From Baksan to ->

A. Smolnikov

International Session-Conference of RAS "Physics of fundamental interactions" dedicated to 50th anniversary of Baksan Neutrino Observatory, Nalchik, Russia, June 6-8, 2017
to worldwide experiments searching for neutrinoless double beta decay

A. Smolnikov

International Session-Conference of RAS "Physics of fundamental interactions“
dedicated to 50th anniversary of Baksan Neutrino Observatory, Nalchik, Russia, June 6-8, 2017
Dedicated to the memory of the first Director of Baksan Neutrino Observatory

Alexander Alexandrovich Pomansky
Double Beta Decay

- DBD unique tool to study neutrino properties:
  - Majorana vs. Dirac, mass scale, hierarchy, CP phases

**2νββ:** \((A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e\)

**0νββ:** \((A, Z) \rightarrow (A, Z+2) + 2e^-\)

(Observed for several nuclei, test of nuclear matrix elem. calculations)

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

\[
m_{ee} = \left| \sum_i U_{ei} \right|^2 m_i
\]
$0\nu\beta\beta$ 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** ($\sim Q_{bb}^5$)
- **Nuclear matrix element**
- **Effective Majorana neutrino mass**

$$Q = E_{e1} + E_{e2} - 2m_e$$

$$\langle m_{\beta\beta} \rangle = \left| \sum_j m_j U_{e j}^2 \right| = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_1} + m_3 |U_{e3}|^2 e^{i\alpha_2}$$

- $U_{ei}$ (complex) neutrino mixing matrix
- $\alpha_{1,2}$ - complex CP-violating Majorana phases

coherent sum
$0\nu\beta\beta$ 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
(-$Q_{bb}^5$)

Nuclear matrix element

Effective Majorana neutrino mass

$Q = E_{e1} + E_{e2} - 2m_e$

$$\langle m_{\beta\beta} \rangle = \left| \sum_j m_j U_{e j}^2 \right| = m_1 |U_{e1}|^2.$$ 

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

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

The effective mass

$m_{ee} |e^{2i\beta} | \quad m_{ee} |e^{2i\alpha}$

$m_{ee} |$
9 physical parameters in neutrino mass matrix $m_\nu$

- $\theta_{12}$ and $m_{22} - m_{21}$
- $\theta_{23}$ and $|m_{23} - m_{22}|$
- $\theta_{13}$ (or $|U_{e3}|$)
- $m_1, m_2, m_3$
- $\text{sgn} \ (m_{33} - m_{22})$
- Dirac phase $\delta$
- Majorana phases $\alpha$ and $\beta$ (or $\alpha_1$ and $\alpha_2$, or $\phi_1$ and $\phi_2$, or ...)


$\text{0νββ} \rightarrow 7 \text{ out of 9 parameters of neutrino mass matrix!}$

$$\mathcal{L} = \frac{1}{2} \nu^T m_\nu \nu \quad \text{with} \quad m_\nu = U \text{diag}(m_1, m_2, m_3) U^T$$

where

$$U = \begin{pmatrix}
    c_{12} c_{13} & s_{12} c_{13} & s_{12} e^{-i\delta} \\
    -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} \\
    s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13}
\end{pmatrix} P$$

with $P = \text{diag}(e^{i\alpha}, e^{i\phi}, 1)$

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

$\Rightarrow$ 3 angles, 3 phases, 3 masses
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?

2$\nu\beta\beta$
Neutrino accompanied Double-Beta Decay:

\[ n \rightarrow p e^- e^- \]
\[ n \rightarrow p W^- \overline{\nu}_e \overline{\nu}_e \]
\[ n \rightarrow p W^- \overline{\nu}_e \nu_e \]
\[ \Delta l = 0 \]

0$\nu\beta\beta$
Neutrinoless Double-Beta Decay:

\[ n \rightarrow p e^- e^- \]
\[ \nu_e = \overline{\nu}_e \]
\[ \Delta l = 2 \]

Light neutrino exchange

Energy [a.u.]

\[ A = 76 \]

\[ Z \]

\[ dN/dE \]

Arbitrary Units

1% resolution

Summed $\beta$ Eneray [MeV]
What we should observe in experiments?

