Double beta decay

- First interest in DBD
- Old and new techniques
- Present results
- The future
1935 M. Goeppert-Mayer, P.R. 48 (1935) 512 \ T>10^{20}
1967: \textsuperscript{130}Te, Geochemical Ogata and Takaoka, Kirsten

Source=detector => M. Goldhaber E. Fiorini

1987: \textsuperscript{82}Se, Direct counting Moe et al.
1989 -2008 \textsuperscript{100}Mo, \textsuperscript{116}Cd, \textsuperscript{76}Ge, \textsuperscript{130}Te etc.

DBD and DM (P. Belli)

E. Majorana, Nuovo Cimento 14 (1937) 171

G. Racah, Nuovo Cimento 14 (1937) 322

W.H. Furry Phys. Rev. 56 (1939) 11984

A.S. Barabash: Hystorical review of 75 years of research
arXiv: 1104.2714v2 \{nuc-ex\} 25 April 2011
Double Beta-Disintegration

M. Goeppert-Mayer, The Johns Hopkins University
(Received May 20, 1935)

From the Fermi theory of $\beta$-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over $10^{17}$ years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.
1. \((A,Z) \Rightarrow (A,Z+2) + 2 \, e^- + 2 \, \bar{\nu}_e\)
   Two neutrino double beta decay Allowed by the standard model
   Found in ten nuclei to ground state and in two to excited state

2. \((A,Z) \Rightarrow (A,Z+2) + 2 \, e^- + \chi (\ldots 2,3 \, \chi)\)
   Emission of a massless Goldston boson named Majoron

3. \((A,Z) \Rightarrow (A,Z+2) + 2 \, e^-\)
   Neutrinoless double beta decay. The two electrons share the total
   transition energy \(E_1 + E_2 \Rightarrow \Delta E \Rightarrow \) a peak appers in the sum
   spectrum of the two electrons

Other possible “\(\Delta L=2\)” decays

- Double positron decay \(\Rightarrow \beta^+ \beta^+\)
- Positron decay + Electron Capture \(\Rightarrow \text{EC-} \beta^+\)
- Double electron capture \(\Rightarrow \text{EC-EC}\)
The shape of the two electron sum energy spectrum enables to distinguish among the most relevant decay modes.

- **Two neutrino DBD**
  - Continuum with maximum at ~$1/3 \, Q$

- **Neutrinoless DBD**
  - Peak enlarged only by the detector energy resolution

Additional signatures:
- Single electron energy distribution
- Angular distribution
- Topology
Which is the nature of neutrino and its mass

The second mystery of Ettore Majorana

Teoria simmetrica dell’eletrone e del positrone

Nota di Ettore Majorana

Sunto. — Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell’eletrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di Dirac ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; né a presumere per ogni altro tipo di particelle, particolarmente neutre, l’esistenza di “antiparticelle” corrispondenti ai “vuoti” di energia negativa.
Chi l’ha visto?

Ettore Majorana, ordinario di fisica teorica all’Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Mariantecci, Viale Regina Margherita 66 - Roma.
Neutrinoless double beta decay and *Majorana neutrinos*

\[ \nu \neq \bar{\nu} \]

\[ \nu = \bar{\nu} \]

**Majorana \Rightarrow 1937**

What about the **neutrino mass** \( \Rightarrow <m_\nu> \)?
Neutrino oscillations show that $\Delta(m_1^2 - m_2^2) \neq 0$
What could we expect?

- **Degeneration**: $m_1 \approx m_2 \approx m_3$
- **Inverse Hierarchy**: $m_3 \ll m_1 \approx m_2$
- **Normal Hierarchy**: $m_1 \approx m_2 \gg m_3$

\[
\langle m \rangle = f(m_{\text{low}}, U_{\text{eff}})
\]
From cosmology $\Rightarrow \Sigma m_\nu \sim 1$ eV
From single beta decay

Present $\Rightarrow m_\nu < 2.2 \text{ eV}$

Future (KATRIN) $\Rightarrow m_\nu < .2 \text{ eV}$
0ν-DBD and neutrino physics

how 0ν-DBD is connected to neutrino mixing matrix and masses in case of process induced by mass mechanism

neutrinoless Double Beta Decay rate
Phase space
Nuclear matrix elements
Effective Majorana mass

1/τ = G(Q,Z) \left| M_{\text{nucl}} \right|^2 \left( M_{\beta\beta} \right)^2

what the experimentalists try to measure

what the nuclear theorists try to calculate

\left\langle M_{\beta\beta} \right\rangle = \left| U_{e1} \right|^2 M_1 + e^{i\alpha_1} \left| U_{e2} \right|^2 M_2 + e^{i\alpha_2} \left| U_{e3} \right|^2 M_3 \right|
<table>
<thead>
<tr>
<th>$\beta\beta$ Decay Reaction</th>
<th>Isotopic Abundance [atomic %]</th>
<th>Q-value [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>0.2</td>
<td>4274</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>7.6</td>
<td>2039</td>
</tr>
<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>8.7</td>
<td>2996</td>
</tr>
<tr>
<td>$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$</td>
<td>2.8</td>
<td>3348</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
<td>9.6</td>
<td>3034</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$</td>
<td>7.5</td>
<td>2809</td>
</tr>
<tr>
<td>$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$</td>
<td>5.8</td>
<td>2288</td>
</tr>
<tr>
<td>$^{128}\text{Te} \rightarrow ^{128}\text{Xe}$</td>
<td>31.8</td>
<td>866</td>
</tr>
<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>34.2</td>
<td>2528</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>8.9</td>
<td>2458</td>
</tr>
<tr>
<td>$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$</td>
<td>5.6</td>
<td>3368</td>
</tr>
</tbody>
</table>

**Fig. 1:** Left: Phase space factors including Coulomb corrections for some of the most interesting isotopes, normalise to $^{76}\text{Ge}=1$. Values taken from [4]. Right: Product of phase space and IBM matrix elements [8] as conversion factor of half-lives into neutrino masses. Again the plot is normalised to $^{76}\text{Ge}=1$. 


Calculation is a severe challenge in nuclear structure physics.
- 2 neutrino $\beta\beta$ decay can be described by pure Gamow-Teller transitions through intermediate 1+-states
- neutrinoless mode can occur through other multipoles

Very first approach Primakoff and Rosen: all matrix elements equal.
A silly note by E.F. => the case of 48Ca

Three methods are employed:
- The Shell Model (SM)
- The Quasiparticle Random Phase Approximation (QRPA) with their modifications
- The Interactiong Boson Model (IBM), more recently

Some help can come from experiments, for instance:
=> charge exchange reactions via (d,2He) and (3He,t) linked to the Gamow-Teller strength BGT for 1+-states
=> ft-value measurements of electron capture and beta decay of the intermediate nucleus
Shell model

Uses Pauli principle to describe (1949) nuclear structure in terms of nuclear levels. Nobel prize to E. Wigner, M. Goeppert Mayer and J. Jensen.

Disadvantage => small number of single-particle states outside the inert code which can be included.

Advantage => one can include correlations of arbitrary complexity since they are few.

Started in 1984, but recently calculations have been carried out on various nuclei ($^{48}$Ca, $^{76}$Ge, $^{72}$Se, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{136}$Xe) and attempted on others.

Difficult for deformed nuclei like $^{160}$Nd.
Quasiparticle Random Phase Approximation
(QRPA, RQRPA, pnQRPA)

Includes many single-particle states outside a relatively small inert core. At the beginning considerable difficulties and disagreement with experimental data, in particular for geochemical experiments by one to two order of magnitude.

Explanation on both sides of the Pacific:

Inclusion of the particle-particle interaction in the nucleus allow to evaluate correctly the disagreement with experimental data. However:

$=>$ strong dependance of the rate from $g_{pp}$ (the particle-particle correlation strenght).

How to evaluate $g_{pp}$ ?

$=>$ from two neutrino double beta decay

$=>$ from single beta and EC processes of the intermediate nuclei
The microscopic Interacting Boson Model (IBM)

Introduced many years ago by Arima and F. Iachello in nuclear physics. Recently applied by Iachello and collaborators to Double Beta Decay.

=> protons and neutrons pair essentially acting as a single particle with boson properties with integral spin of 0, 2 or 4.

Seen from the nucleus the process consists in the annihilation of a couple of protons with an angular momentum J in a couple of neutrons with the same angular momentum.

IBM-I treats both type of nucleons the same and considers only pairs of nucleon coupled to an angular momentum of 0 and 2 called s and p.

