhonen (University of Jyväskylä), Ivan Štekl (Czech Technical University)

- organized from 1997 in Czech Technical University every two years
- 40-50 participants from all over the world

Basic features of MEDEX workshop:
direct connections between theoreticians and experimentalists, free discussion during talks, round-table discussions

two working sessions:
NME for double-beta-decay,
Nuclear aspects of neutrino physics and dark matter studies.

section for young scientists and PhD students
Two neutrino double beta decay:
- Second order of weak interaction
- Direct measurement of NME values \(\Rightarrow\) nuclear theory

Very important to measure \(\beta\beta\) decay for many nuclei, for different processes (\(2\beta^-\), \(2\beta^+\), \(K_b^+\), \(2K\), excited states)

**Recommended values for half-lives:**


- \(^{48}\text{Ca}\) - \((4.4^{+0.6}_{-0.5})\cdot10^{19}\) y
- \(^{76}\text{Ge}\) - \((1.65^{+0.14}_{-0.12})\cdot10^{21}\) y
- \(^{82}\text{Se}\) - \((0.92\pm0.07)\cdot10^{20}\) y
- \(^{96}\text{Zr}\) - \((2.3\pm0.2)\cdot10^{19}\) y
- \(^{100}\text{Mo}\) - \((7.1\pm0.4)\cdot10^{18}\) y
- \(^{100}\text{Ru\ (0\,^+_1)}\) - \((6.7^{+0.5}_{-0.4})\cdot10^{20}\) y
- \(^{116}\text{Cd}\) - \((2.87\pm0.13)\cdot10^{19}\) y
- \(^{128}\text{Te\ (geo)}\) - \((2.0\pm0.3)\cdot10^{24}\) y
- \(^{130}\text{Te}\) - \((6.9\pm1.3)\cdot10^{20}\) y
- \(^{136}\text{Xe}\) - \((2.19\pm0.06)\cdot10^{21}\) y
- \(^{150}\text{Nd\ (geo)}\) - \((8.2\pm0.9)\cdot10^{18}\) y
- \(^{150}\text{Nd\ (150Sm\ (0\,^+_1)}\) - \((1.2^{+0.3}_{-0.2})\cdot10^{20}\) y
- \(^{238}\text{U\ (rad)}\) - \((2.0\pm0.6)\cdot10^{21}\) y
- EEC(2v): \(^{130}\text{Ba\ (geo)}\) - \(~10^{21}\) y

11 isotopes – 2\(\nu\)\(\beta\beta\)

2 isotopes – excited state of 2\(\nu\)\(\beta\beta\)

1 isotope – EC/EC decay
Neutrinoless double beta decay was not detected.

Some obtained results:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>half-live [yr]</th>
<th>eff. neutrino mass [meV]</th>
<th>experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>$&gt; 3,0 \times 10^{25}$</td>
<td>$&lt; 0,20-0,40$</td>
<td>GERDA I</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$&gt; 1,1 \times 10^{24}$</td>
<td>$&lt; 0,33-0,62$</td>
<td>NEMO 3</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&gt; 2,8 \times 10^{24}$</td>
<td>$&lt; 0,31-1,10$</td>
<td>Cuoricino</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&gt; 4,0 \times 10^{24}$</td>
<td></td>
<td>CUORE 0 + Cuoricino</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$&gt; 2,6 \times 10^{25}$</td>
<td>$&lt; 0,14-0,28$</td>
<td>KamLAND-Zen</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$&gt; 1,1 \times 10^{25}$</td>
<td>$&lt; 0,19-0,45$</td>
<td>EXO-200</td>
</tr>
</tbody>
</table>

Current oscillation experiments can not tell difference between normal and inverse hierarchy. What is the expectation for $0\nu\beta\beta$?

**Normal hierarchy:**

$$\langle m_\nu \rangle \simeq s_{12}^2 \sqrt{\Delta m^2_{\odot}} + s_{13}^2 \sqrt{\Delta m^2_{\text{Atm}}}$$

$$\simeq (1.7 - 3.9) \times 10^{-3} \text{ eV}$$

**Inverse hierarchy:**

$$\langle m_\nu \rangle \simeq \sqrt{\Delta m^2_{\text{Atm}}} \simeq 5 \times 10^{-2} \text{ eV}$$
Half-life for $0\nu\beta\beta$:

- Source = enriched material ($F_a$)
- Big mass of the source (M)
- Long time of measurement (t)
- "Best" energy resolution of the detector ($\Delta E$)
- Background as low as possible (B)

$T_{1/2} = \frac{\varepsilon}{W} \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$
Candidates with $Q_{2\beta} > 2$ MeV (natural $\gamma$ rays background, $E < 2,615$ MeV)