Angular distribution

Ee₁ – Ee₂ distribution

Mass vs Right-Handed Current mechanism

Decay to Excited States

\[(A, Z) \rightarrow (A, Z+2) + 2 \text{e}^- + 1,2 \gamma\]

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

Identification of daughter nucleus:

\[\text{Xe} \rightarrow \text{Ba}^{++} + 2 \text{e}^-\]
The experimental challenge

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

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 (\( M \cdot T \)),

\( e \) detection efficiency
\( A \) isotopic abundance
\( M \) active target mass
\( T \) measuring time
\( b \) background rate (cts/(keV kg yr))
\( \Delta E \) energy resolution

Controversy V. Egorov, JINR
Baksan Neutrino Observatory
since 1967 ->
50 years anniversary in 2017

Muon Flux (cm^{-2} s^{-1})

A - Scintillator Telescope
B - Gallium-Germanium Neutrino Telescope
D-1, D-2, D-3 - Low Background Chambers
D-3 - Deep Low Background Lab

Baksan river

Global Intensity
\((3.0 \pm 0.15) \times 10^{-9} \text{ cm}^{-2} \cdot \text{s}^{-1}\)
\sim 4800 \text{ m.w.e.}
IGEX / Baksan Phase

Searching for $0\nu\beta\beta$ decay of Ge-76
*in the Laboratory for Low Background Experiments*

BNO INR RAS

First Underground Low Background Facility
*in operation from 1973 -> up to now*

IGEX-Baksan set-up
*in operation from 1991 -> up to now*

A.A.Klimenko, S.B.Osetrov, A.A.Smolnikov, S.I.Vasilyev,
"BAKSAN PHASE OF THE IGEX" Proc. Int. School "PARTICLES AND

F.T.Avignone, R.L.Brodzinski, A.A.Klimenko, S.B.Osetrov,
A.A.Pomansky, A.A.Smolnikov, S.I.Vasilyev et al., Status report on
At the end of the 20th century the IGEX and Heidelberg-Moscow $^{76}$Ge experiments not only yield the best current bounds on $m_\nu$, they also provided most of the technology needed in future $^{76}$Ge experiments.

$6.8 \text{ kg of enriched in } ^{76}\text{Ge detectors, 8.5 kg x yrs of data, 0.17 counts/(kg keV y) around 2040 keV}$

$T_{1/2} \geq 1.6 \times 10^{25} \text{ years (90\% C.L.)}$

Aalseth et al., Phys. Rev. D 09, 2002
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.
Results of GERDA Phase I


$T_{1/2} > 2.1 \times 10^{25}$ years
GERDA Phase II – started Dec 2015

7 strings of HPGe detectors deployed:
37 detectors enriched in 76Ge (35.8 kg)
3 natural detectors (7.6 kg)

For details see talk given by A.Luboshevskiy
Liquid Argon veto for GERDA Phase II

LAr veto

9 off 3” PMTs

copper shroud lined with reflecting TPB coated Tetratex

GERmanium Detector Array

7 off 3” PMTs

TPB coated fiber shroud with SiPMs
The best fit yields zero signal events and a 90% C.L. limit of 2.0 events in 34.4 kgyr total exposure or $T_{1/2} > 5.3 \times 10^{25}$ yr.

GERDA-Phase II: first background-free $0\nu\beta\beta$ experiment

---

**Phase I achievements**

- **background**: \(~10^{-2} \text{ cts/(keV} \cdot \text{ kg} \cdot \text{ yr)}\)
- **exposure**: \(21.5 \text{ kg} \cdot \text{ yr}\)
- **limit**: \(T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr (90\% CL)}\)


**first Phase II achievements**

- **background**: \(~10^{-3} \text{ cts/(keV} \cdot \text{ kg} \cdot \text{ yr)}\)
- **exposure**: \(10.8 \text{ kg} \cdot \text{ yr (34.4 kg} \cdot \text{ yr)}^*\)
- **limit**: \(T_{1/2}^{0\nu} > 5.3 \cdot 10^{25} \text{ yr (90\% CL)}\)

\[m_{\beta\beta} < 0.15 - 0.33 \text{ eV (90\% CL)}\]