IMB-II treats protons and neutrons separately.

GT, Fermi and tensor terms are considered

\[ M^{(0\nu)} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_{F}^{0\nu} - M_{T}^{0\nu} \]
Recent calculations by F. Iachello

Table 3: IBM-2 limits on neutrino mass

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2} y$ (^a)</th>
<th>$\langle m_\nu \rangle$ eV</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{76})Ge</td>
<td>&gt;1.9\cdot10^{25}</td>
<td>&lt;0.29</td>
<td>HM</td>
</tr>
<tr>
<td></td>
<td>\approx1.2\cdot10^{25}</td>
<td>\approx0.34</td>
<td>Part of HM</td>
</tr>
<tr>
<td></td>
<td>&gt;1.6\cdot10^{25}</td>
<td>&lt;0.27</td>
<td>IGEX</td>
</tr>
<tr>
<td>(^{82})Se</td>
<td>&gt;2.1\cdot10^{23}</td>
<td>&lt;1.5</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>(^{100})Mo</td>
<td>&gt;5.8\cdot10^{23}</td>
<td>&lt;0.84</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>(^{116})Cd</td>
<td>&gt;1.7\cdot10^{23}</td>
<td>&lt;1.5</td>
<td>SOLOTVINO</td>
</tr>
<tr>
<td>(^{130})Te</td>
<td>&gt;2.4\cdot10^{24}</td>
<td>&lt;0.39</td>
<td>CUORICINO</td>
</tr>
<tr>
<td>(^{136})Xe</td>
<td>&gt;4.5\cdot10^{23}</td>
<td>&lt;1.0</td>
<td>DAMA</td>
</tr>
</tbody>
</table>

\(^a\) From \(^{14}\) and references therein

Reasonable agreement IMB-II with QRPA but disagreement by a factor around 2 with Shell Model.

A considerable effect is due to the parameter $g_A$ (from 1 to 1.2 whose value is squared in the $\beta\beta$ operator
The difference between IBM-2/QRPA and SM still remains an open problem.
Figure 1: Expected $\beta\beta(0\nu)$ half lives for 50 meV effective neutrino mass and different NME calculations: IBM2 [17], YI09 [18], TU08 [19] and SM08 [20].

• ”we find that, unfortunately, current NME uncertainties appear to prevent a robust determination of the relative contribution of each mechanism to the deacy amplitude, even assuming accurate measurement of the decay lifetimes”

A word from a poor experimentalist

\[ \langle m_\nu \rangle \propto \text{NME} \]

limit on \( \langle m_\nu \rangle \) proportional to \( \tau^{-1/2} \)

\( \tau \) proportional to \( i.a \) and to \( M^{1/2} T^{1/2} B^{-1/2} \)

limit on \( \langle m_\nu \rangle \) proportional to \( M^{-1/4} T^{-1/4} B^{1/4} \)
Indirect experiments

Geochemical experiments
$^{82}\text{Se} = > ^{82}\text{Kr}$, $^{96}\text{Zr} = > ^{96}\text{Mo}$ (?), $^{128}\text{Te} = > ^{128}\text{Xe}$ (confirmed), $^{130}\text{Te} = > ^{130}\text{Xe}$

Radiochemical experiments
$^{238}\text{U} = > ^{238}\text{Pu}$

Direct experiments

Source = detector
(calorimetric)

Source $\neq$ detector
Source=detector => first $^{76}\text{Ge}$ experiment
Very rare radioactive processes =&gt; “cosmic silence” is needed.

Underground laboratories
<table>
<thead>
<tr>
<th>Site</th>
<th>Location and access</th>
<th>Current space</th>
<th>Depth and muon flux (μ m⁻² s⁻¹)</th>
<th>Rock and radon (Bq m⁻³)</th>
<th>Neutrons (m⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(WChe)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Europe</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BNO</td>
<td>Andyrychi, Russia; independent tunnel</td>
<td>3 halls: 26×24×16 m²; 60×10×12 m²; 40,000 m³</td>
<td>850 m.w.e. and 4700 m.w.e. (SAGU area); 3.03±0.19×10⁻¹</td>
<td>40;</td>
<td>1.4×10⁻¹ (1 MeV); 6.28×10⁻¹ (2 MeV)</td>
</tr>
<tr>
<td>BUL</td>
<td>Boulby mine, UK; vertical</td>
<td>1,500 m²</td>
<td>2800 m.w.e. under flat surface; 4.5±0.1×10⁻¹</td>
<td>1-2</td>
<td>1.7×10⁻¹ (0.5 MeV)</td>
</tr>
<tr>
<td>CUPP</td>
<td>Pyhasalmi mine, Finland; vertical</td>
<td>&gt;1000 m²</td>
<td>down to 1400 m</td>
<td>pyrite ore, zinc ore</td>
<td></td>
</tr>
<tr>
<td>LNGS</td>
<td>Gran Sasso, Italy; road tunnel</td>
<td>3 halls plus tunnels total: 17,300 m²; 180,000 m³</td>
<td>3200 m.w.e. under mountain; 3×10⁻¹</td>
<td>50-120</td>
<td>3.78×10⁻¹ (total); 0.32×10⁻¹ (2.5 MeV)</td>
</tr>
<tr>
<td>LSC</td>
<td>Canfranc, Spain; road tunnel</td>
<td>2 halls: 40×15×12 m²; 15×10×8 m²; tot 1000 m³</td>
<td>2400 m.w.e. under mountain; 2×10⁻¹ - 4×10⁻¹</td>
<td>50-80</td>
<td>2×10⁻¹</td>
</tr>
<tr>
<td>LSM</td>
<td>Modane, France; road tunnel</td>
<td>1 hall and service areas; 400 m²</td>
<td>4800 m.w.e. under mountain; 4.7×10⁻¹</td>
<td>15;</td>
<td>5.6×10⁻¹ (work in progress)</td>
</tr>
<tr>
<td>SLANIC</td>
<td>Prahova mine, Romania; vertical</td>
<td>70,000 m² average ht: 52-57 m</td>
<td>208 m. under flat surface</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>SUNLAB</td>
<td>Sieroszowice mine, Poland; vertical</td>
<td>85×15×20 m²</td>
<td>900-950 m (2200 m.w.e.); 650-700 m for large cavems</td>
<td>20</td>
<td>salt and copper ore</td>
</tr>
<tr>
<td>SUL (UK)</td>
<td>Solotzwina mine, Ukraine; vertical</td>
<td>25×18×8 m²; 4 of 6×6×3 m²; total area 1000 m³</td>
<td>1000 m.w.e. under flat surface; 1.7×10⁻¹</td>
<td>33</td>
<td>&lt;2.7×10⁻¹</td>
</tr>
<tr>
<td><strong>Asia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INO (proposed)</td>
<td>Masinagudi, India; independent tunnel</td>
<td>2 halls: 26×135×25 m²; 53×12×9 m²</td>
<td>3500 m.w.e.</td>
<td>-</td>
<td>compacted granite</td>
</tr>
<tr>
<td>Kamioka</td>
<td>Japan; independent horizontal</td>
<td>Hall 5K 50 m dia; 40×40 &amp;100×100 m with L-arm</td>
<td>2700 m.w.e.</td>
<td>20-60</td>
<td>8.25±0.5×10⁻¹ (th); 11.5±1.2×10⁻¹ (fast)</td>
</tr>
<tr>
<td>Oto-cosmo</td>
<td>Tentsuji, Japan; Indep. horizontal</td>
<td>2 halls: 50 m³; 33 m³; total ~100 m³</td>
<td>1400 m.w.e.</td>
<td>4×10⁻¹</td>
<td>4×10⁻¹</td>
</tr>
<tr>
<td>Y2L</td>
<td>YangYang, S. Korea; horizontal</td>
<td>Current space: 100 m²; Planned space: 800 m²</td>
<td>~2000 m.w.e.</td>
<td>40-150</td>
<td>8×10⁻¹ (1.5-6 MeV)</td>
</tr>
<tr>
<td><strong>North America</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DUSEL (proposed)</td>
<td>Homestake, USA; vertical</td>
<td>7200, 4500, 100 m at 1450, 2200, 2038 m dep</td>
<td>233, 4100, 6400, 7000 m.w.e. under flat surface</td>
<td>~40-200 (at 1478 m)</td>
<td>metasedimentary</td>
</tr>
<tr>
<td>SNOLAB</td>
<td>Creighton mine, Canada; vertical</td>
<td>SNO ~200 m²; main 180×15×15-19 m²; ladders 6-7 m; total 46,668 m</td>
<td>6001 m.w.e. under flat surface</td>
<td>120; norite, granite gabbro</td>
<td>4.7×10⁻¹ (th)</td>
</tr>
<tr>
<td>SUL (US)</td>
<td>Soudan mine, USA; ~vertical</td>
<td>2 halls: 72×14×14 m; 82×16×14 m; tot 2300 m³</td>
<td>2000 m.w.e. under flat surface</td>
<td>2×10⁻¹</td>
<td>2×10⁻¹ (calc)</td>
</tr>
<tr>
<td>WIPP</td>
<td>Carlsbad, USA; vertical</td>
<td>500×8×6 m available</td>
<td>2000 m.w.e.</td>
<td>2×10⁻¹ expected</td>
<td>300-700; lily greenstone</td>
</tr>
<tr>
<td>Kimballton</td>
<td>Butt Mountain, USA; horizontal</td>
<td>30×11×6 m</td>
<td>1400 m.w.e.</td>
<td>&lt; 7; salt</td>
<td>115±/22 m² d⁻¹ (th+ath)</td>
</tr>
</tbody>
</table>