There are **6 gold** and **5 silver** isotopes

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>$Q_{2\beta}$, keV</th>
<th>Abundance, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>48Ca</td>
<td>4272</td>
<td>0.187</td>
</tr>
<tr>
<td>150Nd</td>
<td>3371.4</td>
<td>5.6</td>
</tr>
<tr>
<td>96Zr</td>
<td>3350</td>
<td>2.8</td>
</tr>
<tr>
<td>100Mo</td>
<td>3034.4</td>
<td>9.63</td>
</tr>
<tr>
<td>82Se</td>
<td>2996</td>
<td>8.73</td>
</tr>
<tr>
<td>116Cd</td>
<td>2805</td>
<td>7.49</td>
</tr>
<tr>
<td>130Te</td>
<td>2527.5</td>
<td><strong>34.08</strong></td>
</tr>
<tr>
<td>136Xe</td>
<td>2458.7</td>
<td>8.87</td>
</tr>
<tr>
<td>124Sn</td>
<td>2287</td>
<td>5.79</td>
</tr>
<tr>
<td>76Ge</td>
<td>2039.0</td>
<td>7.61</td>
</tr>
<tr>
<td>110Pd</td>
<td>2000</td>
<td>11.72</td>
</tr>
</tbody>
</table>
Background Sources

- **Natural radioactivity** (source itself)
  - Activity in the rock and in surrounding materials
    - (\(\alpha, n\)) processes \(\Rightarrow\) [0, 10] MeV spectrum

- **Neutrons**
  - High-energy \(m\) induced complicated problem
    - Depth
      - Appropriate shielding / coincidence techniques
      - Reliable simulations
      - “Ad hoc” experiments at muon accelerators could be useful

- **Cosmogenic induced activity** (long living)
  - “Ad hoc” bolometers for alpha self-counting
  - Full prototype used to measure contamination (BiPo detector)

- **2ν Double Beta Decay**

Two main sources

Choice of materials

Storage of materials underground

Partial or full detector realization underground (Ge diodes)

\[\Rightarrow\] reliable simulations

\[\Rightarrow\] “Ad hoc” experiments at muon accelerators could be useful
Experimental techniques to observe $\beta\beta$-decay

- **Geochemical & Radiochemical**
  - Source $\equiv$ detector
  - $\beta\beta$-sample $(A,Z)$

- **Calorimetric**
  - $E_1 + E_2$ spectrum

- **Tracking + Calorimetric**
  - $E_1, E_2, \theta$
  - Larger mass
  - Better resolution
  - High (~ 100%) efficiency

- **TPC**
  - Time Projection Chamber
  - $\beta\beta$-foil or $\beta\beta$-gas

There is no “ideal” method to meet all requirements!
The GERDA collaboration

http://www.mpi-hd.mpg.de/gerda

16 institutions
~100 members
The GERDA experiment

- plastic $\mu$-veto
- clean room with lock and glove box for detector handling
- muon & cryogenic infrastructure
- cryostat, $\varnothing 4m$, with internal Cu shield
- Ge-detector array (enriched in $^{76}\text{Ge}$)
- control rooms
- water plant & radon monitor
- water tank, $\varnothing 10m$, part of muon-veto detector
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: 2.4×10^{-2} / 1.0×10^{-2}
- GERDA+IGEX+HdM: 2 × 10^{-4} / -

Limit on half-life:
- GERDA: \( T_{1/2}^{0ν} > 2.1×10^{25} \) yr (90% C.L.)
- GERDA+IGEX+HdM: \( T_{1/2}^{0ν} > 3.0×10^{25} \) yr (90% C.L.) \( (<m_{ee} < 0.2-0.4 \) eV)

After only 5.04 kg yr exposure:
\( T_{1/2}^{0ν}(^{76}\text{Ge}) = (1.84^{+0.14}_{-0.10}) \times 10^{21} \) yr

8 refurbished enriched diodes from HdM & IGEX
- 86\% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

2 diodes shut off because leakage current high:
- total enriched detector mass 14.6 kg
A. Gando,¹ Y. Gando,¹ H. Hanakago,¹ H. Ikeda,¹ K. Inoue,¹,² K. Ishidoshiro,¹ R. Kato,¹ M. Koga,¹,² S. Matsuda,¹ T. Mitsui,¹ D. Motoki,¹ T. Nakada,¹ K. Nakamura,¹,² A. Obata,¹ A. Oki,¹ Y. Ono,¹ M. Otani,¹ I. Shimizu,¹ J. Shirai,¹ A. Suzuki,¹ Y. Takemoto,¹ K. Tamae,¹ K. Ueshima,¹ H. Watanabe,¹ B.D. Xu,¹ S. Yamada,¹ H. Yoshida,¹ A. Kozlov,² S. Yoshida,³ T.I. Banks,⁴ S.J. Freedman,²,⁴ B.K. Fujikawa,²,⁴ K. Han,⁴ T. O’Donnell,⁴ B.E. Berger,⁵ Y. Efremenko,²,⁶ H.J. Karwowski,⁷ D.M. Markoff,⁷ W. Tornow,⁷ J.A. Detwiler,⁸ S. Enomoto,²,⁸ and M.P. Decowski²,⁹

(The KamLAND-Zen Collaboration)

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⁸Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA
⁹Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands
KamLAND-Zen (Kamioka 2700 mw.e.)

