GERDA: first background free search for neutrinoless double beta decay

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for the GERDA collaboration

ICNFP 2017
August 2017 – Crete – Greece
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 in 0νββ-decay

$
\text{Ge} \rightarrow \text{As} + e^- + v_e
$

energetically forbidden

$Q = 2039 \text{ keV}$

$\text{Se} \rightarrow 2e^- + 2v_e$

2nd order allowed weak process

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Short intro

Why (0ν)ββ-decay?

2νββ

- violates lepton number? **NO**
- forbidden in SM? **NO**
- but half life is $10^{10}$ longer than the age of the universe, however already observed!

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

0νββ

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

**New Physics!**

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

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- forbidden in SM? **NO**

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

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

**New Physics!**

- $\nu$ has **Majorana** mass component
- 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

\[ T^{0ν}_{1/2} > 10^{25}\text{yr} \]

2νββ:
Continuous spectrum

\[ T^{2ν}_{1/2} \sim 10^{21}\text{yr} \]

Background for 0νββ

Energy resolution essential
Short intro

What about mass?

Effective Majorana neutrino mass contributes in the decay rate:

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

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

\[
m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|
\]
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
Short intro
How to measure?

Experimental sensitivity:

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

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

- \( M t \) – exposure (kg yr)
- \( \Delta E \) – energy resolution (keV)
- \( BI \) – background index (counts/keV kg yr)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( G^{0\nu} ) (10(^{-14}) yr)</th>
<th>( Q ) (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

- enrichment required except for \(^{130}\text{Te}\), not (yet) possible for all, costs differ
Short intro

Two experimental approaches

**Source = Detector**

- GERDA, Majorana, CUORE, EXO, Kamland-Zen, ...
- + High detection efficiency
- + Large target mass possible
- ± Reconstruction of event topologies
- – Restricted number of isotopes

**Source ≠ Detector**

- SuperNEMO
- + Reconstruction of event topologies
- + Coincidence scheme → zero background
- + No restriction on isotopes
- – Difficult to obtain large masses

More about 0νββ searches on Aug 26th & ICNFP17 in B. Schwingenheuer’s talk
GERDA approach

HPGe detectors enriched in $^{76}$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
GERDA approach
enriched HPGe detectors in cryogenic liquid

- detector-grade germanium is high-purity material ⇒ low background
- established detector technology ⇒ industrial support
- very good energy resolution ~0.1% at $Q_{\beta\beta}$
- high detection efficiency
  source = detector
- bare detectors in liquid argon
GERDA
the Collaboration

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

16 institutions
~110 members
GERDA
the Collaboration
GERDA Sensitivity

Phase I (Nov 2011 – May 2013):
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

Phase II (Dec 2015 – ongoing):
Add new BEGe detectors (20 kg)
BI ≈ 0.001 cts / (keV kg yr)
Sensitivity after 100 kg yr

$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr (90% CL)

(PRL 111 (2013) 122503)
GERDA location

✓ deep underground – Hall A of LNGS, Italy

3500 m.w.e
1.1 µ / (m² h)
GERmanium Detector Array

HPGe detectors

Coaxials:
- from Hdm and IGEX
- reprocessed by Canberra
- total mass ~ 18 kg

BEGes:
- novel Ge detectors
- produced by Canberra
- total mass ~ 20 kg
- better PSD and FWHM

Phase I
- 8 enriched coaxials
- 1 natural coaxial
- 5 Phase II BEGes

Phase II
- 7 enriched coaxials
- 3 natural coaxials
- 30 BEGes

! Bare Ge detectors in LAr – first time ever

! Pulse shape discrimination (PSD) + active veto (in Phase II)