Paleozoic dolomite
Table 1. $Q$-value, natural abundance and phase space factor $G$ (standard mechanism) for all isotopes with $Q \geq 2$ MeV using $r_0 = 1.2$ fm. Values taken from Table 6 of $^6$ and scaled to $g_A = 1.25$. Note that there is a misprint in Ref.$^6$, which quotes $G^{0\nu}$ for $^{100}$Mo as $11.3 \times 10^{-14}$ yrs$^{-1}$.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$G$ [$10^{-14}$ yrs$^{-1}$]</th>
<th>$Q$ [keV]</th>
<th>nat. abund. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>6.35</td>
<td>4273.7</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>0.623</td>
<td>2039.1</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.70</td>
<td>2995.5</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>5.63</td>
<td>3347.7</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>4.36</td>
<td>3035.0</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>1.40</td>
<td>2004.0</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>4.62</td>
<td>2809.1</td>
<td>7.6</td>
</tr>
<tr>
<td>$^{124}$Sn</td>
<td>2.55</td>
<td>2287.7</td>
<td>5.6</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>4.09</td>
<td>2530.3</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>4.31</td>
<td>2461.9</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>19.2</td>
<td>3367.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Two neutrino $\beta\beta$ decay

\[(\tau_{1/2}^{2\nu})^{-1} = G^{2\nu} |M^{2\nu}|^2\]

### TABLE II. Half-life and nuclear matrix element values for two-neutrino double-$\beta$ decay (see Sec. IV).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}(2\nu)$ (years)</th>
<th>$M^{2\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>$4.4^{+0.6}_{-0.5} \times 10^{19}$</td>
<td>$0.0238^{+0.0015}_{-0.0017}$</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>$(1.5 \pm 0.1) \times 10^{21}$</td>
<td>$0.0716^{+0.0025}_{-0.0023}$</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>$(0.92 \pm 0.07) \times 10^{20}$</td>
<td>$0.0503^{+0.0020}_{-0.0018}$</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>$(2.3 \pm 0.2) \times 10^{19}$</td>
<td>$0.0491^{+0.0023}_{-0.0020}$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>$(7.1 \pm 0.4) \times 10^{18}$</td>
<td>$0.1258^{+0.0037}_{-0.0034}$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}-^{100}\text{Ru}(0^+_1)$</td>
<td>$5.9_{-0.6}^{+0.8} \times 10^{20}$</td>
<td>$0.1017^{+0.0056}_{-0.0063}$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>$(2.8 \pm 0.2) \times 10^{19}$</td>
<td>$0.0695^{+0.0025}_{-0.0024}$</td>
</tr>
<tr>
<td>$^{128}\text{Te}$</td>
<td>$(1.9 \pm 0.4) \times 10^{24}$</td>
<td>$0.0249^{+0.0031}_{-0.0023}$</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>$(6.8_{-1.1}^{+1.2}) \times 10^{20}$</td>
<td>$0.0175^{+0.0016}_{-0.0014}$</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>$(8.2 \pm 0.9) \times 10^{18}$</td>
<td>$0.0320^{+0.0018}_{-0.0017}$</td>
</tr>
<tr>
<td>$^{150}\text{Nd}-^{150}\text{Sm}(0^+_1)$</td>
<td>$1.33_{-0.26}^{+0.45} \times 10^{20}$</td>
<td>$0.0250^{+0.0029}_{-0.0034}$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$(2.0 \pm 0.6) \times 10^{21}$</td>
<td>$0.0271^{+0.0053}_{-0.0033}$</td>
</tr>
<tr>
<td>$^{130}\text{Ba}; \text{ECEC}(2\nu)$</td>
<td>$(2.2 \pm 0.5) \times 10^{21}$</td>
<td>$0.105^{+0.014}_{-0.010}$</td>
</tr>
</tbody>
</table>

$^{130}\text{Te}$ \quad $\tau^{2\nu} \Rightarrow (7.0 \pm 0.9_{\text{stat}} \pm 1.1_{\text{sist}}) \times 10^{20} \ \text{a}$

\[
M^{2\nu} = 0.017 \pm 0.002
\]
# Neutrinoless $\beta\beta$ decay

<table>
<thead>
<tr>
<th>Nucl.</th>
<th>Experiment</th>
<th>$%$</th>
<th>$Q_{\beta\beta}$</th>
<th>Enr</th>
<th>Technique</th>
<th>$T_{0\nu}$ (y)</th>
<th>$&lt;m_{\nu}&gt;$</th>
<th>Iachello</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>Elegant IV</td>
<td>0.19</td>
<td>4271</td>
<td></td>
<td>scintillator</td>
<td>$&gt;1.4\times10^{22}$</td>
<td>20-28</td>
<td></td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>Heidelberg-Moscow</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>ionization</td>
<td>$&gt;1.9\times10^{25}$</td>
<td>.23 – .64</td>
<td>&lt;.29</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>IGEX</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>Ionization</td>
<td>$&gt;1.6\times10^{25}$</td>
<td>.25 – .70</td>
<td>&lt;.27</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>Klapdor et al</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>ionization</td>
<td>$1.2\times10^{25}$</td>
<td>.29-81</td>
<td>~.34</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>NEMO 3</td>
<td>9.2</td>
<td>2995</td>
<td>97</td>
<td>tracking</td>
<td>$&gt;3.6\times10^{23}$</td>
<td>.9-.24</td>
<td>1.1</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>NEMO 3</td>
<td>9.6</td>
<td>3034</td>
<td>95-99</td>
<td>tracking</td>
<td>$&gt;1.1\times10^{24}$</td>
<td>.41-.91</td>
<td>.49</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>Solotvina</td>
<td>7.5</td>
<td>2809</td>
<td>83</td>
<td>scintillator</td>
<td>$&gt;1.7\times10^{23}$</td>
<td>1.5 – 2.8</td>
<td>1.5</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>Bernatovitz</td>
<td>34</td>
<td>866</td>
<td></td>
<td>geochem</td>
<td>$&gt;7.7 \times 10^{24}$</td>
<td>.8-1.9</td>
<td></td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>Cuoricino</td>
<td>33.8</td>
<td>2528</td>
<td></td>
<td>bolometric</td>
<td>$&gt;2.8 \times 10^{24}$</td>
<td>.3-.7</td>
<td>.36</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>DAMA</td>
<td>8.9</td>
<td>2476</td>
<td>69</td>
<td>scintillator</td>
<td>$&gt;1.2\times10^{24}$</td>
<td>1.1 -2.9</td>
<td>.61</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>Irvine</td>
<td>5.6</td>
<td>3367</td>
<td>91</td>
<td>tracking</td>
<td>$&gt;1.2\times10^{21}$</td>
<td>3 - ?</td>
<td></td>
</tr>
</tbody>
</table>
Limits on $0\nu\chi$

**Table 3.** Best present limits on $0\nu\chi^0\beta\beta$ decay (ordinary Majoron) at 90% C.L.

<table>
<thead>
<tr>
<th>Isotope ($E_{2\beta}$, keV)</th>
<th>$T_{1/2}$, yr</th>
<th>$\langle g_{ee}\rangle$ [10–13]</th>
<th>$\langle g_{ee}\rangle$ [42]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$ (2039)</td>
<td>$&gt;6.4 \times 10^{22}$ [43]</td>
<td>$(0.54–1.44) \times 10^{-4}$</td>
<td>$&lt;2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{82}\text{Se}$ (2995)</td>
<td>$&gt;1.5 \times 10^{22}$ [48]</td>
<td>$(0.58–1.19) \times 10^{-4}$</td>
<td>$&lt;1.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$ (3034)</td>
<td>$&gt;2.7 \times 10^{22}$ [48]</td>
<td>$(0.35–0.85) \times 10^{-4}$</td>
<td>–</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$ (2805)</td>
<td>$&gt;8 \times 10^{21}$ [47]</td>
<td>$(0.79–2.56) \times 10^{-4}$</td>
<td>$&lt;1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{128}\text{Te}$ (867)</td>
<td>$&gt;2 \times 10^{24}$ (geochem) [49]</td>
<td>$(0.61–0.97) \times 10^{-4}$</td>
<td>$&lt;1.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$ (2458)</td>
<td>$&gt;1.6 \times 10^{22}$* [46]</td>
<td>$(1.51–3.54) \times 10^{-4}$</td>
<td>$&lt;2.9 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

* Conservative limit from [46] is presented.