Contain the Xe-loaded scintillator in a small balloon
Dissolve isotopically enriched Xe in KamLAND's ultra low background liquid scintillator.

- 1 kton Scintillation Detector
- 6.5m radius balloon filled with:
  - 20% Pseudocumene (scintillator)
  - 80% Dodecane (oil)
  - PPO
- 34% PMT coverage
- ~1300 17” fast PMTs
- ~550 20” large PMTs
- Multi-hit electronics
- Water Cherenkov veto counter

Half life limit (90% CL) derived using this background subtraction:

\[ T^{0\nu}_{1/2} = 2.30 \pm 0.02 \text{ (stat)} \pm 0.12 \text{ (sys)} \times 10^{21} \text{ yr} \]

\[ T^{\nu}_{1/2} > 1.9 \times 10^{25} \text{ yr} \]
\[ \langle m_{\beta\beta} \rangle < 143-338 \text{ meV} \]

KamLAND-Zen combined their limit with that of EXO-200 to obtain:

\[ T^{\nu}_{1/2} > 3.4 \times 10^{25} \text{ yr} \]
The EXO-200 Collaboration

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Pieper, R. Tsang
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University of Massachusetts, Amherst MA, USA - J. Abdollahi, S. Feyzbakhsh, S. Johnston, A. Pocar, D. Shy
IBS Center for Underground Physics, Daejeon, South Korea - D.S. Leonard
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Stony Brook University, SUNY, Stony Brook, NY, USA - K. Kumar, O. Njoya, M. Tarka
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fleringer, M. Marino
TRIUMF, Vancouver BC, Canada - J. Dilling, R. Krücker, F. Retière, V. Strickland
EXO-200 (WIPP 1620 mw.e.)

Large liquid (enriched) liquid Xe tracking calorimeter (TPC) with simultaneous read-out of ionization and scintillation.

\[
T_{1/2}^{2\nu\beta\beta} = (2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{sys}}) \cdot 10^{21} \text{y}
\]

\[
T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25} \text{y}
\]

\[
\langle m_{\beta\beta} \rangle < 187 - 445 \text{ meV}
\]

Sensitivity goal

\[
T_{1/2}^{0\nu\beta\beta} > 5.7 \cdot 10^{25} \text{y}
\]

\[
\langle m_{\beta\beta} \rangle < 82 - 195 \text{ meV}
\]

DOE has just approved 3 more years of data taking.
Czech participation in double beta decay

1) Our activities are concentrated in Modane underground laboratory (France), which is included into Roadmap of large research infrastructures in Czech Republic (from 2010 – 2022)

2) Two participating institutions (Czech Technical University in Prague, Charles university in NEMO3/SuperNEMO experiment)

3) NEMO3 - provided precise results for $2\nu\beta\beta$ decay of 7 isotopes
   SuperNEMO - $0\nu\beta\beta$ decay of $^{82}$Se,
   responsibility of Czech side = radon program, improvement of energy resolution of scintillating detectors, shielding, construction of SuperNEMO frame
   TGV – double electron capture of $^{106}$Cd
   SPT – double electron capture of $^{106}$Cd using Si pixel detectors
   OBELIX – ultra-pure HPGe detector (600 cm$^3$)
   R&D of needed technologies – removing radon from air (1 mBq/m$^3$), ultra sensitive detection techniques (detection of radon, selection of ultra-pure construction materials), theoretical calculations of NME
Search for double electron capture in $^{106}$Cd (TGV collaboration)

JINR Dubna, Russia; IEAP CTU in Prague, Czech Republic; CSNSM Orsay, France; Comenius University, Slovakia.

Since 2000, focus on 2nEC/EC decay of $^{106}$Cd

$$2e + \ ^{106}_{48}Cd \rightarrow \ ^{106}_{46}Pd + 2\nu_e + (\gamma, X-rays)$$

$$Q_{EC/EC} = 2778\text{ keV}, \ \text{ROI: } 19 \text{ keV} \leq E_x \leq 23 \text{ keV}$$

$13.6$ g of $^{106}$Cd (enrichment $75\%$)
Detector “Obelix”  
(JINR/IEAP CTU/LSM)

P type coaxial HPGe detector Canberra in U-type ultra low background cryostat located at LSM, France (4800 m w.e.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive volume</td>
<td>600 cm³</td>
</tr>
<tr>
<td>Efficiency</td>
<td>162%</td>
</tr>
<tr>
<td>Peak/Compton</td>
<td>83</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>~1.2 keV at 122 keV ($^{57}$Co), ~2 keV at 1332 keV ($^{60}$Co)</td>
</tr>
<tr>
<td>Distance from cap</td>
<td>4 mm</td>
</tr>
<tr>
<td>Entrance window</td>
<td>Al, 1.6 mm</td>
</tr>
<tr>
<td>~12 cm</td>
<td>arch. Pb</td>
</tr>
<tr>
<td>~20 cm</td>
<td>low active Pb</td>
</tr>
<tr>
<td>Radon free air</td>
<td></td>
</tr>
</tbody>
</table>
$^{100}\text{Mo} \rightarrow 0^+, 1130 \text{ keV} \; ^{100}\text{Ru}$