**Phase II goals**

- **background**: \(~10^{-3} \text{ cts/(keV} \cdot \text{ kg} \cdot \text{ yr)}\)
- **exposure**: \(\geq 100 \text{ kg} \cdot \text{ yr}\)
- **sensitivity**: \(T_{1/2}^{0\nu} \geq 10^{26} \text{ yr}\)
**LEGEND (Large Enriched Germanium Experiment for Neutrinoless \(\beta\beta\) Decay)**

- **LEGEND** (Large Enriched Germanium Experiment for Neutrinoless \(\beta\beta\) Decay) collaboration has been formed in October 2016
  - 219 members, 48 institutions, 16 countries
  - www.legend-exp.org

**LEGEND goals**

- background: \(~10^{-4}\text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})\)
- detector mass: \(O(1)\)
- discovery potential: \(T_{1/2} > 10^{27}\text{ yr}\)
- first stage: 200 kg in upgrade of existing infrastructure at LNGS

---

**First stage:**

- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- bkg reduction by factor 3-5 w.r.t GERDA

**Subsequent stages:**

- 1000 kg (staged)
- timeline connected to DOE down select process
- Bgd factor 30 w.r.t GERDA
- Location tbd
- Required depth (Ge-77m) under investigation

---

S. Schönert (TUM): GERDA Phase II & LEGEND, XVII NuTel, Venice 15.
IGEX / Baksan Phase

Searching for $2\nu\beta\beta$ and $0\nu\beta\beta$ decay of Ge-76 to excited states of 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].

Data from 228 days of measurements performed with four HPGe detectors in the low background laboratory of the Baksan Neutrino Observatory (BNO) yield a new limits on half-lives: $T_{1/2}(0^+ \rightarrow 0^+_1, 2\nu) \geq 6.2 \times 10^{21}$ yr at 90 % C.L., $T_{1/2}(0^+ \rightarrow 0^+_1, 0\nu) \geq 4.7 \times 10^{22}$ yr at 90 % C.L. for transition of $^{76}$Ge to $0^+_1$ level

Two neutrino double beta decay of $^{76}$Ge to excited states of $^{76}$Se has been studied using data from Phase I of the GERDA experiment.

An array composed of up to 14 germanium detectors made from isotopically enriched in $^{76}$Ge was deployed in liquid argon. The analysis is based on coincidence events between pairs of detectors.

No signal has been observed and an event counting profile likelihood analysis has been used to determine 90% C.L. bounds for three transitions:

- $0^+_{\text{g.s.}} \rightarrow 2/1^+$: $T_{1/2} > 1.6 \times 10^{23}$ yr,
- $0^+_{\text{g.s.}} \rightarrow 0/1^+$: $T_{1/2} > 3.7 \times 10^{23}$ yr,
- $0^+_{\text{g.s.}} \rightarrow 2/2^+$: $T_{1/2} > 2.3 \times 10^{23}$ yr,

These bounds are more than two orders of magnitude larger than those reported previously.

Searching for $0\nu\beta\beta$ decay of Nd-150 to excited states of Se-76

Table 1: Limits on half-lives of $^{150}\text{Nd}$ and $^{76}\text{Ge}$, compared to $^{150}\text{Sm}(0^+_1)$

<table>
<thead>
<tr>
<th>$\beta\beta$ transition</th>
<th>$T_{1/2}$, yr, this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{150}\text{Nd}(2\nu + 0\nu)^{150}\text{Sm}(0^+_1)$</td>
<td>$\geq 1.5 \times 10^{20}$ (90% C.L.)</td>
</tr>
<tr>
<td>$^{76}\text{Ge}(2\nu)^{76}\text{Se}(0^+_1)$</td>
<td>$\geq 6.2 \times 10^{21}$ (90% C.L.)</td>
</tr>
<tr>
<td>$^{76}\text{Ge}(0\nu)^{76}\text{Se}(0^+_1)$</td>
<td>$\geq 4.7 \times 10^{22}$ (90% C.L.)</td>
</tr>
</tbody>
</table>

Available experimental techniques:

Ionization detectors, Scintillation detectors, Time Projection Chambers, Cryogenic bolometers, ...

