Neutrinoless double beta decay: Experimental challenges

Konstantin Gusev
JINR, Dubna

NOW 2018
September 2018 – Rosa Marina (Ostuni, Italy)
In 1936 Maria Göppert-Mayer noted, that in some even-even nuclei the single β-decay is energetically forbidden whereas the simultaneous but independent β-decay of two nucleons (so-called double beta decay) is allowed.
Short intro

Why $(0\nu)\beta\beta$-decay?

• violates lepton number? **NO**
• forbidden in SM? **NO**

• but half life is $10^{10}$ longer than the age of the universe, however already observed!

$^{76}\text{Ge}: \ T_{1/2}^{2\nu} = 1.92 \times 10^{21}\text{yr}$

• violates lepton number? **YES!**
• forbidden in SM? **YES!**

**New Physics!**

• $\nu$ has **Majorana** mass component
Short intro

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- violates lepton number? **YES!**
- forbidden in SM? **YES!**

**New Physics!**

- $\nu$ has **Majorana** mass component
- IF light neutrino exchange

**Access to $\nu$ mass scale**
Short intro

What are we measuring?

Summed electron spectrum ($^{76}$Ge):

0νββ:
Sharp peak at Q-value of the decay

$T_{1/2}^{0ν} > 10^{25}$ yr

2νββ:
Continuous spectrum

$T_{1/2}^{2ν} \sim 10^{21}$ yr

Background for 0νββ

Energy resolution essential
Short intro

What are we measuring?

✓ Resolution remains essential due to $2\nu\beta\beta$
Short intro
How to measure?

Experimental sensitivity:

- **Zero** background:
  \[ T^{0\nu}_{1/2} \propto M t \]

- Non-zero background:
  \[ T^{0\nu}_{1/2} \propto \sqrt{\frac{M t}{\Delta E BI}} \]

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( G^{0\nu} (10^{-14} \text{yr}) )</th>
<th>( Q (\text{keV}) )</th>
<th>Nat. ab. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{48}\text{Ca})</td>
<td>6.3</td>
<td>4273.7</td>
<td>0.187</td>
</tr>
<tr>
<td>(^{76}\text{Ge})</td>
<td>0.63</td>
<td>2039.1</td>
<td>7.8</td>
</tr>
<tr>
<td>(^{82}\text{Se})</td>
<td>2.7</td>
<td>2995.5</td>
<td>9.2</td>
</tr>
<tr>
<td>(^{100}\text{Mo})</td>
<td>4.4</td>
<td>3035.0</td>
<td>9.6</td>
</tr>
<tr>
<td>(^{130}\text{Te})</td>
<td>4.1</td>
<td>2530.3</td>
<td>34.5</td>
</tr>
<tr>
<td>(^{136}\text{Xe})</td>
<td>4.3</td>
<td>2461.9</td>
<td>8.9</td>
</tr>
<tr>
<td>(^{150}\text{Nd})</td>
<td>19.2</td>
<td>3367.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

- Target mass and detector efficiency as high as possible
- **“Zero-background”** to have linear increase of sensitivity vs exposure

*Target mass and detector efficiency as high as possible)*

"Zero-background" to have linear increase of sensitivity vs exposure
Short intro

What about mass?

Effective Majorana neutrino mass contributes in the decay rate:

\[
\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2
\]

\[
\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|
\]

\[
m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|
\]

Dell'Oro et al., PRD 90, 033005 (2014)
Short intro
NME

\[
\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2
\]

- No preferred isotope from Nuclear Physics (G*M)

Engel & Menéndez
arXiv: 1610.06548v2

See today’s talk by Fedor Simkovic
Short intro

Two experimental approaches

Source = Detector

GERDA, MJD, CUORE, EXO, Kamland-Zen, SNO+, ...