590.8+539.5 keV*

Published at:


- in Marinelli bobbin
- Mass of foils – 2595.02 g
- Mass of $^{100}\text{Mo}$ – 2517.15 g
- Total measurement time – 2288 h

<table>
<thead>
<tr>
<th>Process</th>
<th>$T_{1/2}$ [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\nu 2\beta^-$ decay to</td>
<td>$7.5 \times 10^{20}$</td>
</tr>
<tr>
<td>$0^+_1 [1130 \text{ keV}]$</td>
<td></td>
</tr>
<tr>
<td>$2\nu 2\beta^-$ decay to</td>
<td>$&gt; 2.5 \times 10^{21}$</td>
</tr>
<tr>
<td>$2^+_1 [540 \text{ keV}]$</td>
<td></td>
</tr>
</tbody>
</table>
A(222Rn) in LSM ~ 10-15 Bq/m³

May 2004: detector NEMO-3 in tent

A(222Rn) ~ Bq/m³

Antiradon setup: starts running Oct. 2004

2x500 kg charcoal @ -50°C, 7 bars

Activity: A(222Rn) < 10 mBq/m³ !!!

Flux: 150 m³/h

(produced by ATEKO company, Czech rep.)
Each measurement was performed in a lightproof box, in which scintillators up to 2.2 m long and 1 m wide could be tested.

Improved $\Delta E/E$ for blocks for SuperNEMO experiment @ 1.5 % pTP and 0.05 % - 0.005 % POPOP.
**Experiment NEMO-3 and SuperNEMO**

(France, UK, Czech Rep., Russia, Spain, USA, Japan, Ukraine, Finland, Slovakia)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}^{\beta\beta 2\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>$[7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (sys)}] \times 10^{18}$ y</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$[9.6 \pm 0.1 \text{ (stat)} \pm 1.0 \text{ (sys)}] \times 10^{19}$ y</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$[2.88 \pm 0.04 \text{ (stat)} \pm 0.16 \text{ (sys)}] \times 10^{19}$ y</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$[7.0 \pm 0.9 \text{ (stat)} \pm 0.9 \text{ (sys)}] \times 10^{20}$ y</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>$[9.11 + 0.25 - 0.22 \text{(stat)} \pm 0.63 \text{(sys)}] \times 10^{18}$ y</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>$[2.35 \pm 0.14 \text{ (stat)} \pm 0.16 \text{ (sys)}] \times 10^{19}$ y</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>$[4.4 + 0.5 - 0.4 \text{ (stat)} \pm 0.4 \text{ (sys)}] \times 10^{19}$ y</td>
</tr>
</tbody>
</table>

700,000 2νββ events $^{100}$Mo

Signal/Backgr. ratio: 76

$^{100}$Mo $T_{1/2}^{\beta\beta 0\nu} > 1.0 \times 10^{24}$ y $<m_\nu> < 0.31 - 0.96$ eV

$^{82}$Se $T_{1/2}^{\beta\beta 0\nu} > 3.2 \times 10^{23}$ y $<m_\nu> < 0.94 - 2.6$ eV

**SuperNEMO 3: $\beta\beta(0\nu)$ $T_{1/2} > 2 \times 10^{26}$ yr $<m_\nu> < 0.04 - 0.09$ eV**

Tracko-calor with 100 kg of $^{82}$Se or $^{150}$Nd

Background reduction: $^{214}$Bi $\leq 10 \mu$Bq/kg

$\text{Rn} \leq 0.15$ mBq/m$^3$

R&D funded by France, UK, Spain, Russia, Czech Republic

2010-2011: TDR

2014-2015: commissioning of first module in LSM (France)

2016: Full detector running
SuperNEMO demonstrator (first module):
- Sensitivity of 1 module in 2.5 years, 7 kg of Se, no background – $T_{1/2}$ of $0\nu\beta\beta$ decay > $6.5 \times 10^{24}$ y
- Reach sensitivity of NEMO-3 in 5 months
- $10M$, operational costs 100 k€/year

Full SuperNEMO (19 additional modules):
- 2017-2020,
- Estimated costs $2M/module (capital)
- reach 500 kg.y exposure in 2025

Source: 7 kg of $^{82}$Se
Tracking: 2016 drift cells
Calorimeter: 712 scintillator blocks
32 t, 6,2 x 2,1 x 4,1 m$^3$, 25 Gauss magnetic field
Start: 2016 in LSM