Calorimeter
- Ge diode $\epsilon, \Delta E$ $^{76}$Ge
- Bolometers $\epsilon, \Delta E$ $^{130}$Te, $^{82}$Se, $^{100}$Mo
- Liquid Xe $\epsilon, M (N_{bbkd})$ $^{136}$Xe
- Scintillator $\epsilon, M$ $^{136}$Xe, $^{48}$Ca, $^{150}$Nd, $^{100}$Mo

Tracker
- Tracko-calor $N_{bbkd}$, isotopes $^{82}$Se ($^{150}$Nd, $^{48}$Ca)
- Pixelized CdZnTe $\epsilon, N_{bbkd}$ $^{116}$Cd
- TPC $\epsilon, N_{bbkd}$ $^{136}$Xe, $^{150}$Nd

Multilevel
- KamLAND-Zen CANDLES SNO+ Borexino CdWO4 AMoRE
- TGV -2 TGV -3

SuperNEMO
- COBRA
- NEXT

CUORE LUCIFER ZnMo4
- EXO

GERDA MAJORANA
Presently used isotopes

No favorite isotope / experimental techniques

Several experiments using different isotopes and methods are needed
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Technique</th>
<th>Mass $\beta\beta(0\nu)$ isotope</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORiCINO</td>
<td>130Te</td>
<td>TeO$_2$ Bolometer</td>
<td>10 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>NEMO3</td>
<td>100Mo/82Se</td>
<td>Foils with tracking</td>
<td>6.9/0.9 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>GERDA I</td>
<td>76Ge</td>
<td>Ge diodes in LAr</td>
<td>15 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>EXO200</td>
<td>136Xe</td>
<td>Xe liquid TPC</td>
<td>160 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>KamLAND-ZEN</td>
<td>136Xe</td>
<td>2.7% in liquid scint.</td>
<td>380 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>CUORE-0</td>
<td>130Te</td>
<td>TeO$_2$ Bolometer</td>
<td>11 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>GERDA II</td>
<td>76Ge</td>
<td>Point contact Ge in LAr</td>
<td>15+30 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>Majorana D</td>
<td>76Ge</td>
<td>Point contact Ge</td>
<td>30 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>CUORE</td>
<td>130Te</td>
<td>TeO$_2$ Bolometer</td>
<td>206 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>SNO+</td>
<td>130Te</td>
<td>0.3% natTe suspended in Scint</td>
<td>55 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>136Xe</td>
<td>High pressure Xe TPC</td>
<td>80 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>SuperNEMO D</td>
<td>82Se</td>
<td>Foils with tracking</td>
<td>7 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>CANDLES</td>
<td>48Ca</td>
<td>305 kg of CaF$_2$ crystals - liq. scint.</td>
<td>0.3 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>LUCIFER</td>
<td>62Se</td>
<td>ZnSe scint. bolometer</td>
<td>18 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>1T Ge - LEGEND</td>
<td>76Ge</td>
<td>Best technology from GERDA and MAJORANA</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>CUPID</td>
<td>-</td>
<td>Hybrid Bolometers</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>nEXO</td>
<td>136Xe</td>
<td>Xe liquid TPC</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>82Se</td>
<td>Foils with tracking</td>
<td>100 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>AMoRE</td>
<td>100Mo</td>
<td>CaMoO$_4$ scint. bolometer</td>
<td>50 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>MOON</td>
<td>100Mo</td>
<td>Mo sheets</td>
<td>200 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>COBRA</td>
<td>116Cd</td>
<td>CdZnTe detectors</td>
<td>10 kg/183 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>CARVEL</td>
<td>48Ca</td>
<td>48CaWO$_4$ crystal scint.</td>
<td>~ tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>DCBA</td>
<td>150Nd</td>
<td>Nd foils &amp; tracking chambers</td>
<td>20 kg</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>

