Experimental searches of neutrinoless double beta decay

Oliviero Cremonesi
INFN, Sezione di Milano Bicocca

NOW2012 - September 10, Otranto, Italy
Outline

Neutrinoless Double Beta Decay
Experimental approaches and technologies
Present status: few relevant examples
Future perspectives: a critical comparison
Conclusions
Neutrinoless Double Beta Decay

Neutrinoless double beta decay (0νββ)

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

is a very rare nuclear decay, particularly intriguing for its implications in particle Physics. First of all

- **Lepton Number non conservation**

that would be a cogent manifestation of incompleteness of the standard model.
Neutrinoless Double Beta Decay

Neutrinoless double beta decay ($0\nu\beta\beta$)

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

is a very rare nuclear decay, particularly intriguing for its implications in particle Physics. First of all

- **Lepton Number** non conservation

that would be a cogent manifestation of incompleteness of the standard model.

From a theoretical point of view it can be considered as a black box diagram with only few constraints.

In principle any theory satisfying the constraints must be taken into account to fill the box.
Neutrinoless Double Beta Decay

Neutrinoless double beta decay ($0\nu\beta\beta$)

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

is a very rare nuclear decay, particularly intriguing for its implications in particle Physics. First of all

- **Lepton Number** non conservation
  that would be a cogent manifestation of incompleteness of the standard model.

From a theoretical point of view it can be considered as a black box diagram with only few constraints.
In principle any theory satisfying the constraints must be taken into account to fill the box.

It was originally proposed in the framework of the weak interactions (Furry 1939) as a possible mode of the nuclear double beta decay proceeding through the exchange of a virtual neutrino.
Since then it is considered as a unique tool to check
- **Majorana nature of the neutrino**

and provide relevant information on
- **Absolute $\nu$ mass scale**
- **Neutrino mass hierarchy**
- **CP violation in the leptonic sector**

Such a mission has become particularly compelling after the evidence of neutrino oscillations.
0νββ: mass mechanism

Exchange of a light Majorana neutrino

- RH antineutrino (L=1) is emitted at one vertex
- LH neutrino (L=-1) is absorbed at the other vertex

- **Majorana particle**
- **Helicity flip**

In the limit of small neutrino masses, the half lifetime can be expressed as

\[ \tau^{-1}_{0\nu} = G_{0\nu}(Q, Z) |M^{0\nu}|^2 < m_{ee} > \]

Seven unknown quantities:
- 3 masses: \( m_k \)
- 2 angles: \( \theta_{12} \) and \( \theta_{13} \)
- 2 CP violating phases: \( \alpha \) and \( \beta \)

N.B.: Majorana phases make \( m_{ee} \) cancellation possible (\( m_{ee} \) could be smaller than any of the \( m_i \)).

Only one experimental constraint
More complementary measurements needed!
Thanks to the information from oscillations $m_{ee}$ can be expressed in terms of three unknown quantities:

- the mass scale, represented by the mass of the lightest neutrino $m_{\text{min}}$
- the two Majorana phases.

It is then common to distinguish three mass patterns:

- **normal hierarchy (NH)**, where $m_1 < m_2 < m_3$
- **inverted hierarchy (IH)** where $m_3 < m_1 < m_2$
- **quasi-degenerate pattern (QD)**, where the differences between the masses are small with respect to their absolute values
Nuclear matrix elements (NME) are calculated according to various models: QRPA (RQRPA, SQRPA, ……), Shell model, IBM2 ...

Calculation discrepancies are one of the largest sources of uncertainties


- more groups calculate NME with different methods
- NSM lower than other calculations
- NME vary by factor 2-3 for a given nucleus
- "errors" on NME calculations largely correlated for different A
- difference between QRPA calculations small
- no "super" element from NME point-of-view
$$(A,Z) \rightarrow (A,Z+2)^{++} + 2 \, e^-$$

- A new (ionised) isotope
- Two electrons

**Minimal information:**
- two $e^-$ energy sum spectrum

$0\nu\beta\beta$ exhibits a **peak at $Q$** over $2\nu\beta\beta$ tail
(and background contributions)