**Table 4.** Best present limits on $T_{1/2}$ for decay with one and two Majorons at 90% C.L. for modes with spectral index $n = 2$, $3$, and $7$

<table>
<thead>
<tr>
<th>Isotope ($E_{2\beta}$, keV)</th>
<th>$n = 2$</th>
<th>$n = 3$</th>
<th>$n = 7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$ (2039)</td>
<td>–</td>
<td>$&gt;5.8 \times 10^{21}$ [50]</td>
<td>$&gt;6.6 \times 10^{21}$ [50]</td>
</tr>
<tr>
<td>$^{82}\text{Se}$ (2995)</td>
<td>$&gt;6 \times 10^{21}$ [48]</td>
<td>$&gt;3.1 \times 10^{21}$ [48]</td>
<td>$&gt;5 \times 10^{20}$ [48]</td>
</tr>
<tr>
<td>$^{90}\text{Zr}$ (3550)</td>
<td>–</td>
<td>$&gt;6.3 \times 10^{19}$ [51]</td>
<td>$&gt;2.4 \times 10^{19}$ [51]</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$ (3034)</td>
<td>$&gt;1.7 \times 10^{22}$ [48]</td>
<td>$&gt;1 \times 10^{22}$ [48]</td>
<td>$&gt;7 \times 10^{19}$ [48]</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$ (2805)</td>
<td>$&gt;1.7 \times 10^{21}$ [47]</td>
<td>$&gt;8 \times 10^{20}$ [47]</td>
<td>$&gt;3.1 \times 10^{19}$ [47]</td>
</tr>
<tr>
<td>$^{130}\text{Te}$ (2529)</td>
<td>–</td>
<td>$&gt;9 \times 10^{20}$ [53]</td>
<td>–</td>
</tr>
<tr>
<td>$^{128}\text{Te}$ (867) (geochem)</td>
<td>$&gt;2 \times 10^{24}$ [49]</td>
<td>$&gt;2 \times 10^{24}$ [49]</td>
<td>$&gt;2 \times 10^{24}$ [49]</td>
</tr>
</tbody>
</table>
Table 8. Best present limits on $0\nu\beta\beta$ transition to the $2^+_1$ excited state (90% C.L.)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$E_{2\beta}$, keV</th>
<th>Experiment $T_{1/2}$, yr</th>
<th>Theory [79] $T_{1/2}$, yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\langle m_\nu \rangle = 1$ eV</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>1480</td>
<td>$&gt;8.2 \times 10^{23}$ [80]</td>
<td>$8.2 \times 10^{31}$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>2494.5</td>
<td>$&gt;1.6 \times 10^{23}$ [61]</td>
<td>$6.8 \times 10^{30}$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>1992.7</td>
<td>$&gt;1.4 \times 10^{23}$ [53]</td>
<td>–</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>1511.5</td>
<td>$&gt;2.9 \times 10^{22}$ [47]</td>
<td>–</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>1649.4</td>
<td>$&gt;6.5 \times 10^{21}$ [81]</td>
<td>–</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2218.5</td>
<td>$&gt;2.8 \times 10^{21}$ [82]</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 9. Best present limits on $0\nu\beta\beta$ transition to the $0^+_1$ excited state (90% C.L.) (theoretical predictions are given for $\langle m_\nu \rangle = 1$ eV)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$E_{2\beta}$, keV</th>
<th>Experiment $T_{1/2}$, yr</th>
<th>Theory $T_{1/2}$, yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>[83, 85–87]</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>2627.1</td>
<td>$&gt;1.0 \times 10^{20}$ [69]</td>
<td>–</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>2202.5</td>
<td>$&gt;6.8 \times 10^{19}$ [70]</td>
<td>$2.4 \times 10^{24}$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>1903.7</td>
<td>$&gt;8.9 \times 10^{22}$ [61]</td>
<td>$2.6 \times 10^{26}$</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>1507.5</td>
<td>$&gt;3.0 \times 10^{21}$ [72]</td>
<td>$9.5 \times 10^{26}$</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>1274.8</td>
<td>$&gt;1.5 \times 10^{20}$ [68]</td>
<td>–</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>1048.2</td>
<td>$&gt;1.4 \times 10^{22}$ [47]</td>
<td>$1.5 \times 10^{27}$</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>916.7</td>
<td>$&gt;1.3 \times 10^{22}$ [89]</td>
<td>$4.9 \times 10^{26}$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>735.3</td>
<td>$&gt;3.1 \times 10^{22}$ [53]</td>
<td>$7.5 \times 10^{25}$</td>
</tr>
</tbody>
</table>
Possibile Evidence of $0\nu\beta\beta$ in $^{76}$Ge

\[ T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \times 10^{25} \text{ yr}. \]
NEMO 3:

100Mo

V. Tretyak
NEMO-3 Results

$^{100}$Mo, 7 kg, 4.5 years

$^{82}$Se, 1 kg, 4.5 years

$\nu \nu \beta \beta$ results:

$[2.8-3.2]$ MeV: 18 evts (data) vs 16.4±1.4 (MC)

$\tau^{0\nu}_{1/2}>1.0 \times 10^{24}$ years @ 90% C.L.

$m_{\nu \nu}< (0.47-0.96)$ eV

$[2.6-3.2]$ MeV: 14 evts (data) vs 10.9±1.3 (MC)

$\tau^{0\nu}_{1/2}>3.2 \times 10^{23}$ years @ 90% C.L.

$m_{\nu \nu}< (0.9-2.5)$ eV

Plus measurements of $2\nu \beta \beta$ lifetimes for 7 isotopes

A new technique $\Rightarrow$ Thermal detectors

$$\Delta T = \frac{Q}{C_V}$$

$$C_V = 1944 \frac{V}{V_m} \left(\frac{T}{\Theta}\right)^3 \text{ J/K}$$

Energy resolution
- $<1 \text{ eV}$
- $\sim 2\text{ eV}$
- $\sim 10 \text{ eV}$
- $\sim \text{keV}$
- $\oplus 6 \text{ keV}$
- $\oplus 2 \text{ MeV}$
First ideas

1880 => Langley => resistive bolometers for infrared rays from SUN

1903 => Curie et Laborde => calorimetric measurement of radioactivity

1927 => Ellis and Wuster => heat less then expected => the neutrino

1949 => D. Andrews, R. Fowler, M. Williams => a particle detection

1983 => T.Niinikoski => observe pulses in resistors due to cosmic rays

1984 => S.H.Moseley et LT detectors for astrophysics and n mass

=> Fiorini and Niinikoski Low temperature detectors for rare events

=> A. Drukier, L. Stodolsky, => neutrino physics and astronomy
Doped Semiconductors

- $\alpha$ negative; $|\alpha| < 10$
- Resistance large
- Current bias and read voltage

Superconducting transition-edge

- $\alpha$ positive; $10 < \alpha < 1000$
- Resistance small
- Voltage bias and read current
**Simon's wish**

- **TES**
  - 1.8 eV FWHM
  - 240x240x6.7μm³
  - Bi/Au

- **Si Thermistor**
  - 3.2 eV
  - 410x410x8μm³
  - HgTe Mn K$_{\alpha_1}$

- **MMC**
  - 2.7 eV
  - 180x180x5μm³
  - Au
Energy resolution of a TeO$_2$ crystal 5x5x5 cm$^3$ (~ 760 g):

- 0.8 keV FWHM @ 46 keV
- 1.4 keV FWHM @ 0.351 MeV
- 2.1 keV FWHM @ 0.911 MeV
- 2.6 keV FWHM @ 2.615 MeV
- 3.2 keV FWHM @ 5.407 MeV