Tracker R&D
Low background R&D
BiPo setup
Pixel detectors in $\beta\beta$ decay

$\beta^-\beta^-$ decay

- Segmented e.g. CdTe pixel detectors (enriched Cd)
- **Signature** = two tracks of electrons from one pixel, final pixels of both tracks due to Bragg curve
- Particle identification / rejection (alpha, electrons, photons)

EC/EC decay

- Si pixel detectors in coincidence mode
- Thin foil of enriched isotope
- **Signature** = two hitted pixels with X-rays of precise energy
- Efficiency (factor 2x comparing with TGV II)
- Particle identification (alpha, electrons)

Examples of particle type identification

$^{214}$Bi $\beta$ $^{214}$Po $\alpha$ $^{210}$Pb
R&D of pixel telescopes in underground physics

A) **Problem of radioactivity in standard PCB (FR4)** – two solutions (CuFlon, Flexible PCB)

- Reduction of background (factor 4)

B) **Development of hardware (CuFlon, Flexible PCB)** - 2 prototypes:

- CdTe Pixel Telescope (CuFlon Version)
- 4 units of Flex-rigid Si Pixel Telescope (with 500 µm and 1000 mm Si sensors)

Figure 8.13: Comparison of SPT and SPD spectra from underground measurements with 5 cm of Pb shielding. Total time of measurement was 411.8 hours and 219 hours for SPT and SPD, respectively. Spectrum is normalized per detector per day for both measurements.
SPT background (full shielding) vs with TGV II background

- No background events in ROI for 60 days of measurement (8 Si pixel detectors)

<table>
<thead>
<tr>
<th>Data set</th>
<th>All event/h</th>
<th>SSE/h (all criteria)</th>
<th>DSE/h (all criteria)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>ROI</td>
<td>Total</td>
</tr>
<tr>
<td>SPT Full shielding</td>
<td>6.41</td>
<td>0.15</td>
<td>6.34×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGV II in full shielding</td>
<td>1.18</td>
<td>0.036</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

1425 h of data

<table>
<thead>
<tr>
<th></th>
<th>All events/h</th>
<th>In ROI/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>32.23 ± 0.15</td>
<td>0.81 ± 0.02</td>
</tr>
<tr>
<td>SSE with dist.</td>
<td>0.05 ± 0.0059</td>
<td>&lt; 9.09 x 10⁻⁴*</td>
</tr>
<tr>
<td>DSE</td>
<td>0.06 ± 0.0067</td>
<td>&lt; 9.09 x 10⁻⁴</td>
</tr>
</tbody>
</table>

View of full shielding partially opened

Scatter plot of SSE and DSE events from measurement with full shielding
SPT setup proposal

Estimation of limit for EC/EC decay of $^{106}$Cd for 1 pair of Timepix quads:

If background = 0:

$$T_{1/2} > (e \cdot t \cdot N_{at} \cdot \ln 2) / \ln (1-CL) = 1.95 \times 10^{20} \text{ years}$$

90% CL $\Rightarrow \ln (1-CL) = 2.3$

e ...... full efficiency (for SPT = 8.54 %)
t ...... time of measurement [years], expected 4 years
$N_{at}$ ... number of $^{106}$Cd atoms in foil, 98% of enrichment
  $\Rightarrow N_{at} = 1.89 \times 10^{21}$ atoms

To reach limit of $10^{21}$ years:

We would need 5-7 quad Timepix pairs

(for 8 gr. we need 25-30 quad pairs)
<table>
<thead>
<tr>
<th>Experiment</th>
<th>nucleus</th>
<th>mass (kg)</th>
<th>status</th>
<th>$T_{1/2}(y)$</th>
<th>$\langle m_\nu \rangle$ meV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>11</td>
<td>current</td>
<td>$5 \times 10^{24}$</td>
<td>230 - 820</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600</td>
<td>in progress</td>
<td>$10^{26}$</td>
<td>50 - 180</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>35</td>
<td>in progress</td>
<td>$1.5 \times 10^{26}$</td>
<td>90 - 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>R&amp;D</td>
<td>$6 \times 10^{27}$</td>
<td>15 - 35</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>$^{76}$Ge</td>
<td>35</td>
<td>in progress</td>
<td>$1.5 \times 10^{26}$</td>
<td>90 - 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>R&amp;D</td>
<td>$6 \times 10^{27}$</td>
<td>15 - 35</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>200</td>
<td>current</td>
<td>$4 \times 10^{25}$</td>
<td>100 - 320</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>R&amp;D</td>
<td>$10^{27} - 10^{28}$</td>
<td>10 - 50</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se</td>
<td>7</td>
<td>in progress</td>
<td>$6.5 \times 10^{24}$</td>
<td>240 – 560</td>
</tr>
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<td></td>
<td></td>
<td>100-200</td>
<td>R&amp;D</td>
<td>$2 \times 10^{26}$</td>
<td>44 – 140</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}$Xe</td>
<td>383</td>
<td>current</td>
<td>$4 \times 10^{25}$</td>
<td>100 – 320</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>R&amp;D</td>
<td>$6 \times 10^{26}$</td>
<td>25 – 80</td>
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<tr>
<td>SNO+</td>
<td>$^{130}$Te</td>
<td>600</td>
<td>in progress</td>
<td>$10^{26}$</td>
<td>50 - 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8000</td>
<td>R&amp;D</td>
<td>$10^{27}$</td>
<td>15 - 60</td>
</tr>
</tbody>
</table>
Neutrinoless double beta decay could provide for us:
- Lepton number non-conservation
- Nature of neutrino mass (Dirac or Majorana?)
- Absolute mass scale (value or limit on $m_1$)
- Type of hierarchy (normal, inverted, quasi-degenerated)
- CP violation in the lepton sector