**Additional signatures:**
- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species

Track and event topology
Time Of Flight
Experimental sensitivity

\[ \tau_{1/2}^{0\nu} = \ln 2 \frac{\epsilon N_{\text{nuclei}} t_{\text{meas}}}{N_{\beta\beta}} \]

Lifetime corresponding to the minimum detectable number of events over background at a given confidence level

\[ N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{\text{meas}}} \]

\[ N_B = bkg \Delta E T M \]

number of background events expected along the experiment lifetime

\[ N_B >> 1 \]

\[ S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} \sqrt{M \cdot t_{\text{meas}}} \]

\[ N_B \leq O(1) \rightarrow \text{“zero background”} \]

\[ S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} M \cdot t_{\text{meas}} \]

\[ S_{1/2}^{0\nu}(m_{\text{ee}}) \propto \epsilon \frac{i.a.}{A} \frac{1}{\sqrt{G^{0\nu} \left| M^{0\nu} \right|}} \frac{4}{\sqrt{bkg \cdot \Delta E}} \sqrt{M \cdot t_{\text{meas}}} \]

- Isotope choice
- Isotopical abundance
- Mass
- Energy resolution
- Background level

O.Cremonesi - 10/09/2012 NOW2012 @ Otranto
Experimental strategy

The sensitivity formula drives the experimental strategy. In all cases develop of a proper nuclear detector to reveal the two emitted electrons in real time:

- **Minimal information**
  - measure their sum energy spectrum
- **(If possible) add more information**
  - single electron energy and initial momentum
  - species of the daughter nucleus
- **Nucleus choice**
  - favourable nuclear factor of merit \((F=G\times M^2)\)
  - high istopic abundance
  - large Q value (\(^{130}\)Te \((Q=2527\) keV), \(^{116}\)Cd \((Q=2802\) keV), \(^{76}\)Ge \((Q=2039\) keV), \(^{136}\)Xe \((Q=2479\) keV), \(^{82}\)Se \((Q=2995\) keV), \(^{100}\)Mo \((Q=3034\) keV), \(^{150}\)Nd \((Q=3367\) keV) and \(^{48}\)Ca \((Q=4270\) keV))

Desirable features of the nuclear detector:

- **High energy resolution**
- **Low background**
  - Underground detector operation (to shield cosmic rays)
  - Very radiopure material
  - Well designed passive and/or active shielding against local environmental radioactivity.
- **Large targets** (now 10-100 kg → 1-10 tons)
- **Track events or add any piece of information that can help distinguishing from background**

Normally, these features cannot be met simultaneously in a single set-up
Experimental approaches

Two main approaches:
- homogeneous (calorimetric or source \( \subseteq \) detector)
- inhomogeneous (external-source)

Calorimeters
Solid-state devices, bolometers, scintillators, gas detectors
+ Very large M possible (demonstrated \(~50\text{kg},\) proposed \(~1t\))
+ High efficiency \((\varepsilon\sim1)\)
+ Very high energy resolution \((\Delta E\sim0.015\%\) with Ge-diodes, bolometers)
+ Event topology (in gas/liquid Xe detectors or pixellization)
+ Good background levels
- Constraints on detector choice (except for bolometers)
- No or partial particle id

External-source detectors
Scintillators, gas TPC, gas DC, magnetic field and TOF
+ Event topology allowing "clean bkg" (except 2\(\nu\)\(\beta\beta\))
+ Several \(\beta\beta\) candidates can be studied with same detector
- Difficult to get large source M
- Difficult to get high efficiency
- Difficult to get good resolution
**Status: (Near) Past**