(The best $\alpha$ spectrometer so far)
A very interesting application of thermal detectors $\Rightarrow$ decay of $^{209}$Bi

$^{209}$Bi considered the only stable isotope of Bi and the stable nucleus with higher Z

Scintillation and heat experiment in Paris by P.de Marcillac et al with a BGO of 47 g

$$\text{DE} = 3137 \quad 1_{\text{stat}} \quad 2_{\text{syst}} \Rightarrow 1.9 \quad 0.2 \times 10^{19} \quad \text{a}$$
$^{130}\text{Te} = ^{130}\text{Xe} + 2\text{e}^- (+2\bar{\nu})\text{ a.i., } \sim 34\% \Delta E = 2528\text{ keV}$

Experiments with thermal detectors

Mibeta (only Milano) 20 TeO$_2$ bolometers of 340 g $\Rightarrow$ 6.8 kg

CUORICINO (CUORICINO Coll.) 44 crystals of 790 g and 18 of 330 g (enrich.) $\Rightarrow$ 40.7 kg

CUORE (CUORE coll) 988 crystals 750 g $\Rightarrow$ 741 kg
Progress of thermal detectors
CUORICINO
Detectors assembling

Operations carried out
In a clean room
Funny consequence in change of $\Delta Q \Rightarrow$ New

Statistics          Q- value    Background     Limit (90% cl)     $<m_\nu > < 0.3 \cdot 0.7$

yr $\times$ kg$^{130}$Te  (keV)    c/kev/kg/y   years
19.75       ~2527.5   0.162± 0.006   2.8 $10^{24}$

(was $3 \times 10^{24}$)
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMO III</td>
<td>$^{100}$Mo et al</td>
<td>10 kg of enrich. Isotopes -tracking</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>$^{130}$Te + etc.</td>
<td>40 kg of TeO$_2$ bolometers (nat)</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}$Te + etc.</td>
<td>750 kg of TeO$_2$ bolometers (nat)</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>200kg - 1 t Xe TPC</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>30 Š 40 kg Š 1t Ge diodes in LN</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>180 kg - 1t Ge diodes</td>
</tr>
<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>nat.Mo sheets in plastic sc.</td>
</tr>
<tr>
<td>DCBA</td>
<td>$^{150}$Nd</td>
<td>20 kg Nd-tracking</td>
</tr>
<tr>
<td>CAMEO</td>
<td>$^{116}$Cd</td>
<td>1 t CdWO$_4$ in liquid scintillator</td>
</tr>
<tr>
<td>COBRA</td>
<td>$^{116}$Cd, $^{130}$Te</td>
<td>10 kg of CdTe semiconductors</td>
</tr>
<tr>
<td>Candles</td>
<td>$^{48}$Ca</td>
<td>Tons of CaF$_2$ in liquid scintillators</td>
</tr>
<tr>
<td>GSO</td>
<td>$^{116}$Cd</td>
<td>2 t Gd$_2$SiO$_5$:Ce scintill.in liquid sc.</td>
</tr>
<tr>
<td>Xe</td>
<td>$^{136}$Xe</td>
<td>1.56 Xenon in liquid scintillator.</td>
</tr>
<tr>
<td>Xmass</td>
<td>$^{136}$Xe</td>
<td>1 t of liquid Xe</td>
</tr>
</tbody>
</table>
Approximate price of $^{2\beta}$ isotopes (obtained by centrifugation)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance, %</th>
<th>Price per kg, k$</th>
<th>Cost of 10 t, Mln.$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>7.61</td>
<td>$\sim$ 80</td>
<td>800</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>8.73</td>
<td>$\sim$ 120</td>
<td>1200</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>9.63</td>
<td>$\sim$ 80</td>
<td>800</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>7.49</td>
<td>$\sim$ 180</td>
<td>1800</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>34.08</td>
<td>$\sim$ 20</td>
<td>200</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>8.87</td>
<td>~5-10</td>
<td>50-100</td>
</tr>
<tr>
<td>$^{150}$Nd (?)</td>
<td>5.6</td>
<td>&gt; 200</td>
<td>&gt; 2000</td>
</tr>
</tbody>
</table>

*Estimation uncertainty can be 30%.

}\Sum\left(\tau_{1/2}^{0}\right) \propto \varepsilon \ \frac{a.i.}{A} \ \sqrt{\frac{M \cdot t_{\text{meas}}}{\Delta E \cdot \text{bkg}}}
# Summary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Mass [kg]</th>
<th>$\tau^{0\nu}_{1/2}$ [y]</th>
<th>$m_{\beta\beta}$ [meV]</th>
<th>When</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>200</td>
<td>$2 \times 10^{26}$</td>
<td>35-80</td>
<td>2014-2019</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>17</td>
<td>$3 \times 10^{25}$</td>
<td>180-500</td>
<td>2010-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>$2 \times 10^{26}$</td>
<td>70-200</td>
<td>2012-2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$6 \times 10^{27}$</td>
<td>10-40</td>
<td>2015-2025</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>$^{76}$Ge</td>
<td>33</td>
<td>$1.5 \times 10^{26}$</td>
<td>70-200</td>
<td>2012-2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$6 \times 10^{27}$</td>
<td>10-40</td>
<td>2015-2025</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>200</td>
<td>$6 \times 10^{25}$</td>
<td>130-190</td>
<td>2010-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$8 \times 10^{26}$</td>
<td>30-60</td>
<td>2015-2025</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se</td>
<td>100-200</td>
<td>$(1-2) \times 10^{26}$</td>
<td>40-140</td>
<td>2013-2019</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}$Xe</td>
<td>400</td>
<td>$4 \times 10^{26}$</td>
<td>40-80</td>
<td>2011-2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$&lt;10^{27}$</td>
<td>25-50</td>
<td>2014-2016</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{150}$Nd</td>
<td>40-120</td>
<td>$\sim 4 \times 10^{24}$</td>
<td>80-130</td>
<td>2013-2016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>$\sim 3 \times 10^{25}$</td>
<td>40-100</td>
<td>2016-2020</td>
</tr>
</tbody>
</table>
Near-Term Experiments

- Four complementary approaches, multiple isotopes
  - High-resolution calorimeters (source=detector)
    - Bolometers: CUORE ($^{130}\text{Te}$)
    - Ionization: GERDA ($^{76}\text{Ge}$), MAJORANA ($^{76}\text{Ge}$), COBRA ($^{130}\text{Te}$, $^{116}\text{Cd}$)
  - Tracking detectors (source=detector)
    - Liquid Xe or high-pressure gas TPC: EXO-200, NEXT ($^{136}\text{Xe}$)
  - Tracking detectors (source$\neq$detector)
    - SuperNEMO, MOON, DCBA
  - DBD-loaded scintillators (source=detector)
    - SNO+ ($^{150}\text{Nd}$), KamLAND-Zen ($^{136}\text{Xe}$), XMASS ($^{136}\text{Xe}$)

NEW $\Rightarrow$ AMoRE $\Rightarrow$ CaMoO4 (S.K.Kim)
COBRA
K. Zuber  CdTe
Semiconductors with good E-resolution to study $^{116}$Cd onbb
and others at Gran sasso
Goal 64K 1% $10^{-1}$/t y

Use large amount of CdZnTe
Semiconductor Detectors

K. Zuber, Phys. Lett. B 519, 1

K. Zuber

Ionization

Background at 2.8 MeV around 5 counts/keV/kg/yr
CdZnTe detectors
Most promising $^{116}$Cd, $Q_{\beta\beta} = 2809$ keV

COBRA Setup at LNGS

- 1st layer of 16 crystals
  - FWHM 3.5% - 8.5% @ 2.8 MeV
  - stopped end of 2008
  - exposure 18 kg*days

- Physics results on $^{113}$Cd & DBD limits

- Upgrade to 64 detectors in near future

Background at 2.8 MeV:
$\sim 5$ cts/(keV·kg·yr)
Two options

Energy measurement only

Energy measurement and tracking

1024 pixel, pixel size: 625 µm

Alphas

Electrons

Muons
Semiconductor detectors

Advantages for $0^{\nu}\beta\beta$ decay search:

- detector-grade semiconductors are high-purity materials (low background)
- very good detection efficiency due to: detectors made of source material
- established detector technologies $\Rightarrow$ industrial support
- very good energy resolution: 
  $\sim$2-3 keV for Ge ($\sim$15-20 keV for CdZnTe)

**COBRA: CdZnTe detectors**
Room temperature operation

**GERDA & MAJORANA: Ge det.**
Cryogenic operation

Coplanar grid detector

Coaxial p-type detector

germanium detector operating principle
(CZT principle similar)
Ge Detection Principle

- >40 years of experience
- Ge is semiconductor -- Diode.
- Ionizing radiation creates electron-hole pairs.
- Signal generated by collecting electrons and holes.
- Gamma-ray spectroscopy

**Mature Technology**

**GERDA in Hall A @ LNGS, Italy**
- 3400 m.w.e.
- Suppression of $\mu$-flux $> 10^6$
- Phase I: $B < 10^{-2}$ cts/(keV kg y)
- Phase II: $B < 10^{-3}$ cts/(keV kg y)

- Full scale experiment: $B \sim 10^{-4}$ cts/(keV kg y)

**MAJORANA @ DUSEL, USA**
- $\sim 3000$ m.w.e.
- Partly funded; under construction
- Demonstrator: $B \sim 10^{-3}$ cts/(keV kg y)
• Modules of $^{\text{enr}}\text{Ge}$ housed in high-purity electroformed copper cryostat
• Shield: electroformed copper / lead
• Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.)