There is a hope to reach sensitivity to $<m_\nu>$ on the level $\sim (0.01-0.05)\ eV$ in 2020-2025 (Degenerate: can be tested; Inverted: maybe it can be tested; Normal: inaccessible, new approach is needed)

Present status (simplified): experiments with <10 kg of enriched isotopes are finished (precise detection of $2\nu\beta\beta$, $0\nu\beta\beta \sim 100\ meV$)
Present generation – $\sim 100\ kg$ of enriched isotopes are running or under construction ($10^{26}\ years$), reasonable teams and detector dimension.
Problems: background ($\sim \mu\text{Bq/kg}$), enrichment of isotopes in big amount, not big enough (we need 1 ton experiment)
Conclusion:

- Significant progress in 2νββ decay (NEMO 3, EXO, GERDA, …)
- Present limit for \( <m_\nu> \) is \( \sim 100 \) meV
- 4 running experiments (GERDA-I, EXO-200, KamLAND-Zen, CUORE-0)
- 2015-2016 new experiments are expected to start (SuperNEMO 1. module, GERDA-II, Majorana-demonstrator, CUORE, SNO+)

For 1 ton detectors (10 meV region) – we need “improved or new” detection techniques and methods for more effective suppression of background

- to investigate different isotopes (3-4)
- to use different experimental techniques
Cuore Experiment

$\rightarrow^{130}\text{Te}$

$Q_{\beta\beta} = 2530$ keV

$\sim 34\%$ natural abundance

Detector: array of 62 5x5x5 cm$^3$ TeO$_2$ bolometers @ $\sim 10$ mKelvin

Energy resolution: 0.28% @ Qvalue

Location: LNGS (Italy)
$2\nu\beta\beta$ decay:

$$\left[T^{2\nu\beta\beta}_{1/2}\right]^{-1} = G_{2\nu} |M_{GT}^{2\nu\beta\beta}|^2$$

$G_{2\nu}$ - phase space integral
$M_{GT}^{2\nu\beta\beta}$ - nuclear structure matrix element

$0\nu\beta\beta$ decay (mass mechanism):

$$\left[T^{0\nu\beta\beta}_{1/2}\right]^{-1} = G_{0\nu} |\langle m_\nu \rangle|^2 |M_{m_\nu}^{0\nu\beta\beta}|^2$$

$G_{0\nu}$ - phase space integral
$M_{m_\nu}^{0\nu\beta\beta}$ - nuclear structure matrix element. Note: $M_{m_\nu}^{0\nu\beta\beta} \neq M_{GT}^{2\nu\beta\beta}$
$\langle m_\nu \rangle$ - effective Majorana neutrino mass

⇒ Phase space can be calculated “easily”

⇒ Uncertainty completely dominated by $M_{GT}^{2\nu\beta\beta}, M_{m_\nu}^{0\nu\beta\beta}$
CUORE (Gran Sasso)

Cryogenic Underground Observatory for Rare Events
Closely packed array of 988 TeO$_2$ crystals 5×5×5 cm$^3$ (750 g)
741 kg TeO$_2$ granular calorimeter
600 kg Te = 203 kg $^{130}$Te

- Single high granularity detector

Beginning of measurements ~ 2015

CUORE-0 is operated in Gran Sasso now
Towards 1TGe

- Modules of $\text{enrGe}$ housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total $\sim$40 kg (up to 30 kg enr.) - 2015

- ‘Bare’ $\text{enrGe}$ array in liquid argon
- Shield: high-purity liquid Argon / H$_2$O
- Phase I (2011): $\sim$18 kg (HdM/IGEX diodes)
- Phase II (2015): add $\sim$20 kg new detectors - Total $\sim$35 kg

Joint Cooperative Agreement:

- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention is to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA

1 t detector: $\sim$ 2020-2025
Overall mass: 5 tonnes, 90% enriched $^{136}\text{Xe}$

Time Projection Chamber (TPC)

Location: SNOLAB (Canada)

Running time: 10 years

Energy resolution: 2.35% (FWHM)