**Heidelberg – Moscow (HM) (stopped in May 2003)**

-dominated DBD scenario over a decade. **claim of evidence!!**

**NEMO3**

-intermediate generation experiment capable to study different isotopes

**CUORICINO (stopped in June 2008)**

-intermediate generation experiment based on the bolometric technique

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Detector</th>
<th>EXP</th>
<th>Material</th>
<th>kg y</th>
<th>$\tau_{1/2}$ Limit (y) (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>Ge diode</td>
<td>IGEX/HDM*</td>
<td>Ge</td>
<td>~ 47.7</td>
<td>$&gt; 1.6 - 1.9 \times 10^{25}$</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>Tracking</td>
<td>NEMO3</td>
<td>Se</td>
<td>4.5</td>
<td>$&gt; 3.2 \times 10^{23}$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>Tracking</td>
<td>NEMO3</td>
<td>Mo</td>
<td>31.5</td>
<td>$&gt; 1.0 \times 10^{24}$</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>Tracking</td>
<td>NEMO3</td>
<td>Zr</td>
<td>0.03</td>
<td>$&gt; 9.2 \times 10^{21}$</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>Tracking</td>
<td>NEMO3</td>
<td>Nd</td>
<td>0.1</td>
<td>$&gt; 1.8 \times 10^{21}$</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>Bolometer</td>
<td>Cuoricino</td>
<td>$\text{TeO}_2$</td>
<td></td>
<td>$&gt; 1.1 \times 10^{23}$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>Bolometer</td>
<td>Cuoricino</td>
<td>$\text{TeO}_2$</td>
<td>19.75</td>
<td>$&gt; 2.8 \times 10^{24}$</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>Xe scint</td>
<td>DAMA</td>
<td>L Xe</td>
<td>~ 4.5</td>
<td>$&gt; 1.2 \times 10^{24}$</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td></td>
<td>Solotvina</td>
<td></td>
<td></td>
<td>$&gt; 1.7 \times 10^{23}$</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&gt; 1.4 \times 10^{22}$</td>
</tr>
<tr>
<td>$^{160}$Gd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&gt; 1.3 \times 10^{21}$</td>
</tr>
</tbody>
</table>

* Existing claim for a positive result by part of the same group
First claim in January 2002 (Klapdor-Kleingrothaus HV et al. hep-ph/0201231) with a statistics of 55 kg y and a 2.2-3.1 statistical significance $\rightarrow$ strong criticism

Claim confirmed in 2004 with the addition of a significant (~1/4) new statistics and improved in the following years

1990 - 2003 data, all 5 detectors
exposure = 71.7 kg x y

$\tau_{1/2} = 1.2 \times 10^{25}$ years

$\langle m \rangle = 0.44$ eV


1995-2003 data new re-analysis:
SSE selection by MC & ANN

6.4$\sigma$ signal
7.05 $\pm$ 1.11 events

$2.23^{+0.44}_{-0.31}$ $10^{25}$ years / $0.32^{\pm}0.03$ eV


all future experiment will certainly have to cope with this result

arXiv:1006.2025v1 [hep-ph]: Kirpichnikov alternate interpretation of 2039 keV line
Many project have been proposed. Many of them are R&D or still only proposals. Only a representative list is given here.
Experiments: group 1

Homogeneous with high energy resolution

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
</table>
| **CUORE** $^{130}\text{Te}$ | Array of low temperature natural TeO$_2$ calorimeters operated at 10 mK  
                          | First step: 200 Kg (2014) – LNGS – **takes advantage of Cuoricino experience** 
                          | Proved energy resolution: 0.2 % FWHM                                      |
| **GERDA** $^{76}\text{Ge}$   | Array of enriched Ge diodes operated in liquid argon                        
                          | First phase: 18 Kg; second phase: 40 Kg - LNGS                            
                          | Proved energy resolution: 0.2 % FWHM                                      |
| **MAJORANA** $^{76}\text{Ge}$ | Array of enriched Ge diodes operated in conventional ultra-pure Cu cryostats  
                          | Modular; first step (demonstrator): 2x20 Kg modules                      
                          | Proved energy resolution: 0.16 % FWHM                                    |
| **LUCIFER** $^{82}\text{Se} – ^{116}\text{Cd} – ^{100}\text{Mo}$ | Array of scintillating ZnSe bolometers operated at 10 mK                  
                          | First step: ~ 10 Kg (2014) – LNGS – R&D project to fully test the principle 
                          | Proved energy resolution: 0.3 – 0.7 % FWHM                                |
Experiments: group 2