! Blind analysis – first time in the field

K. Gusev | ICNFP 2017
GERDA
Design

a) overview

- plastic scintillator panels
  - muon veto
- clean room
- lock system
- 590 m$^3$ ultra-pure water
  - neutron moderator/absorber
  - muon Cherenkov veto
- 64 m$^3$ LAr cryostat
  - coolant, shielding
GERDA
Design

a) overview
b) liquid argon (LAr) veto instrumentation

590 m³ ultra-pure water neutron moderator/absorber muon Cherenkov veto

64 m³ LAr cryostat coolant, shielding

low activity PMTs
wavelength shifting fibers with SiPM read-out

plastic scintillator panels muon veto

lock system

clean room
GERDA
Design

a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array

- plastic scintillator panels
- muon veto
- lock system
- clean room
- 590 m³ ultra-pure water
- neutron moderator/absorber
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- 64 m³ LAr cryostat
- coolant, shielding
- low activity PMTs
- wavelength shifting fibers with SiPM read-out
- low-mass, low-activity electronics
- Ge detector array
GERDA Design

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a) Overview
b) Liquid argon (LAr) veto instrumentation
c) Detector array
d) Detector module

- Low activity PMTs
- Wavelength shifting fibers with SiPM read-out
- Ge detector array
- Low mass detector holder
- BEGe detector
- Low mass, low activity electronics
GERDA Phase II
Final integration (Dec 2015)

All 40 channels working!!!
GERDA Phase II
Final integration (Dec 2015)

All 40 channels working!!!
GERDA
Background rejection

Background:
Multi-site energy deposition:
- 1 HPGe – Pulse Shape Discrimination (PSD)
- > 1 HPGe – anti-coincidence (AC)
- HPGe + LAr – LAr veto

Surface events – PSD

- ✓ PSD and LAr complementary
- ✓ All α-s cut by PSD!
GERDA Performance

- Dec 2015 to April 2017, 93% duty cycle
- Weekly calibrations with $^{228}$Th sources
- Energy reconstruction with ZAC filter
  

- Final resolution corrected for $^{40/42}$K lines in physics data

FWHM at $Q_{\beta\beta}$:
Coaxial: $3.90(7) \text{ keV}$
BEGe: $2.93(6) \text{ keV}$
Gerda Performance

- Leakages current of detectors – no increase
- LAr veto performance – stays unchanged
- FWHM of HPGe diodes – stable
GERDA

Previous Phase II results (Phase IIa)

- New $T^{0νββ}_{1/2}$ limit from Phase I & Phase IIa data:
  - Sensitivity: $T^{0ν}_{1/2} > 4 \times 10^{25}\text{yr (90\% CL)}$
  - Limit: $T^{0ν}_{1/2} > 5.3 \times 10^{25}\text{yr (90\% CL)}$

- Background index (BI) for BEGe: $0.7^{+1.1}_{-0.5} \times 10^{-3}\text{cts/(keV kg yr)}$

  < 1 count in ROI up to design exposure (100 kg yr)

  background free!
GERDA
Current data taking

- Data taking is ongoing
  - Phase II exposure increased by \textbf{x3} with respect to Nature paper (Phase IIa)
  - \textbf{Valid} exposure accumulated \textbf{34.4 kg yr} up to Apr 15\textsuperscript{th} (Phase IIb)
    - 18.2 kg·yr of BEGe data
    - 16.2 kg·yr of Coaxial data
  - A few more kg·yr already available (Apr-Aug)

- Only BEGe dataset unblinded (\textbf{12.4 kg yr})
- New coaxial data (11.2 kg yr) still blinded:
  - \textbf{Background} similar to Phase IIa
  - Can be improved further by better rejection of $\alpha$-s from the groove
  - Work on better $\alpha$ cut is ongoing
- Total unblinded exposure: \textbf{23.3 kg yr}
GERDA Spectra

After LAr veto:

- Enriched coaxial - 16.2 kg yr
- Enriched BEGe - 18.2 kg yr

Graphs showing counts per 25 keV for different elements and decay modes, with annotations for Monte Carlo 2νββ decay and T1/2 = 1.92 × 10^{21} yr.
GERDA Spectra