Sensitivity: $\sim 4 \times 10^{27}$ yr (without Ba)  
$\sim 2 \times 10^{28}$ yr (with Ba)

Design still not finalized

Start of data taking ~ 2025
SNO+

Reuse of SNO equipment with Liquid Scintillator in the Acrylic Vessel (Energy resolution is $\sim 10.5\%$ (FWHM) at 2.5 MeV)

Original plan: $^{150}\text{Nd}$

Current plan: $^{130}\text{Te}$ (using natural Te)
- good Te solubility is demonstrated (0.3-3%)
- 34.5% vs 5.6% natural abundance

Scintillator fill in 2015

Initially 0.3% loading ($\sim 800$ kg of $^{130}\text{Te}$; maybe increased)

Sensitivity is $\sim 10^{26}$ yr (Phase I)
$\sim 10^{27}$ yr (Phase-II)

Start of data taking in $\sim 2016$
There are many experiments on the search for $0
\nu\beta\beta$ of different nuclei. The process was not observed. Very large lower bounds for half-lives were obtained

Some recent data

**EXO-200.**

$T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.1 \cdot 10^{25}$ y (90\% CL) \quad |m_{\beta\beta}| < (1.9 - 4.5) \cdot 10^{-1}$ eV

**KamLAND-Zen**

$T^{0\nu}_{1/2}(^{136}\text{Xe}) > 2.6 \cdot 10^{25}$ y (90\% CL) \quad |m_{\beta\beta}| < (1.4 - 2.8) \cdot 10^{-1}$ eV

**GERDA, Heidelberg-Moscow, IGEX**

$T^{0\nu}_{1/2}(^{76}\text{Ge}) > 3.0 \cdot 10^{25}$ y (90\% CL) \quad |m_{\beta\beta}| < (2 - 4) \cdot 10^{-1}$ eV

$|m_{\beta\beta}|$ can be predicted only if we make assumption about neutrino spectrum. If there is the inverted hierarchy ($m_3 \ll m_1 < m_2$) and neutrinos are Majorana particles from oscillation data it follows

$|m_{\beta\beta}| \simeq$ a few $\cdot 10^{-2}$ eV

Next experiments on the search for $0\nu\beta\beta$ are planned to reach this region.
**Future plans:**

1. Continuation of the measurement with enriched $^{106}$Cd (2vEC/EC decay on the level $10^{21}$ yrs.)

2. Conceptual design study (MC, theoretical calculations, background study) –
   a) the possibility to measure 2vEC/EC decay with other isotopes ($^{162}$Er, $^{156}$Dy) V.Ceron, J.Hirsch, arXiv:nucl-th/9911021v1
   b) the study of the possibility to measure 0vEC/EC decay ($^{152}$Gd g.s., $^{112}$Sn exc. state – resonance enhancement of the 0vEC/EC process if $Q - Q_r < 1$ keV)
   Z.Sujkowski, S.Wycech, Phys. Rev. C70, 052501, 2004

   **signature** – X-rays $< 100$ keV + $\gamma$ or $e^- e^+$ or Majoron

   **advantage**: good value of the rates between 0vEC/EC and 2vEC/EC processes

3. Pixel detectors (Si or Ge) in EC/EC decay – thickness between 300 $\mu$m-1 mm (coincidence measurement, position of detection, energy of X-ray)
Table I: present results on neutrinoless DBD

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Experiment</th>
<th>%</th>
<th>Q_{BB}</th>
<th>Enrich</th>
<th>Technique</th>
<th>T_{0\nu} (y)</th>
<th>&lt;m_\nu&gt;</th>
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<tr>
<td>48Ca</td>
<td>Elegant IV</td>
<td>0.19</td>
<td>4271</td>
<td></td>
<td>scintillator</td>
<td>&gt;1.4x10^{22}</td>
<td>20-28</td>
</tr>
<tr>
<td>76Ge</td>
<td>IGEX</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>Ionization</td>
<td>&gt;1.6x10^{25}</td>
<td>.23 – .64</td>
</tr>
<tr>
<td>76Ge</td>
<td>Klapdor et al</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>ionization</td>
<td>1.2x10^{25}</td>
<td>.29-.81</td>
</tr>
<tr>
<td>82He</td>
<td>NEMO 3</td>
<td>9.2</td>
<td>2995</td>
<td>97</td>
<td>tracking</td>
<td>&gt;1.0x10^{23}</td>
<td>1.7-4.5</td>
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<td>100Mo</td>
<td>NEMO 3</td>
<td>9.6</td>
<td>3034</td>
<td>95-99</td>
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<td>&gt;1x10^{24}</td>
<td>.46-1.1</td>
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<td>116Cd</td>
<td>Solotvina</td>
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<td>3034</td>
<td>83</td>
<td>scintillator</td>
<td>&gt;1.7x10^{23}</td>
<td>1.2 – 2.7</td>
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<td>128Te</td>
<td>Bernatovitz</td>
<td>34</td>
<td>2529</td>
<td></td>
<td>geochem</td>
<td>&gt;7.7 x 10^{24}</td>
<td>.82-1.9</td>
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<td>130Te</td>
<td>Cuoricino</td>
<td>33.8</td>
<td>2529</td>
<td></td>
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<td>&gt;2.8 x10^{24}</td>
<td>.3-.7</td>
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<td>136Xe</td>
<td>DAMA</td>
<td>8.9</td>
<td>2476</td>
<td>69</td>
<td>scintillator</td>
<td>&gt;1.2x10^{24}</td>
<td>.64-1.6</td>
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<td>150Nd</td>
<td>Irvine</td>
<td>5.6</td>
<td>3367</td>
<td>91</td>
<td>tracking</td>
<td>&gt;1.2x10^{21}</td>
<td>14 - ?</td>
</tr>
</tbody>
</table>