Homogeneous with high energy resolution and tracking

**NEXT - $^{136}$Xe**
- High pressure Xe (gas) TPC
- Total mass: 100 kg
- Energy resolution (goal) down or below 1% FWHM (electroluminesce in high field region)
- Detection concept and performance proved with 2 small rototypes

**COBRA - $^{116}$Cd** competing candidate – 9 $\beta\beta$ isotopes
- Array of $^{116}$Cd enriched CdZnTe (semiconductor detectors) at room temperatures
- Small scale prototype at LNGS
- Energy resolution: 1.9% FWHM
- Tracking capability: pixellization
Homogeneous with low energy resolution + tracking

**EXO-200 $^{136}$Xe**

- TPC of enriched liquid (first phase) and gaseous (second phase) Xenon
- Event position and topology; in prospect, tagging of Ba single ion (DBD daughter) through optical spectroscopy ⇒ only 2ν DBD background
- EXO-200: funded, taking data: 200 kg – WIPP facility
- Further steps: 1-10 ton
- In parallel with the EXO-200 development, R&D for Ba ion grabbing and tagging
Experiments: group 4

Homeogeneous with low energy resolution

**KamLAND-ZEN** $^{136}$Xe
- Enriched Xe gas dissolved in KAMLAND liquid scintillator (3% wt)
- Dedicated balloon immersed in the main vessel.
- Larger number of PMT and different scintillator – up to 400 kg of enriched Xe in the first phase

**SNO+** – $^{150}$Nd
- SNO detector filled with Nd-loaded liquid scintillator
- 0.1% loading with natural Nd → 1000 Kg Nd in 1000 tons scintillator → 56 Kg of isotope
- Nd enrichment and purity are an issue.

**XMASS** – $^{136}$Xe
- Multipurpose (Dark Matter, Double Beta Decay, solar neutrinos) scintillating liquid Xe detector
- Three development stages: 3 Kg (prototype) → 1 ton → 10 tons natural or 1 ton enriched
- DBD option: low background in the MeV region (water tank)
- Good light yield and collection efficiency ⇒ energy resolution down to 1.4%

**CANDLES** – $^{48}$Ca
- Array of natural (no Eu doping) CaF$_2$ scintillators
- Proved energy resolution: 3.4 % FWHM
- Very high Q-value of $^{48}$Ca: 4.27 MeV
- PSD and space-time correlation for Bi-Po and Bi-Tl
### Experiments: group 5

#### Inhomogeneous with low energy resolution

**SUPERNEMO** - $^{82}\text{Se}$ or $^{150}\text{Nd}$
- Modular (source foils). Tracking (drift chamber in Geiger mode) and calorimetric (low Z scintillator) sections - Magnetic field for charge sign.
- 20 modules with 5 kg source for each module $\Rightarrow 100\ \text{Kg}$ in Modane extension.
- Energy resolution: 4 % FWHM. Takes advantage of NEMO3 experience
- First step: single module (demonstrator) @ Modane

**MOON** - $^{100}\text{Mo}$ or $^{82}\text{Se}$ or $^{150}\text{Nd}$
- Multilayer plastic scintillators interleaved with source foils + tracking section (PL fibers or MWPC)
- MOON-1 prototype without tracking section (2006)
- MOON-2 prototype with tracking section
- Proved energy resolution: 6.8 % FWHM
- Final target: collect 5 y x ton

**DCBA** - $^{150}\text{Nd}$
- Momentum analyzer for beta particles consisting of source foils inserted in a drift chamber with magnetic field
- Test prototype DCBA-T2 completed: space resolution $\sim 0.5\ \text{mm}$; energy resolution 6 % FWHM at 3 MeV
- Test prototype DCBA-T3 under construction: improved energy resolution (higher magnetic field 2kG) and better space resolution
- Final target: 10 modules with 84 m² source foil for module (126 through 330 Kg total mass)
## Experimental Status