+ High detection efficiency
+ Large target mass possible
± Reconstruction of event topologies

Source ≠ Detector

SuperNEMO

Decay vertex
Charged particle trajectory
Particle individual energy and TOF

Modular thin \( \beta \beta \) source foil
High granularity tracking volume
Segmented calorimeter

+ Reconstruction of event topologies
+ Coincidence scheme
→ zero background
+ No restriction on isotopes

– Difficult to obtain large masses

K. Gusev | NOW 2018
### 0νββ-experiments

**Now**

<table>
<thead>
<tr>
<th>Source ≠ Detector</th>
<th>Easy to get huge mass</th>
<th>Energy resolution</th>
</tr>
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<tbody>
<tr>
<td>Gas or liquid TPCs</td>
<td>EXO-200</td>
<td></td>
</tr>
<tr>
<td>Liquid scintillators</td>
<td>KamLAND-Zen</td>
<td></td>
</tr>
<tr>
<td>Crystal Bolometers</td>
<td>CUORE</td>
<td></td>
</tr>
<tr>
<td>Ge-detectors</td>
<td>GERDA</td>
<td></td>
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Adapted from A. Giuliani, Neutrino2018
0νββ-experiments
Soon

<table>
<thead>
<tr>
<th>Gas or liquid</th>
<th>TPCs</th>
<th>EXO-200 NEXT-10</th>
<th>NEXT-100 PANDA-X-III</th>
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<tr>
<td>Liquid scintillators</td>
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<td>KZ-800 SNO+ phase I</td>
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<thead>
<tr>
<th>Crystal</th>
<th>Bolometers</th>
<th>CUORE CUPID-0,-Mo AMoRE</th>
<th>AMoRe II</th>
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<td>Ge-detectors</td>
<td>GERDA MJD</td>
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<td>LEGEND-200</td>
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| Source ≠ Detector | | | SuperNEMO |

Adapted from A. Giuliani, Neutrino2018

K. Gusev | NOW 2018
### 0νββ-experiments

#### Future

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<th>Gas or liquid</th>
<th>TPCs</th>
<th>Now</th>
<th>Soon</th>
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<td>Liquid scintillators</td>
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<td>KZ-800 SNO+ phase I</td>
<td>KamLAND2-Zen SNO+ phase II</td>
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| Source ≠ Detector | | | | | SuperNEMO |

*Easy to get huge mass*

*Energy resolution*

*Adapted from A. Giuliani, Neutrino2018*
## $0\nu\beta\beta$-experiments

### Now 2018

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<th>Now</th>
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K. Gusev | NOW 2018
0νββ-decay with TPCs
EXO-200 and nEXO

EXO-200 will finish data taking in 2018

<table>
<thead>
<tr>
<th>Method</th>
<th>Liquid TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>WIPP, USA</td>
</tr>
<tr>
<td>Isotope</td>
<td>136Xe</td>
</tr>
<tr>
<td>$T_{1/2}$ sensitivity</td>
<td>$&gt; 3.7 \times 10^{25}$ yr (90% CL)</td>
</tr>
<tr>
<td>Limit</td>
<td>$&gt; 1.8 \times 10^{25}$ yr (90% CL)</td>
</tr>
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</table>

From EXO-200 to nEXO:
- 150 kg $\rightarrow$ 5000 kg
- WIPP $\rightarrow$ SNOLAB
- $3.7 \rightarrow 920 \times 10^{25}$ yr

PRL 120 072701 (2018)
0νββ-decay with liquid scintillators
KamLAND-Zen, 800, 2-Zen

**Past**

KamLAND-Zen 400
320-380 kg of Xenon
Data taking 2011 ~ 2015

**Present**

KamLAND-Zen 800
~750 kg of Xenon
DAQ to start in this year

**Future**

KamLAND2-Zen
~1 ton of $^{136}$Xe
Better energy resolution

<table>
<thead>
<tr>
<th>Method</th>
<th>Xe-loaded LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Kamioka, JAPAN</td>
</tr>
<tr>
<td>Isotope</td>
<td>$^{136}$Xe</td>
</tr>
<tr>
<td>$T_{1/2}$ sensitivity</td>
<td>$&gt; 5.6 \cdot 10^{25}$ yr (90% CL)</td>
</tr>
<tr>
<td>Limit</td>
<td>$&gt; 1.1 \cdot 10^{26}$ yr (90% CL)</td>
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Status 2018:
✓ New balloon installed
✓ Filled in May 2018 with dummy LS
✓ Will be replaced with Xe-loaded LS

See today’s talk by Yoshihito Gando

PRL 117 109903 (2016)
$0\nu\beta\beta$-decay with liquid scintillators

**SNO+**

- SNOLAB, Ontario
- 780 ton LAB/PPO (2g/L) in 6m radius acrylic vessel
- ~9400 PMTs at 8.5m