*Table adopted from presentation of O.Cremonesi at TAUP-2015*
<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Technique</th>
<th>Mass</th>
<th>$T^{0\nu}_{1/2}$ (90%) limit [$\text{y}$]</th>
<th>$m_{\beta\beta}$ limit [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>CANDLES</td>
<td>Scintillation</td>
<td>0.01 kg</td>
<td>$&gt; 5.8 \times 10^{22}$</td>
<td>$&lt; 3.55 - 9.91$</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>GERDA I+II-A</td>
<td>Ionisation</td>
<td>17/36 kg</td>
<td>$&gt; 5.3 \times 10^{25}$</td>
<td>$&lt; 0.14 - 0.33$</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>NEMO-3</td>
<td>Tracko-calorimeter</td>
<td>930 g</td>
<td>$&gt; 3.2 \times 10^{23}$</td>
<td>$&lt; 0.85 - 2.08$</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>NEMO-3</td>
<td>Tracko-calorimeter</td>
<td>9.43 g</td>
<td>$&gt; 9.2 \times 10^{21}$</td>
<td>$&lt; 3.97 - 14.4$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>NEMO-3</td>
<td>Tracko-calorimeter</td>
<td>6.9 kg</td>
<td>$&gt; 1.1 \times 10^{24}$</td>
<td>$&lt; 0.33 - 0.62$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>Solotvina</td>
<td>Scintillation</td>
<td>80 g</td>
<td>$&gt; 1.7 \times 10^{23}$</td>
<td>$&lt; 1.22 - 2.30$</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>CUORE-0+cino</td>
<td>Bolometer</td>
<td>$\sim 20$ kg</td>
<td>$&gt; 4.0 \times 10^{24}$</td>
<td>$&lt; 0.23 - 0.48$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>EXO-200</td>
<td>Liquid TPC</td>
<td>$\sim 110$ kg</td>
<td>$&gt; 1.1 \times 10^{25}$</td>
<td>$&lt; 0.17 - 0.43$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>KamLAND-Zen</td>
<td>Scintillation</td>
<td>$\sim 500$ kg</td>
<td>$&gt; 1.1 \times 10^{26}$</td>
<td>$&lt; 0.06 - 0.161$</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>NEMO-3</td>
<td>Tracko-calorimeter</td>
<td>36.5 g</td>
<td>$&gt; 2.0 \times 10^{22}$</td>
<td>$&lt; 2.23 - 8.21$</td>
</tr>
</tbody>
</table>
Majorana Demonstrator

started in 2015

$^{76}$Ge offers an excellent combination of capabilities & sensitivities. (Excellent energy resolution, intrinsically clean detectors, commercial technologies, best 0νββ 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 0νββ 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.)
EXO-200 Experiment

200 kg liquid Xenon TPC at WIPP under 1585 m.w.e.

Ionization and 178 nm scintillation

Calorimeter with 3D position and single-site (SS) or multi-sites (MS) events distinction

~110 kg of LXe active volume

Xe enrichment at 80.7 % in $^{136}$Xe
Based on the successful operation of EXO-200

~ 5,000kg LXe detector
1.3 × 1.3 m cylinder TPC
~ 1% energy resolution
pre-conceptual stage
based at SNOLAB

For details -> Talk by V.Belov
For details -> Talk by Yu.Efremenko

KamLAND-Zen
Phase 1

2011 2012 2013

KamLAND-Zen
Phase 2

2014 2015 2016

KamLAND-Zen2

2017 2018 2019 2020

KamLAND2-Zen?

202?

MIB: \(~ \Phi 3.12 m\)

Livetime 112.3 days,
\(^{136}\)Xe \(~ 320\)kg (91%)
FV: \(^{136}\)Xe 125 kg.

Livetime > 600 days?

\(^{136}\)Xe \(~ 383\)kg (91%)

- LS & \(^{136}\)Xe Purification
- More \(^{136}\)Xe

MIB: \(~ \Phi 4 m\)

 Livetime > 600 days?

\(^{136}\)Xe \(~ 700\)kg (91%)

FV: \(^{136}\)Xe 125 kg.