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Mass</th>
<th>Technique</th>
<th>Location</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current experiments (funded, construction, running)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GERDA I/II</strong></td>
<td>$^{76}$Ge</td>
<td>15/35</td>
<td>ionization</td>
<td>LNGS</td>
<td>2011/13</td>
</tr>
<tr>
<td><strong>Majorana</strong></td>
<td>$^{76}$Ge</td>
<td>30</td>
<td>ionization</td>
<td>SUSEL</td>
<td>2014</td>
</tr>
<tr>
<td><strong>EXO200</strong></td>
<td>$^{136}$Xe</td>
<td>200</td>
<td>liquid TPC</td>
<td>WIPP</td>
<td>2011</td>
</tr>
<tr>
<td><strong>CUORE0/CUORE</strong></td>
<td>$^{130}$Te</td>
<td>10/200</td>
<td>bolometer</td>
<td>LNGS</td>
<td>2012/14</td>
</tr>
<tr>
<td><strong>Kamland-Zen</strong></td>
<td>$^{136}$Xe</td>
<td>400</td>
<td>liquid scintillator</td>
<td>Kamioka</td>
<td>2011</td>
</tr>
<tr>
<td><strong>SNO+</strong></td>
<td>$^{150}$Nd</td>
<td>44</td>
<td>liquid scintillator</td>
<td>Sudbury</td>
<td>2014</td>
</tr>
<tr>
<td><strong>NEXT</strong></td>
<td>$^{136}$Xe</td>
<td>100</td>
<td>gas TPC</td>
<td>Canfranc</td>
<td>2013+</td>
</tr>
<tr>
<td><strong>Candles III</strong></td>
<td>$^{48}$Ca</td>
<td>0.35</td>
<td>scintillating crystals</td>
<td>Oto Cosmo</td>
<td>2011</td>
</tr>
<tr>
<td><strong>MOON</strong></td>
<td>$^{82}$Se/$^{150}$Nd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DCBA</strong></td>
<td>$^{150}$Nd</td>
<td>32</td>
<td>tracking</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cobra</strong></td>
<td>$^{116}$Cd</td>
<td></td>
<td>solid TPC</td>
<td>LNGS</td>
<td></td>
</tr>
<tr>
<td><strong>SuperNEMO</strong></td>
<td>$^{82}$Se</td>
<td>7/100-200</td>
<td>track/calorimeter</td>
<td>Modane</td>
<td>2014/?</td>
</tr>
<tr>
<td><strong>XMASS</strong></td>
<td>$^{136}$Xe</td>
<td></td>
<td>liquid scintillator</td>
<td>Kamioka</td>
<td></td>
</tr>
<tr>
<td><strong>Lucifer</strong></td>
<td>$^{82}$Se</td>
<td>17.6</td>
<td>scintillating bolometer</td>
<td>LNGS</td>
<td>2014</td>
</tr>
</tbody>
</table>

R&D (funding, prototyping)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Mass</th>
<th>Technique</th>
<th>Location</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEXT</td>
<td>$^{136}$Xe</td>
<td>100</td>
<td>gas TPC</td>
<td>Canfranc</td>
<td>2013+</td>
</tr>
<tr>
<td>Candles III</td>
<td>$^{48}$Ca</td>
<td>0.35</td>
<td>scintillating crystals</td>
<td>Oto Cosmo</td>
<td>2011</td>
</tr>
<tr>
<td>MOON</td>
<td>$^{82}$Se/$^{150}$Nd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCBA</td>
<td>$^{150}$Nd</td>
<td>32</td>
<td>tracking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobra</td>
<td>$^{116}$Cd</td>
<td></td>
<td>solid TPC</td>
<td>LNGS</td>
<td></td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se</td>
<td>7/100-200</td>
<td>track/calorimeter</td>
<td>Modane</td>
<td>2014/?</td>
</tr>
<tr>
<td>XMASS</td>
<td>$^{136}$Xe</td>
<td></td>
<td>liquid scintillator</td>
<td>Kamioka</td>
<td></td>
</tr>
<tr>
<td>Lucifer</td>
<td>$^{82}$Se</td>
<td>17.6</td>
<td>scintillating bolometer</td>
<td>LNGS</td>
<td>2014</td>
</tr>
</tbody>
</table>
**GERDA**