• ‘Bare’ $^{\text{enr}}\text{Ge}$ array in liquid argon
• Shield: high-purity liquid Argon / H$_2$O
• Phase I (2011): ~18 kg (HdM/IGEX diodes)
• Phase II (2012): add ~20 kg new detectors - Total ~40 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
Enriched Crystal Production

Enrichment (86% $^{76}$Ge)

E. E. Haller

Crystal growth

Polycrystalline bars

Zone refinement

6/15/11

R. Henning, MEDEX 2011, Prague
P-type Point-Contact (PPC) Detectors

Point contact:
• Small capacitance: ~1pF
• Pronounced weighting field
• Small electrical fields
• Sub-keV Thresholds
• Excellent Pulse-shape Analysis
• Use Commercial BEGe Design
Sanford Underground Laboratory, Davis Campus, 4850’ level, near Yates shaft SNOLAB as backup site.
Majorana Underground Electroforming at Sanford Lab

View of Sanford 4850' area where the future TCR would be located
The Majorana Demonstrator will use modified Broad Energy Ge (BEGe) detectors [8], which are a variation on the p-type, point-contact (P-PC) detector design [9, 10]. P-PC de-

**Demonstrator Schedule**

- Prototype Module (all natural Ge) on-line: Summer 2012
- First module (~12 kg enriched) on-line: Summer 2013.
- Second Module (additional ~18 kg enriched) on-line: Spring 2014.
GERDA design

Ionization

Cleanroom

Lock for detector insertion

Water tank (650 m³ H₂O)

Equipped with 66 PMTs for μ-veto

Cryostat (70 m³ LAr)

LAr scintillation light readout can be implemented

Detector Array
Cryostat installed in Hall A of LNGS – 6th March 2008
Background predicted in GERDA

<table>
<thead>
<tr>
<th>Source</th>
<th>$B \left[ 10^{-3} \text{ cts/(keV kg y)} \right]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ext. $\gamma$ from $^{208}$Tl ($^{232}$Th)</td>
<td>$\ll 1$</td>
</tr>
<tr>
<td>Ext. neutrons</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>Ext. muons (veto)</td>
<td>$&lt; 0.03$</td>
</tr>
<tr>
<td>Int. $^{68}$Ge ($t_{1/2} = 270$ d)</td>
<td>12</td>
</tr>
<tr>
<td>Int. $^{60}$Co ($t_{1/2} = 5.27$ y)</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{222}$Rn in LN/LAr</td>
<td>$&lt; 0.2$</td>
</tr>
<tr>
<td>$^{208}$Tl, $^{238}$U in holder</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Surface contam.</td>
<td>$&lt; 0.6$</td>
</tr>
</tbody>
</table>

Derived from measurements and MC simulations

Target for phase II: $\sum B \leq 10^{-3} \text{ cts/(keV kg y)}$

$\Rightarrow$ additional bad. reduction techniques
Phase I detectors

8 diodes (from HdM, IGEX):
- Enriched 86% in $^{76}\text{Ge}$
- All diodes reprocessed with new contacts optimized for LAr
- Well tested procedure for detector handling
- Long term stability in LAr established
- All detectors mounted in low-mass holder & tested in LAr
- Energy resolution in LAr:
  ~2.5 keV (FWHM) @1.3 MeV
- Total mass 17.66 kg

6 diodes from Genius-TF $^{\text{nat}}\text{Ge}$:
- Same reprocessing & testing as enriched diodes
- Total mass: 15.60 kg

Detector handling under $\text{N}_2$ atmosphere
Towards 1TGe

- Modules of $^{76}$Ge 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.)

- ‘Bare’ $^{76}$Ge array in liquid argon
- Shield: high-purity liquid Argon / H$_2$O
- Phase I (2011): $\sim$18 kg (HdM/IGEX diodes)
- Phase II (2012): add $\sim$20 kg new detectors - Total $\sim$40 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
DCBA Experiment

Solenoid Magnet

Source plate

$^{150}$Nd

$2\nu\beta\beta$ candidate

B=600G

(Z-direction)

$\beta_1$

(0.93MeV)

$\beta_2$

(0.63MeV)

FADC time counts

See poster by N. Ishihara

Geant4

B=2.4 kG

He+CO$_2$

(10%)

$\beta_2$

$\beta_1$

$\nu$

VTX

Wire number (pickup)

80 keV FWHM

@ 1.7 MeV

Nd$_2$O$_3$

40 mg/cm$^2$

Energy (MeV)

Corresponding

$\Delta E/E$

=3.4% (FWHM)

at Q of $^{150}$Nd

(=3.37 MeV)

Plots courtesy of DCBA collaboration
SuperNEMO (~100 people)

Planar and modular design:
~ 100 kg of enriched isotopes (20 modules x 5 kg)

1 module:

Source (~40 mg/cm²) 4 x 2.7 m²

$^{82}\text{Se}$ first but almost any isotope possible

($^{82}\text{Se}$: High $Q_{\beta\beta}$, long $T_{1/2}(2\nu)$,
proven enrichment technology)

$^{150}\text{Nd}, \; ^{48}\text{Ca}$ being looked at

Tracking: drift chamber ~2000 cells
in Geiger mode

Calorimeter: scintillators + PMTs
550 PMTs + scint. blocks

Modules surrounded by water
passive shielding
Super NEMO

Modular detector with a planar geometry
- source: 4 x 3 m² foil (40 mg/cm²)
- tracking: drift cells in Geiger mode
- calorimeter: scintillators + PMTs

First Module / Demonstrator running in 2012 with 7 kg of $^{82}$Se

Demonstrator sensitivity (15 kg.y of $^{82}$Se): 210 – 570 meV
Full Detector Target sensitivity (500 kg.y of $^{82}$Se): 53 – 145 meV
SuperNEMO schedule highlights

- NEMO-3 decommissioning - early 2011
- Demonstrator construction - 2010-2012
- Demonstrator physics run start-up - 2013
- Full detector construction start-up - 2014
- Target sensitivity (~0.05 eV) - 2019

KK claim to be verified with Demonstrator by 2015
(TPC) filled with high-pressure gaseous xenon, calorimetry and tracking => $^{136}$Xe, to be installed in the Canfranc Underground Laboratory.

NEXT

Tracking +light

electrons => ionization + excitation, emission of UVL-**primary scintillation** => start up

negative charges => drift towards TPC anode (EL region with intense field)

=> scatter, excite or even ionize gas => further VUV emitted isotropically

=> detected by photo detectors behind cathode => energy measurement
Figure 3.15: Monte Carlo simulation of the image of $\beta\beta 0\nu$ event in a plane of SiPMs.
MOON 1 prototype detector
PL 6 layers, 53x53x1 cc BC408. equiv.¹⁰⁰Mo, 142g 40mg, 3 layers


Resolution s = 2.8 % → 2.2 % position dep. corrected at Q_{bb}=3 MeV

ELEGANT V 1990

Fig. 4.3.6. This show the energy resolution of plastic scintillator (PL), which is seen by 31 PMTs. The energy resolution of PL are obtained by reconstructing the γ rays from radioactive isotopes (⁴⁰K 1.46 MeV, ²⁰⁸Tl 2.61 MeV) and checking source (²²Na 1.27 MeV). Here, the energy E_{PL} is determined by using the energy resolution of a NaI detector (ID) at the energy regions (511 keV, 1.27 MeV).