EXO $T_{1/2}^{0\nu} (136\text{Xe}) > 1.6 \times 10^{25}$ yr $<m_\nu> 140–380$ meV
KAMLAND-ZEN $> 3.4 \times 10^{25}$ yr $<m_\nu> 120-250$
GERDA I $^{76}\text{Ge}$ to be filled by S. Shoenert
CUORE0 (New) $^{130}\text{Te} > 4 \times 10^{24}$ yr $<m_\nu> 270-760$
Range of half-lives preferred at 90% C.L. by the 0νββ claim of evidence compared with the 90% exclusion limits placed by other experiments.

The comparison involves the NME and their errors as well as their correlations.
KamLAND2-Zen project

1st phase  enriched Xe 400kg (2011)
R=1.7m balloon
V=20.5m³, S=36.3m²
LS : C₁₀H₁₂(81.8%)+PC(18%)
+PPO+Xe(~2.5wt%)
ρLS : 0.78kg/ℓ
high sensitivity with low cost

tank opening (2015)

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

Beginning of measurements with 1000 kg - after 2017
2νββ-decay NMEs

\[
\frac{1}{T_{1/2}^{2ν-exp}} = G^{2ν}(E_0, Z) \ g_A^A \ |M^{2ν}_{GT}|^2
\]

Why the spread of the 2νββ NMEs is large and of the 0νββ NMEs is small?

Are both type of NMEs related?

Differences among 2νββ-decay NMEs: up to factor 10
IBM: Interacting Boson Model (F. Iachello)

Is there a connection between $0\nu\beta\beta$- and $2\nu\beta\beta$-decay NME?

$0\nu\beta\beta$-decay half-life

$m_{\beta\beta}=50$ meV
The $0\nu\beta\beta$-decay NMEs (Status: 2015)

Nobody is perfect:

Systematic errors – Calculations can be improved

Differences:
1) mean field;
2) residual int.;
3) size of the m.s.
4) many-body appr.

LSSM (small m.s., negative parity states)
PHFB (GT force neglected)
IBM (Hamiltonian truncated)
(R)QRPA (g.s. correlations not accurate enough)
$^{100}$Mo $2\beta2\nu$: Experimental Study of SSD Hypothesis

Single electron spectrum different between SSD and HSD

Šimkovic, Šmotláč, Semenov

NEMO 3 exp.

$4.57 \text{ kg.y}$
$E_1 + E_2 > 2 \text{ MeV}$

$\chi^2/\text{ndf} = 139. / 36$

$\chi^2/\text{ndf} = 40.7 / 36$

$^{100}$Mo $2\beta2\nu$ single energy distribution in favour of Single State Dominant (SSD) decay

$T_{1/2} = 8.61 \pm 0.02 \text{ (stat)} \pm 0.60 \text{ (syst)} \times 10^{18} \text{ y}$

$T_{1/2} = 7.72 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y}$
From NEMO to SuperNEMO

NEMO-3 successful experience allows to extrapolate tracko-calor technique on larger mass next generation detector to reach new sensitivity level.

\[ T_{1/2}^{0\nu}(y) \propto \frac{a \varepsilon}{W} \times \sqrt{\frac{M \times t}{N_{BGR} \times \Delta E}} \]

### NEMO-3

- **100Mo, 7kg**
- **208Tl**: < 20 μBq/kg
- **214Bi**: < 300 μBq/kg
- 8%
- 8% @ 3 MeV
- \( T_{1/2} > 2 \times 10^{24} \text{ y} \)
- \( <m_{\nu}> < 0.3 - 0.8 \text{ eV} \)

### SuperNEMO

- **82Se, 100-200 kg**
- **208Tl**: < 2 μBq/kg
- **214Bi**: < 10 μBq/kg
- 30%
- 4% @ 3 MeV
- \( T_{1/2} > 1-2 \times 10^{26} \text{ y} \)
- \( <m_{\nu}> < 40 - 100 \text{ meV} \)

**SUPERNEMO R&D was finished, 1st module in 2016**