**Ge diodes** (86% enriched $^{76}$Ge) **in Lar cryostat** (active in phase II) **in water tank** (active)

**BEGe technology** in phase-II: better E resolution, Multi/Single interaction discrimination

@LNGS  
Phase-I ~ end 2011  
Phase-II ~ 2013

---

**ββ candidate:** $^{76}$Ge – $Q$ 2039 keV

**Source Mass:**
- Phase-I: 18 kg $^{76}$Ge – $N_{ββ}$ $1.4 \times 10^{26}$
- Phase-II: 40 kg $^{76}$Ge – $N_{ββ}$ $3.2 \times 10^{26}$

**Projected Bkg:**
- Phase-I: 0.01 c/keV/kg/y
- Phase-II: 0.001 c/keV/kg/y

**Sensitivity $T_{1/2}^{0ν}$:**
- Phase-I: $2.5 \times 10^{25}$ y in 1 y
- Phase-II: $1.9 \times 10^{26}$ y in 5 y

**Sensitivity $<m_{ee}>$:**
- I: Scrutinize KK claim (if true 7 $ββ$ cts over 0.5 cts of bkg) in < 2 y
- II: $<m_{ee}> < 73 \div 203$ meV in 5 y > IH
GERDA is running and taking data
- **statistics**: 1.11.2011 – 21.5.2012 (enrGe exposure 6.10 kg yr)
- **systematics**: blinding 2019 – 2059 keV
- **background index** (BI): 0.020 +0.006 -0.004 cts/(keV kg yr) [68% coverage]
- **LAr**: $^{42}$Ar ($^{42}$K) activity determined: (93.0 Å)

$T_{1/2}^{0\nu\beta\beta (^{76}\text{Ge})} = (1.88 \pm 0.10) \times 10^{21}$ y

S/B~10/1
**CUORE**

988 TeO$_2$ (33.8% ai $^{130}$Te) **bolometers at ~ 10 mK in a granular structure** (741 kg mass)

@LNGS  Phase-I (CUORE0): starts ~ mid 2012  Phase-II: ~ 2014  Future: enr., scintillating bolom.?

**ββ candidate:** $^{130}$Te – Q 2527.5 keV

**Source Mass:**
- Phase-I: 10.8 kg $^{130}$Te – $N_{ββ}$ 5.0 x10$^{25}$
- Phase-II: 206 kg $^{130}$Te – $N_{ββ}$ 9.6 x10$^{26}$

**Projected Bkg:**
- Phase-I : 0.05 c/keV/kg/y
- Phase-II: 0.01 c/keV/kg/y

**Resolution:** ~ 5 keV @ROI

**Sensitivity $T_{1/2}^{0ν}$:**
- Phase-I: 4.2x10$^{24}$ y in 1 y
- Phase-II: 1.6x10$^{26}$ y in 5 y

**Sensitivity Phase-II $<m_{ee}>$:**

$<m_{ee}> < 40 ÷ 94$ meV in 5y (IH)

F. Alessandria et al., nucl-ex:1109.0494v1
CUORE-0

Goals:
• full test and debug of the new CUORE assembly line
• high statistics check of the improved uniformity of bolometric response

→ P.Gorla talk
CUORE status

- Crystals, almost completely arrived (all at LNGS by the end of 2012)
- Copper parts are being machined and cleaned
- Dilution unit performance better than expected and delivered to LNGS
- CUORE Hut, and most of all the infrastructures, ready
- Detector assembly line, ready and tested (CUORE0)
- Radon abatement system installed
- 3 (of 6) cryostat vessels tested and delivered at LNGS
- Commissioning of the cryostat started on July 2012
Crystat commissioning in the CUORE underground lab @ LNGS
~16 t (40 t in 2nd phase) Liquid Scintillator 2.5wt% $^{136}$Xe loaded (91% enrichment of $^{136}$Xe) in a Ø3.4m Mini Balloon in Kamland detector (1000t LS+Buffer Oil+Water Cherenkov Outer Detector) @Kamioka mine 1st Phase~ end 2011 2nd Phase >2013

$\beta\beta$ candidate: $^{136}$Xe – Q 2476 keV

**Source Mass:**
1st Phase: 364 kg $^{136}$Xe – $N_{\beta\beta}$ 1.6 x10$^{27}$
2nd Phase: 700 kg $^{136}$Xe – $N_{\beta\beta}$ 4.0 x10$^{27}$