After LAr veto + PSD:

- Prior liquid argon (LAr) veto
- After LAr veto
- After LAr veto and PSD
- 50 keV blinding

BEGe PSD removes all α-s!
GERDA

New unblinding (Cracow, 30th of June 2017)

BEGe dataset (18.2 kg yr)

<table>
<thead>
<tr>
<th>Counts in ROI</th>
<th>Bi at $Q_{\beta\beta}$ $\times 10^{-3}$ cts/ (keV kg yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$0.5^{+0.5}_{-0.3}$</td>
</tr>
</tbody>
</table>
GERDA
New unblinding

BEGe dataset (18.2 kg yr)

<table>
<thead>
<tr>
<th></th>
<th>Counts in ROI</th>
<th>Bl at $Q_{\beta\beta}$ x 10^{-3} cts/ (keV kg yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>2</td>
<td>$0.5^{+0.5}_{-0.3}$</td>
</tr>
<tr>
<td>After</td>
<td>4</td>
<td>$1.0^{+0.6}_{-0.4}$</td>
</tr>
</tbody>
</table>
**GERDA**

**New result**

Full exposure (46.7 kg yr)

<table>
<thead>
<tr>
<th>Exposure (kg yr)</th>
<th>Profile likelihood 2-side test stat.</th>
<th>Bayesian flat prior on cts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I (4 sets)</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>Phase IIa – coaxials</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Phase IIb – BeGe</td>
<td>5.8 + 12.4 = 18.2</td>
<td></td>
</tr>
</tbody>
</table>

**0νββ cts best fit value (cts)**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>0</th>
</tr>
</thead>
</table>

**$T_{1/2}^{0νββ}$ lower limit ($\times 10^{25}$ yr)**

<table>
<thead>
<tr>
<th></th>
<th>&gt; 8.0 (90% CL)</th>
<th>&gt; 5.1 (90% CL)</th>
</tr>
</thead>
</table>

**$T_{1/2}^{0νββ}$ median sensitivity ($\times 10^{25}$ yr)**

<table>
<thead>
<tr>
<th></th>
<th>5.8 (90% CL)</th>
<th>4.5 (90% CL)</th>
</tr>
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</table>

Best in 0νββ field!
GERDA

First background free 0νββ search

• Phase II is successfully taking data since December 2015

• Background design goal reached:
  ✓ BI in ROI for BEGe ~ $10^{-3}$ counts/(keV kg yr)
  ! best BI in ROI ever achieved!

• GERDA will stay background free up to 100 kg yr

• Sensitivity goal (~ $10^{26}$ yr):
  ✓ should be reached in 2018

• New $T_{1/2}^{0\nu\beta\beta}$ limit from Phase I & Phase II data:

  ✓ Sensitivity: $T_{1/2}^{0\nu} > 5.8 \times 10^{25}$ yr (90% CL) (best in the field)

  ✓ Limit: $T_{1/2}^{0\nu} > 8.0 \times 10^{25}$ yr (90% CL)
Beyond GERDA

LEGEND project

LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay):

- Collaboration formed in Oct 2016
- First stage with 200 kg of $^{76}$Ge in modified GERDA cryostat at LNGS

More about LEGEND in my talk on Aug 29$^{th}$ & ICNFP17
Additional slides
Phase II upgrade
LAr veto

- works well
- suppression factors depend on isotope, location and detector configuration
Phase II detector array

- 7 strings of detectors
- 30 BEGe detectors
- 10 semi-coaxial (Phase I) detectors: 7 enriched + 3 non-enriched

- Dense packing of detectors allows better anti-coincidence cut
- Each string enclosed by transparent nylon mini-shroud against $^{42}$K-ions:

  Suppression factor > 1000 for $^{42}$K bkg has been demonstrated in LArGe test facility (nylon mini-shroud + PSD + LAr veto)