Resolution s = 2.8 % → 2.2 % position dep. corrected at Q_{bb}=3 MeV
Multilayer PL plates and PL fiber planes with thin ββ source film. 
\langle m \rangle \sim 44–31 \text{ meV for } ^{100}\text{Mo}–^{82}\text{Se} 90 \% \text{ CL}

Detector ≠ ββ source 
Select ββ sources 
Solar ν as well

MOON 1 shows the efficiency \( \epsilon = 0.25 \)
E-resolution \( \sigma = 2.2 \sim 1.7 \% 

H. Ejiri et al., Czech. J. Phsy. 56, ‘06. 
H. Ejiri European Phys. J. 162 ‘08
Possible search of solar neutrinos

$^\text{100} \text{Mo} \rightarrow \nu, \beta$

$^\text{100} \text{Tc} \rightarrow \beta$

$^\text{100} \text{Mo}$

$^\text{0+} 1.293$

$^\text{0+} 1.904$

$^\text{2+} 2.594$

$^\text{0+} 3.034$

$^\text{100} \text{Mo}$
**MOON** \( ^{100} \text{Mo} \) with

\( Q_{\beta\beta} = 3.034 \text{MeV} \)  BG free except \( 2\nu\beta\beta \quad Q_{\beta} = 0.167 \text{MeV} \)  solar/low \( E_{\nu} \)

<table>
<thead>
<tr>
<th>Phase</th>
<th>(^{100}\text{Mo} ) kg</th>
<th>Detector</th>
<th>year</th>
<th>BG / ton y</th>
<th>( \Delta E ) keV</th>
<th>m eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>12</td>
<td>ZnMoO(_4)</td>
<td>3</td>
<td>50</td>
<td>5</td>
<td>115</td>
</tr>
<tr>
<td>II</td>
<td>220</td>
<td>ZnMoO(_4)</td>
<td>5</td>
<td>50</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>III</td>
<td>480</td>
<td>PL</td>
<td>5</td>
<td>16</td>
<td>115</td>
<td>45</td>
</tr>
</tbody>
</table>

_A. PS-CUORE / MOON Phonon Scintillator (Fiorini)_

![Graph showing count vs. energy for \(^{100}\text{Mo} 2\nu\beta\beta\) and \(^{100}\text{Mo} 0\nu\beta\beta\) transitions. The graph includes an energy scale and a peak at \( \Delta E = 5 \text{keV} \) (FWHM).]
Scintillation

$^{48}\text{Ca} \ 0.187 \ %$

Extension of ELEGANT VI

CaF$_2$: $10^3 \text{ cm}^3 \times 60$ (191 kg)

Concepts of CANDLES

- Undoped CaF$_2$ (CaF$_2$(pure))
  - $^{48}\text{Ca} \ (Q_{\beta\beta}=4.27 \text{ MeV})$
  - 300 kg $\Rightarrow$ 3 t $\Rightarrow$ 100 t
- Liquid Scintillator (LS)
  - $4\pi$ active shield
  - Passive shield
  - Wavelength shifter for CaF$_2$
- Photomultiplier
  - Large photo-coverage

CANDLES III.bmp
SNO+: $^{150}\text{Nd}$ dissolved in liquid scintillator
Pros: large mass (1 ton of Nd), high purity, well understood backgrounds
Con: poor energy resolution
Stage-1: $^{\text{nat}}\text{Nd}$ (120 kg of $^{150}\text{Nd}$), reach $m_{\beta\beta}\sim80$-150 meV
Possible Stage-2: $^{\text{enr}}\text{Nd}$ (1 ton of $^{150}\text{Nd}$), reach $m_{\beta\beta}\sim50$ meV

KamLAND-Zen: $^{136}\text{Xe}$ dissolved in liquid scintillator (mini-balloon inside KamLAND)
Pros: large mass (400 kg of $^{136}\text{Xe}$), high purity, well understood backgrounds
Con: poor energy resolution
Stage-1: $m_{\beta\beta}\sim60$ meV by end of 2013
Stage-2: 1 ton of $^{136}\text{Xe}$ (depends on funding)

Simulated Energy Spectrum at KamLAND
• It will be in two phases, pure LSci and Nd-loaded LSci for double beta decay searches of Nd-150

Detector filled with scintillator => April 2012

SNO+

1000 t D₂O will be replaced by Nd loaded LS
0.1 wt% = 780 kg Nd(natural) = 44 kg Nd-150

9500 PMTs
Energy res = 5 %@1 MeV

7000 t pure water shield

Hold down ropes will be installed
Major problem: Scintillator lighter than water

New, cleaner ropes
+ electronic upgrade, maintenance....

Currently: Work on the AV,
Next: New rope installation
SNO+ \((^{150}\text{Nd} \nu - \text{less Double Beta Decay})\)

0ν: For example: 1057 events per year with 500 kg \(^{150}\text{Nd}\)-loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland. (Borexino has done better)

\(~\text{Flat}^8\text{B Solar }\nu\) “background”

Sensitivity Limits (3 yrs):
1000 kg natural Nd (56 kg isotope): \(m_{\nu\beta\beta} \sim 0.1\) eV (start 2011)
With 500 kg \(^{150}\text{Nd}\): \(m_{\nu\beta\beta} \sim 0.04\) eV
KamLAND-Zen

Electronics Hut

Calibration system at access chimney

1200 m³ LS + 1800 m³ BO
1325 17” PMTs + 554 20” PMTs

Energy Res. = 7 % / $\sqrt{E}$

Water Cherenkov Outer Detector
225 20” PMTs
Going to be installed this year
BOREXINO in the Italian Gran Sasso Underground Laboratory in the mountains of Abruzzo, Italy, ~120 km from Rome.

External Labs

Laboratori Nazionali del Gran Sasso LNGS

Shielding ~3500 m.w.e

Borexino Detector and Plants

Diagram showing the location and layout of the Borexino laboratory.
BOREXINO

0.7-2% $^{136}$Xe
0.32-0.9 t in FV
100 meV 5y

- $^{238}$U : $(1.6 \pm 0.1) \times 10^{-17}$ g/g
- $^{232}$Th : $(6.8 \pm 1.5) \times 10^{-18}$ g/g
- $^{85}$Kr : 29 ± 14 cpd/100tons

T2=3.2x10^{21}
EXO-200: 200 kg of LXe (80% $^{136}\text{Xe}$): TPC + Scintillation
Prototype for a 1-ton detector, aiming at \(~100\) meV $m_{\beta\beta}$ sensitivity
Commissioning since \(~\text{Nov. 2010, coming along well}\)

EXO-1000: 1 ton LXe TPC
Barium ion extraction and atomic spectroscopy tagging: potential for zero-background detection (except for $2\nu\beta\beta \rightarrow 0\nu\beta\beta$)

**EXO-200 Sensitivity**

<table>
<thead>
<tr>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E @ 2.5\text{MeV}$ (%)</th>
<th>Radioactive Background (events)</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ (yr, 90% CL)</th>
<th>$m_{\beta\beta}$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6</td>
<td>40</td>
<td>$6.4 \times 10^{25}$</td>
<td>133-186</td>
</tr>
</tbody>
</table>
EXO-200 engineering run Dec 2010

- Check stability of all LXe/GXe systems
- Check Xe purity
- Check electronics
- Generally test detector performance
- Test Xe emergency recovery

- No front shielding
- No Rn enclosure
- No Rn trap in Xe system
- No veto counter
EXO-200: Liquid Xe TPC

X and Y wire grids provide position-sensitive collection of ionization. LAAPDs collect scintillation signal and give timing information [Nielson et al., NIM A608, 68 (2009)].

See poster by T. Daniels.

 Ionization alone:
\[ \sigma(E)/E = 3.8\% \text{ @ 570 keV} \]
\[ \text{or } 1.8\% \text{ @ } Q_{\beta\beta} \]

 Ionization & Scintillation:
\[ \sigma(E)/E = 3.0\% \text{ @ 570 keV} \]
\[ \text{or } 1.4\% \text{ @ } Q_{\beta\beta} \]

EXO-200: WIPP

EXO-200 is sited at the Waste Isolation Pilot Plant in Carlsbad, NM, a radioactive waste disposal facility located 2150 ft underground in a salt deposit.

- ~1600 m water equivalent flat overburden [Esch et. al., NIM A538, 516(2005)]
- Relatively low levels of U and Th (measurements < 100 ppb in EXO-200 drift), Rn (~20 Bq/m³)

Presently taking data !
EXO-200: Sensitivity

2 year sensitivities for the EXO-200 0νββ search.