**Main Bkg:**
- $2\nu\beta\beta$ $^{136}$Xe (slow: $T_{1/2}\sim10^{22}$ y)
- $^{10}$C, $^{11}$Be (1/10 with tag)
- $^{8}$B solar $\nu$
- $^{214}$Bi, $^{208}$Tl from MB (vertex cut)

**Target Sensitivity:**
1st phase: $<m_{ee}> \sim 60$ meV @1 y
2nd phase: $<m_{ee}> \sim 25$ meV @5 y (IH)

**Measured FWHM:** ~ 10% @ROI
LY: 8000 photons/MeV

$\Rightarrow$ expected S/Bkg ~ 2
precise measurement of the $2\nu\beta\beta$ half-life:

$$T_{1/2}^{2\nu\beta\beta} \left( ^{136}\text{Xe} \right) = (2.30 \pm 0.02 \text{ stat} \pm 0.12 \text{ sys}) \cdot 10^{21} \text{ yr}$$
Results and perspectives:
• validity of using the low radioactivity environment of neutrino detector for a rare phenomena study
• better understanding of background → effective purification is about to start (reduction factor 100)
• R&D for larger Xe concentration and better light yield

KL-Zen: 112 days
$^{110}\text{Ag} + ^{208}\text{Bi}$ fit

$\tau_{1/2}^{0\nu\beta\beta} \left(^{136}\text{Xe}\right) > 6.2 \cdot 10^{24}$ y
EXO-200

~ 1 ton TPC of liquid $^{136}\text{Xe}$ (80.6% of $^{136}\text{Xe}$) at 167 K with double read-out (ion+scint) allowing event 3D tracking and $\alpha/\beta$ discrimination + Ba$^+$ daughter tag for free bkg exp.

GOAL of EXO-200: 1$^{st}$ step with 175 kg LXe without Ba$^+$ tag for QD region @WIPP

Exo-200: Started 2011 – 2$v\beta\beta$ result: $T_{1/2} \sim 2.1 \times 10^{21}$ y

Start Exo-full?

$\beta\beta$ candidate: $^{136}\text{Xe} – Q 2458$ keV

Source Mass:
- Exo-200: ~ 80 kg FMass $^{136}\text{Xe} – N_{\beta\beta} 3.5 \times 10^{26}$

Bkg Strategy:
- low activity materials / LXe purity check
- conventional screening techniques+ FV cut
- 3D track (double grid (xy) + Avalanche Photo Diodes ($t_o \rightarrow z$))
- $\alpha/\beta$ discrimination through ion. vs. light
- Ba$^+$ tag with Resonant Ionization Spectrosc.

Projected Bkg: $\sim 10^{-4}$ c/keV/kg/y

Projected FWHM: $\sim 3.7\%$ @ROI (maybe better if gas Xe)

Target Sensitivity:
- Exo-200: $T_{1/2} \sim 6.4 \times 10^{25}$ y @2y $\langle m_{ee} \rangle < 87 \pm 224$ meV in 2y
- Exo-full: $T_{1/2} \sim 2.0 \times 10^{27}$ y @ 5y $\langle m_{ee} \rangle < 16 \pm 40$ meV in 5y
Resolution: scintillation vs charge

- Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa).
- Use projection onto a rotated axis to determine event energy.


Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)
**EXO: 2νββ**

- Trigger fully efficient above 700 keV
- Low background run livetime: 120.7 days
- Active mass: 98.5 kg LXe (79.4 kg 136LXe)
- Exposure: 32.5 kg.yr
- Total dead time from vetos: 8.6%

- ~22,000 2νββ events!
- Also populate MS spectrum, partly due to bremsstrahlung
- MC predicts that 82.5% of 2νββ are SS

\[ \tau_{1/2}^{2\nu\beta\beta} (^{136}\text{Xe}) = (2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys}) \cdot 10^{21} \text{ yr} \]

5 times faster than previous limit
EXO-200 is taking low background data. Detector works well:

- Energy resolution: 1.67% at Qββ
- Background: $1.5 \times 10^{-3}$ (kg keV yr)$^{-1}$
- 1 (5) counts in 1σ (2σ) 0νββ ROI
- Background within expectation

- Improvements on resolution and b in progress
- EXO-200 approved to run for 4 more years
EXO-200 and $\beta\beta0\nu$ evidence

Comparison between $\beta\beta0\nu$ half lifetimes in $^{76}\text{Ge}$ and $^{136}\text{Xe}$ for different matrix element calculations

The claim is excluded by the EXO-200 result according to most NME calculations.