- 2014: KamLAND-Zen w/ lower \(^{110m}\)Ag
  - Just resumed with 380 kg
- 2017: KamLAND-Zen 700 kg
  - with clean mini-balloon
- Future: KamLAND-Zen2
  - high QE PMT
  - high yield LS
  - light concentrator
  - \(\sigma_E(2.6\text{ MeV}) < 2.5\%\)
- Super-KamLAND-Zen

Inverted hierarchy

\(<m_{\beta\beta}> = 50\text{ meV}\)

Next Phase only

\((600 \text{ kg Xe})\)

Phase 2 only

\((383 \text{ kg Xe})\)

Combined

Phase 1

Phase 2

KK claim
conversion from \(^{76}\)Ge half-life with various NME calculations
NEMO 3

Tracking detector: drift chambers (6180 Geiger cells)
\( \sigma_x = 5 \text{ mm}, \sigma_z = 1 \text{ cm} \) (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 MeV] : \( 1.2 \times 10^{-3} \) cts/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

\( E_1 + E_2 = 2088 \text{ keV} \)
\( \Delta t = 0.22 \text{ ns} \)
(A vertex) \( \Delta r = 2.1 \text{ mm} \)

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

\( ^{100}\text{Mo} \)
\( T_{1/2} (\beta\beta0\nu) > 1.0 \times 10^{24} \text{ y} \) (90% C.L.)
\( \langle m_\tau \rangle < 0.31 - 0.79 \text{ eV} \)
Super NEMO Demonstrator
Design

- Ultra low background detector
- Modular detector with 3 main components:
  - Central source foil frame: 7 kg of isotope
  - Tracking: 2000 drift chambers
  - Calorimeter: 712 scintillators + PMTs
- Shielded by iron (300 tons) and water
- Installed at LSM (Modane Underground Laboratory – 4800 m.w.e.)

Plan to start in 2017
Cryogenic Underground Observatory for Rare Events

CUORE detector
- 988 TeO₂ crystals run as a bolometer array
  - 5x5x5 cm³ crystal, 750 g each
- 19 Towers; 13 floors; 4 modules per floor
  - 741 kg total - 206 kg ¹³⁰Te
  - 10^{27} ¹³⁰Te nuclei
- Excellent energy resolution of bolometers
- Radio-pure material and clean assembly to achieve low background at ROI
  - strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
  - transportation at sea level to LNGS
  - bolometric test to check performances and radio-purity
  - TECM protocol (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) for copper surface cleaning
  - limited exposure to cosmic rays: underground storage of the copper parts in between production and cleaning

Complex cryogenic set-up
- Fully cryogen-free system:
  - custom cryostat
  - 5 pulse tubes
  - a powerful dilution refrigerator and
  - ~10 mK operating temperature
- Independent suspension of the detector array
- An embedded detector calibration system
- Radio-pure materials
- Heavy low temperature shield
CUORE Upgrade with Particle IDentification to further reduce backgrounds with $\beta/\gamma - \alpha$ PSD and investigate the IH band.

Scintillating bolometers: TeO$_2$, ZnMoO$_4$, ZnSe, CdWO$_4$  

R&D with Lucifer & Lumineu at LSM and LNGS.
AMoRE-Pilot Setup: 2015

AMoRE-pilot: five $^{40}$Ca$^{100}$MoO$_4$ crystals of 1.5kg
(SB28, S35, SS68, SE01, SB29): 5 phonon detectors + 6 photon detectors