**Phased implementation:**
- Water phase → ongoing
- Pure scintillator phase → LS fill in July 2018
- Loaded scintillator phase → 0.5% $^{130}$Te loading in 2019

1300 kg of $^{130}$Te

$T_{1/2} > 1.9e26$ yrs (90% CL) in 5 years

See talk on Sept 11 by Edward Leming
0νββ-decay with bolometers

CUORE and CUPID

Status 2018:
✓ CUORE is taking data
✓ 5 y projected half-life sensitivity: ~10^{26} y

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<td>T_{1/2} sensitivity</td>
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<tr>
<td>Limit (latest)</td>
<td>&gt; 1.5·10^{25} yr (90% CL)</td>
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_PRL 120 132501 (2018)_

See today’s talk by Paolo Gorla
0νββ-decay with bolometers

CUORE and CUPID

Status 2018:
✓ CUORE is taking data
✓ 5 y projected half-life sensitivity: $\sim 10^{26}$ y

CUORE Upgrade with Particle ID (CUPID)

New detector technology – luminescent bolometers:

- $^{130}$TeO$_2$ + Cherenkov light
- CUPID-0 – Zn$^{82}$Se
- CUPID-Mo – Li$_2^{100}$MoO$_4$ – baseline option for CUPID

Mission:
half-life sensitivity higher than $10^{27}$ y

Method | Bolometers
---|---
Location | LNGS, Italy
Isotope | $^{130}$Te
$T_{1/2}$ sensitivity | $> 0.7 \cdot 10^{25}$ yr (90% CL)
Limit (latest) | $> 1.5 \cdot 10^{25}$ yr (90% CL)

PRL 120 132501 (2018)

See today’s talk by Paolo Gorla
See today’s talk by Nicola Casali
$0\nu\beta\beta$-decay with Ge detectors

HPGe detectors enriched in $^{76}\text{Ge}$

- detector-grade germanium is high-purity material \(\Rightarrow\) low background
- established detector technology \(\Rightarrow\) industrial support
- very good energy resolution \(\sim 0.1\%\) at $Q_{\beta\beta}$
- high detection efficiency

source = detector
0νββ-decay with Ge detectors

MJD

Features:
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics yields better PSD
- Low energy threshold (cosmogenic and low-E background)

Status 2018:
- Data taking ongoing
- Planning an upgrade to improve channel reliability and background

Expect to reach 50-70 kg yr exposure with sensitivity in the range of 10^{26} yr

<table>
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<tr>
<th>Method</th>
<th>Ge detectors</th>
</tr>
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<tbody>
<tr>
<td>Location</td>
<td>SURF, USA</td>
</tr>
<tr>
<td>Isotope</td>
<td>^{76}\text{Ge}</td>
</tr>
<tr>
<td>$T_{1/2}$ sensitivity</td>
<td>$&gt; 4.8 \cdot 10^{25}$ yr (90% CL)</td>
</tr>
<tr>
<td>Limit (latest)</td>
<td>$&gt; 2.7 \cdot 10^{25}$ yr (90% CL)</td>
</tr>
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V. Guiseppe, Neutrino2018

Arrays of Ge-diodes in high purity electroformed Cu cryostat
0νββ-decay with Ge detectors

GERDA

Features:

- LAr active veto
- Low-A shield, no Pb

Method | Ge detectors
Location | LNGS, Italy
Isotope | 76Ge
T_{1/2} sensitivity | $> 1.1 \cdot 10^{26}$ yr (90% CL)
Limit (latest) | $> 0.9 \cdot 10^{26}$ yr (90% CL)

A.J. Zsigmond, Neutrino2018

✓ Bare Ge-diodes array in liquid Ar

GERDA will collect data until the end of 2019
0νββ-decay with Ge detectors

**GERDA**

- Method: Ge detectors
- Location: LNGS, Italy
- Isotope: $^{76}$Ge
- $T_{1/2}$ sensitivity: > $1.1 \cdot 10^{26}$ yr (90% CL)
- Limit (latest): > $0.9 \cdot 10^{26}$ yr (90% CL)