Experimental perspectives

Mass = kg of isotope
B = counts/keV/kg(isotope)/yr

“Finite” Background region

“Zero” Background region

Golden region

K-zen II
K-zen
CUORE
EXO-200
CUORE0

NEXT
sN
sN D
Lucifer
GERDA II
GERDA I
SNO+

Mass = kg of isotope
B = counts/keV/kg(isotope)/yr
### Present/Next Future

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Q</th>
<th>FWHM</th>
<th>bkg</th>
<th>mass</th>
<th>i.a.</th>
<th>counts per year</th>
<th>S(5y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>2527</td>
<td>5</td>
<td>$1 \times 10^{-2}$</td>
<td>750</td>
<td>0.35</td>
<td>32.3</td>
</tr>
<tr>
<td>GERDA-I</td>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>5</td>
<td>$2 \times 10^{-2}$</td>
<td>14.6</td>
<td>0.86</td>
<td>1.1</td>
</tr>
<tr>
<td>GERDA-I/II</td>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>3</td>
<td>$1 \times 10^{-3}$</td>
<td>3.5</td>
<td>0.86</td>
<td>0.0</td>
</tr>
<tr>
<td>GERDA-II</td>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>3</td>
<td>$1 \times 10^{-3}$</td>
<td>24</td>
<td>0.86</td>
<td>0.1</td>
</tr>
<tr>
<td>K-Zen</td>
<td>$^{136}$Xe</td>
<td>2458</td>
<td>243</td>
<td>$8.1 \times 10^{-3}$</td>
<td>320</td>
<td>0.90</td>
<td>266.4</td>
</tr>
<tr>
<td>K-Zen II</td>
<td>$^{136}$Xe</td>
<td>2458</td>
<td>243</td>
<td>$8.1 \times 10^{-3}$</td>
<td>700</td>
<td>0.90</td>
<td>582.9</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>2458</td>
<td>96</td>
<td>$1.5 \times 10^{-3}$</td>
<td>98.5</td>
<td>0.81</td>
<td>11.8</td>
</tr>
<tr>
<td>MJD</td>
<td>$^{76}$Ge</td>
<td>2039</td>
<td>3</td>
<td>$1 \times 10^{-3}$</td>
<td>30</td>
<td>0.86</td>
<td>0.1</td>
</tr>
<tr>
<td>SuperNEMO D</td>
<td>$^{82}$Se</td>
<td>2997</td>
<td>120</td>
<td>7</td>
<td>1.00</td>
<td>0.0</td>
<td>$3.35 \times 10^{25}$</td>
</tr>
</tbody>
</table>

### References

Conclusions

• $0\nu\beta\beta$ searches have still a very strong scientific motivation: lepton number violation, Majorana nature and properties (mass) of $\nu$

• NME calculations: better understanding but still discrepancies $\sim 2$ in calculations

• Present generation experiments look for large masses ($\sim 100$ kg) good energy resolutions and low background to sound the IH region in a variety of DBD nuclei

• Three of them (GERDA, EXO-200 and Kamland-Zen) have already started data taking and have just provided exciting results while CUORE is in an advanced phase of construction.

• Claim for evidence in $^{76}$Ge with $\langle m_{ee} \rangle \sim 0.3$ eV (DH) ($6\sigma$) will be soon scrutinized.

• A number of 10-50 kg projects aim at understanding backgrounds origin and demonstrating the feasibility of high sensitivity "zero background" next generation experiment to sound the NH region in the next 5-10 years.

• Their results will determine the best isotope and technique for future experiments