Shieldings

External Pb shield with 15 cm

Internal Pb shield with 10 cm

Detector tower

Superconducting magnetic shield made of Pb

Thermal radiation shields made of Cu

SS68 350 g  SB28 196 g  S35 256 g

NSB29 390 g  SE#1 354 g

For details see talk given by Hong Joo Kim
### Nearest future

#### Current experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass [kg] * (total/FV)</th>
<th>FWHM [keV]</th>
<th>Background &amp; [cnt/mol yr FWHM]</th>
<th>$T_{1/2}$ limit $[10^{25} \text{ yr}]$ after 4 yr</th>
<th>$\langle m_{ee} \rangle$ limit [meV]</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerda II</td>
<td>Ge 35/27</td>
<td>3</td>
<td>0.0004</td>
<td>15</td>
<td>80-190</td>
<td>-2019</td>
</tr>
<tr>
<td>MajoranaD</td>
<td>Ge 30/24</td>
<td>3</td>
<td>0.0004</td>
<td>15</td>
<td>80-190</td>
<td>-2019</td>
</tr>
<tr>
<td>EXO-200</td>
<td>Xe 170/80</td>
<td>88</td>
<td>0.03</td>
<td>6</td>
<td>80-220</td>
<td>-2019</td>
</tr>
<tr>
<td>Kamland-Zen</td>
<td>Xe 383/88 (600/?)</td>
<td>250</td>
<td>0.03</td>
<td>20</td>
<td>44-120</td>
<td>-2018</td>
</tr>
<tr>
<td>NEXT</td>
<td>Xe 100/80</td>
<td>17</td>
<td>0.0036</td>
<td>6</td>
<td>100-200</td>
<td>-2020</td>
</tr>
<tr>
<td>Cuore</td>
<td>Te 600/206</td>
<td>5</td>
<td>0.02</td>
<td>9</td>
<td>50-200</td>
<td>-2019</td>
</tr>
<tr>
<td>SNO+</td>
<td>Te 2340/160</td>
<td>270</td>
<td>0.02</td>
<td>9</td>
<td>50-200</td>
<td>-2020</td>
</tr>
</tbody>
</table>

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction) & mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for EXO-200 and Kamland-Zen

Ge experiments have lowest background → similar sensitivity despite small mass
Far future

Proposals for ton scale experiments

Next generation experiment with sensitivities $T_{1/2} \sim 10^{27-10^{28}}$ yr

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>LEGEND (GERDA &amp; MAJORANA)</td>
<td>Large Scale Ge, O(tonne) HPGE crystals</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>SuperNEMO</td>
<td>Se foils, tracking and calorimeter, 100 kg scale</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>nEXO</td>
<td>Liquid TPC, 5 tonnes</td>
</tr>
<tr>
<td></td>
<td>NEXT/BEXT</td>
<td>High pressure gas TPC, tonne scale</td>
</tr>
<tr>
<td></td>
<td>KamLAND2-Zen</td>
<td>$^{136}$Xe in scintillator</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>CUPID</td>
<td>Bolometers with light sensor (also $^{82}$Se, $^{116}$Cd, $^{100}$Mo)</td>
</tr>
<tr>
<td></td>
<td>SNO+ II</td>
<td>$^{130}$Te in scintillator</td>
</tr>
</tbody>
</table>
Many other experimental R&D efforts that can not be discussed in detail:

Lucifer – phonons and scintillation

COBRA – pixelized CdZnTe semiconductor detector,

SuperNEMO – full scale,

SNO+, Moon, DCBA, NEXT,.....
Status: near future

CUORE, MIID, GERDA-II, KamLAND-Zen

IH ($\Delta m_{23}^2 < 0$)

NH ($\Delta m_{23}^2 > 0$)

$\tau_{\nu_\tau} > 10^{26} - 10^{27}$ y
Future challenge
Summary

0νββ experimental strategy during the next decade

- 2011-2016: Recent & current experiments: ~1 eV, few 10 kg-year
- 2017-2021: Quasi-degenerate: ~100 meV, 100 kg-year, 4-6 expts
- 2022-2026: Inverted hierarchy: few 10 meV, several ton-years at least 2 expts
- Very far future?: Normal hierarchy: few meV, ~100 ton-years?

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

100 – 300 kg of $^{136}$Xe

Measure ≥8 DBD isotopes with different techniques; Precision $< m >$ & NME, leading term
New sensitive experiments are starting operation ->
-> new important information is expected

5 experiments have reached \([m_{\beta\beta}] < 1\ eV\) sensitivity with 4 isotopes:
GERDA - EXO - KamLAND-Zen – CUORE - NEMO

Upgrades and new experiments coming to investigate
the inverted hierarchy region of \([m_{\beta\beta}] < 10 - 50\ meV\)