**Features:**

- LAr active veto
- Low-A shield, no Pb

**Bare Ge-diodes array in liquid Ar**

**GERDA** will collect data until the end of 2019
0νββ-decay with Ge detectors

GERDA: results 2018

✓ 60 kg yr of data collected in Phase II by April 2018
✓ 82.4 kg yr in total (Phase I + II)
✓ Unique background indices achieved:
  Coax: $5.7^{+4.1}_{-2.6} \times 10^{-4}$ cts/(keV·kg·yr)
  BEGe: $5.6^{+3.4}_{-2.4} \times 10^{-4}$ cts/(keV·kg·yr)
  best in the field when normalized to FWHM!

New 2018 limits:
✓ Median sensitivity for limit setting:
  $1.1 \times 10^{26}$ yr (world best!)
✓ Best fit → no signal
  $T_{1/2}^{0ν} > 0.9 \times 10^{26}$ yr (90% CL)
✓ Probability to have stronger limit 63%

GERDA reached important milestone for 0νββ search!

See today’s talk by Christoph Wiesinger
0νββ-decay with Ge detectors

GERDA: upgrade 2018

Upgrade of the GERDA experiment aims to:
✓ Test the novel detectors + increase the mass of $^{76}\text{Ge}$
✓ Show the possibility to improve the background index
✓ Prove the robustness and reproducibility of the GERDA approach

Upgrade includes:
• New LAr veto:
  ✓ new fiber curtain (improved light collection) + central module to read out hidden Ar volume
• Installation of 5 novel inverted coaxial detectors made from $^{76}\text{Ge}$
  ✓ Total increase of $^{76}\text{Ge}$ mass ~ 6 kg!
• Exchange of all signal and HV cables by new ones with better radiopurity
• New signal cable routing to reduce the cross-talk and improve resolution
• Repairing of broken electronic channels and installation of protective diodes

old curtain          new curtain
810 fiber ends, 90 SiPMs
1215 fiber ends, 135 SiPMs

Central module
$0\nu\beta\beta$-decay with Ge detectors

LEGEND: the best from GERDA and MJD

Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

**First stage (L200):**
- (up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
- bkg reduction by factor 3-5 w.r.t GERDA
- Sensitivity $10^{27}$ yr

**Subsequent stages:**
- 1000 kg (staged)
- timeline connected to DOE down select process
- bkg factor 30 w.r.t GERDA
- Location tbd
- Sensitivity $10^{28}$ yr
0νββ-decay with Ge detectors

**LEGEND**: the best from GERDA and MJD

**Large Enriched Germanium Experiment for Neutrinoless ββ Decay**

**First stage (L200):**
- (up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
- bkg reduction by factor 3-5 w.r.t GERDA
- Sensitivity $10^{27}$ yr
- Plan to **start** data taking in 2019

**Subsequent stages:**
- 1000 kg (staged)
- timeline connected to DOE down select process
- bkg factor 30 w.r.t GERDA
- Location tbd
- Sensitivity $10^{28}$ yr

L200 Funding secured!
0νββ-decay with Ge detectors

LEGEND: sensitivity

- $T_{1/2}$ limit (90% C.L.)
- Discovery (50% chance for a 3σ signal)

- **T$_{1/2}$ unknown**, BSM → 'around corner'
- background reduction in steps → phased approach

- inputs: 60% efficiency (GERDA number)
- Background: GERDA/MJD $\sim$ 3 cts/(FWHM t yr)
  - 200 kg $\sim$ 0.6 cts/(FWHM t yr)
  - 1000 kg $\sim$ 0.1 cts/(FWHM t yr)

N.B.: background-free operation is a prerequisite for a discovery
$0
νββ$-decay experiments

Discovery probability

*Discovery probability of next-generation neutrinoless double-$β$ decay experiments*

M. Agostini, G. Benato and J. A. Detwiler

*Phys. Rev. D 96, 053001 (2017)*
0νββ-decay experiments

Summary

- 0νββ decay is a crucial process, New Physics maybe around the corner
- Very active field: several ton-scale experiments are in preparation
- Huge experimental effort: tons of material, but “zero” background
- The discovery probability for the next generation projects is pretty high
- We need to observe the signal with multiple isotopes using various experimental methods