<table>
<thead>
<tr>
<th>Mass (tonne)</th>
<th>Efficiency (%)</th>
<th>Run time (yr)</th>
<th>(\sigma(E)/E) @ 2.5 MeV (%)</th>
<th>Radioactive background (events)</th>
<th>(T_{1/2}^{0\nu}), 90% C.L. (yr)</th>
<th>Majorana mass (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>70</td>
<td>2</td>
<td>1.6</td>
<td>40</td>
<td>(6.4 \times 10^{25})</td>
<td>109</td>
</tr>
</tbody>
</table>


EXO-200 will also search for 2νββ of \(^{136}\)Xe, which has not been observed.

<table>
<thead>
<tr>
<th>Experimental limit</th>
<th>(T_{1/2}^{2\nu}) (yr)</th>
<th>Events/year (no efficiency applied)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luescher et al, 1998</td>
<td>(&gt; 3.6 \times 10^{20})</td>
<td>(&lt; 1.3\ M)</td>
</tr>
<tr>
<td>Bernabei et al, 2002</td>
<td>(&gt; 1.0 \times 10^{22})</td>
<td>(&lt; 48\ k)</td>
</tr>
<tr>
<td>Gavriljuk et al, 2005</td>
<td>(&gt; 8.5 \times 10^{21})</td>
<td>(&lt; 56\ k)</td>
</tr>
</tbody>
</table>

Theoretical prediction \([T_{1/2}^{max}]\)

| QRPA (Staudt et al) | \(= 2.1 \cdot 10^{22}\) | \(= 23\ k\) |
| QRPA (Vogel et al)  | \(= 8.4 \cdot 10^{20}\) | \(= 0.58\ M\) |
| NSM (Caurier et al) | \((= 2.1 \cdot 10^{21})\) | \((= 0.23\ M)\) |
Ba\textsuperscript{+} Spectroscopy

\[ ^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2\text{e}^- \]

- Ba\textsuperscript{+} system is well studied. See H. Dehmelt et al. Phys. Rev. A22, 1137 (1980).
- Very specific signature with laser induced fluorescence.
- Single ions can be detected from a photon rate of $10^7$/s

---

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass (ton)</th>
<th>Eff. (%)</th>
<th>Run Time (yr)</th>
<th>$\sigma_E/E \text{ @ } 2.5\text{MeV}$ (%)</th>
<th>2$\nu\beta$ Background (events)</th>
<th>$T_{1/2}^{0\nu}$ (yr, 90% CL)</th>
<th>Majorana mass (meV)</th>
<th>QRPA\textsuperscript{±}</th>
<th>NSM\textsuperscript{#}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>1</td>
<td>70</td>
<td>5</td>
<td>1.6\textsuperscript{*}</td>
<td>0.5 (use 1)</td>
<td>$2 \times 10^{27}$</td>
<td>50</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Aggressive</td>
<td>10</td>
<td>70</td>
<td>10</td>
<td>1\textsuperscript{†}</td>
<td>0.7 (use 1)</td>
<td>$4.1 \times 10^{28}$</td>
<td>11</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{*} s(E)/E = 1.4\% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
A new laboratory in South Korea
Mainly for Dark Matter CSNaI (crystals, but also for DBD

Yangyang Underground Laboratory (Y2L)
Yangyang Underground Laboratory
Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant

(Upper Dam)

(Power Plant)

(Lower Dam)

Minimum Access to the lab by car (~2km)

양양양수발전소
Double beta decay

- Passive targets: HPGe + CsI(Tl)
- $^{64}$Zn EC+$\beta^+$ decay
- $^{124}$Sn $\beta\beta$ to excited states of $^{124}$Te
- $^{122}$Sn EC+$\beta^+$ decay

- Active targets
  - $^{124}$Sn $0\nu\beta\beta$: Sn loaded Liquid scintillator
  - $^{84}$Sr EC+$\beta^+$ decay: SrCl$_2$ crystal
  - $^{92}$Mo EC+$\beta^+$ decay: Ca$^{nat}$MoO$_4$ crystal
  - $^{100}$Mo $0\nu\beta\beta$ decay: Ca$^{100}$MoO$_4$ crystal $\rightarrow$ AMoRE

With Calcium depleted of $^{48}$Ca
CaMoO$_4$

- DBD for Mo-100 (3034 keV), Ca-48(4272 keV) high energy $\rightarrow$ less background
- Mo-100 enrichment $>90\%$ not so difficult
- for Mo-100 search, Ca-48 needs to be depleted

Scintillator
- At room temp; 10-20\% of CsI(Tl) at 20$^\circ$
- Decay time; 16 $\mu$ sec
- LY increases at lower temp. (almost the same as CsI(Tl))
- Wavelength; 450-650ns $\rightarrow$ RbCs PMT or APD
- Pulse Shape Discrimination

- Can be used as cryogenic detector
  - Debye temperature: 438 K (Ge: 360 K, Si: 625 K)
  - Combining with Scintillation detection: NR, alpha/gamma separation
  - Good dark matter detector as well
From CUORICINO to CUORE
(Cryogenic Underground Observatory for Rare Events)

CUORE = closely packed array of 988 detectors
19 towers - 13 modules/tower - 4 detectors/module
M = 741 kg ⇒ ~ $10^{27}$ $^{130}$Te nuclides

Compact structure, ideal for active shielding

Each tower is a CUORICINO-like detector

Custom dilution refrigerator
Special crystals produced by the SICCAS factory in Shanghai
1) Kushan Jincheng Chemical Reagent Co. Ltd

high purity grade TeO2 powder production unit

high purity water and reagents production units
A crystal of 2.15 kg
CUORE will be operated @ LNGS in the south wing of experimental “Hall A”

- Average depth
  - 3650 m.w.e

- Muon Flux
  - $(2.58 \pm 0.3) \cdot 10^{-8} \mu \text{s}^{-1} \text{cm}^{-2}$

- Neutron Flux
  - $\sim 4 \cdot 10^{-6} \text{n s}^{-1} \text{cm}^{-2}$

- Gamma Flux
  - $0.73 \gamma \text{s}^{-1} \text{cm}^{-2}$
• No way of measuring directly the background level in the ROI
• Background model needed:
  – MiDBD
  – Cuoricino
  – TTT
  – RAD
  – CCVR
CUORE0
Substantially a column of CUORE to test the automatic construction of CUORE, but also a good starting double beta decay experiment
The calibration system

- Detector suspension
- Pulse tube
- 4 K flange
- TeO$_2$ detectors
- Internal lead shield
The problem of the Roman lead
Lack of $^{210}$Pb ($\tau_{1/2} \sim 22.3$ y)

Lack of U and Th ($< 1$ ng/g measured with neutron activation)
## The future

Other possible candidates for thermal detectors

<table>
<thead>
<tr>
<th>Compound</th>
<th>Isotopic abundance</th>
<th>Transition energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{CaF}_2$</td>
<td>0.0187 %</td>
<td>4272 keV</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.44 &quot;</td>
<td>2038.7 &quot;</td>
</tr>
<tr>
<td>$^{100}\text{MoPbO}_4$</td>
<td>9.63 &quot;</td>
<td>3034 &quot;</td>
</tr>
<tr>
<td>$^{116}\text{CdWO}_4$</td>
<td>7.49 &quot;</td>
<td>2804 &quot;</td>
</tr>
<tr>
<td>$^{130}\text{TeO}_2$</td>
<td>34 &quot;</td>
<td>2528 &quot;</td>
</tr>
<tr>
<td>$^{150}\text{NdF}_3$</td>
<td>5.64 &quot;</td>
<td>3368 &quot;</td>
</tr>
<tr>
<td>$^{150}\text{NdGaO}_3$</td>
<td></td>
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</tr>
</tbody>
</table>
Scintillation + Heat (in coincidence)
The first scintillating bolometer (1992)

CaF$_2$
CdWO4: 508g

ZnSe: 337 g

CaMoO4: 157g

LUCIFER R&D approved by ERC (European Research Council)
Lucifer: a R&D project of the European Community
Conclusions

Searching for neutrinoless $\beta\beta$ decay is a bet
See Blaise Pascal

Neutrinos are Dirac particles $\Rightarrow$ no hope

Neutrinos are Majorana, but direct hierarchy
$\Rightarrow$ for our children or grand children

Neutrinos are Majorana and indirect hierarchy
$\Rightarrow$ we could find it!