New physics search with $^{76}\text{Ge} \, 0\nu\beta\beta$ decay

Yoann KERMAÏDIC

On behalf the GERDA and LEGEND collaborations

Les Rencontres de Physique de la Vallée d’Aoste

La Thuile, Italy

11 March 2019
Crucial open issues in particle physics

Baryonic asymmetry of the Universe

\[ \eta = \frac{n_b - n_b^-}{n_\gamma} = (6.05 \pm 0.07) \times 10^{-10} \]

Number of baryons / antibaryons

\( (\text{matter}) / (\text{antimatter}) \)

Number of photons

\( (\text{light}) \)

Among many theoretical models: the \textbf{leptogenesis}!?

Non-zero but tiny neutrino masses

\textbf{See-saw mechanism?}

- requires neutrinos to be \textbf{Majorana - Lepton Number is violated} in general
- new mass term in the Lagrangian \textbf{explaining the smallness of masses}
- provides a mechanism for \textbf{effective leptogenesis}

\[ \text{HOW TO RELATE THIS TO } ^{76}\text{Ge?} \]
Two neutrinos double beta decay - $2\nu\beta\beta$

![Diagram of double beta decay](image)

Such process:

- energetically favored in some isotopes ($^{76}\text{Ge}$, $^{82}\text{Se}$, $^{130}\text{Te}$, $^{136}\text{Xe}$, ...)
- is predicted by the SM
- is measured experimentally

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Neutrinoless double beta decay - $0\nu\beta\beta$

Such process:

- **Violates the Lepton Number** by 2 units = New Physics!
- Determines the nature of neutrinos: **Majorana particle** $\nu = \bar{\nu}$
- Gives information on the $\nu$ mass via $m_{\beta\beta}$ (light neutrino exchange scenario)
- Has never been observed so far

- High sensitivity due to the Avogadro number: $\sim 10^{25}$ Ge nuclei / kg
$^{76}\text{Ge}$ based $0\nu\beta\beta$ decay experiment

- $Q_{\beta\beta} = 2039$ keV
  - relatively low value as compared to other isotopes

- Calorimetry

- High detection efficiency
  - $2\beta$ decay source = detector

- Excellent energy resolution
  - $3$ keV FWHM @ $Q_{\beta\beta}$ (0.15%)

- Enrichment up to 88% in $^{76}\text{Ge}$
  - current mass scale: 30 - 40 kg

- “Background-free experiment”:
  - Nbkg < 1 expected at full exposure (~100 kg.yr)
  - $\sigma T_{1/2}^{0\nu} \propto M \cdot t$

- Motivating larger mass $^{76}\text{Ge}$ based experiment for the future
Current and planned experiments

- **Running**
  - 30 kg
  - $T_{1/2}^{0\nu} > 10^{26}$ yr

- **Mid-term**
  - 200 kg
  - $T_{1/2}^{0\nu} > 10^{27}$ yr

- **Long-term**
  - 1 ton
  - $T_{1/2}^{0\nu} > 10^{28}$ yr

**LEGEND 200**
- Italy LNGS

**LEGEND 1000**
- Italy LNGS
GERDA collaboration

http://www.mpi-hd.mpg.de/gerda/
GERDA location @ LNGS

• Cosmic ray background mitigation

Deep underground lab
  ➢ Muon flux suppression

Large space available at LNGS
  + convenient access via highway

@ LNGS underground laboratory
  (3500 m.w.e.)

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Toward the background-free regime

• signal signature

\[ \beta\beta \text{ decay signal: single energy deposition in a } 1 \text{ mm}^3 \text{ volume} \]
Toward the background-free regime

- background mitigation

$\beta\beta$ decay signal: single energy deposition in a 1 mm$^3$ volume

Muon veto based on Cherenkov light and plastic scintillator
Toward the background-free regime

• background mitigation

\[ \beta\beta \] decay signal: single energy deposition in a 1 mm\(^3\) volume

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

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Toward the background-free regime

- background mitigation

\[ \beta\beta \text{ decay signal: single energy deposition in a } 1 \text{ mm}^3 \text{ volume} \]

\[ \text{Ge detector anti-coincidence} \]

\[ \text{LAr veto based on Ar scintillation light read by fibers and PMT} \]

\[ \text{Muon veto based on Cherenkov light and plastic scintillator} \]
Toward the background-free regime

• background mitigation

- Pulse shape discrimination (PSD) for multi-site and surface $\alpha, \beta$ events
- Ge detector anti-coincidence
- LAr veto based on Ar scintillation light read by fibers and PMT
-Muon veto based on Cherenkov light and plastic scintillator

$\beta\beta$ decay signal: single energy deposition in a 1 mm$^3$ volume

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GERDA Phase II: From concept to design

- Plastic scintillator panels
- Muon veto
- Clean room
- 64 m³ LAr cryostat
- Coolant, shielding
- 590 m³ ultra-pure water
- BEGe detector
- Low mass detector holder
- LAr veto instrumentation
- Wavelength shifting fibers with SiPM read-out
- Instrumentation
- Low-mass, low-activity electronics
- Ge detector array
- Slide: L. Pandola – TAUP 2017
Ge detectors phase II

7 strings with 40 detectors:
- 3 natural semi-coaxial (7.6 kg)
- 7 enriched semi-coaxial (15.6 kg)
  - Large contact = large capacitance
- 30 enriched BEGe (20.0 kg)
  - Point-contact = small capacitance
Pulse shape discrimination

- $^{208}\text{TI DEP}$ (1592 keV) used as a proxy for **Single-Site Events** (SSE)

- **Multi-Site Events** (MSE) cut set such that 90% of $^{208}\text{TI DEP}$ events survive

- **Alphas** and **Betas** cut due to specific signal time profile

**BEGe detector:**

- BEGe cut parameter: $A/E$
- Coax cut parameter: Artificial Neural network

**NB:** 100 MHz x 10 ns trace
[600-1300] keV - $2\nu\beta\beta$ decays produce single-site events -> No suppression  
[1450-1530] keV - Strong suppression of $^{40}$K and $^{42}$K gamma lines (MSE)  
[> 3000] keV - Suppression of almost all $\alpha$ events (p+ contact)
Energy spectrum after unblinding!

Background index:

- Enriched coaxial: $5.7^{+4.1}_{-2.6} \times 10^{-4}$ cts/(keV ¥ kg ¥ yr)
- Enriched BEGe: $5.6^{+3.4}_{-2.4} \times 10^{-4}$ cts/(keV ¥ kg ¥ yr)

Sensitivity for limit setting:

- Median sensitivity for limit setting: $1.1 \times 10^{26}$ yr (90% CL)
Since Neutrino 2018

Restart of the data taking

- Upgrade of the detector array + LAr veto
- Run until we reach 100 kg.yr

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After GERDA and MAJORANA:

Legend collaboration:
- 52 institutions, ~250 members
- GERDA / MAJORANA / external contributors

Staged approach to reach $10^{28}$ yr sensitivity:
- LEGEND-200 → $10^{27}$ yr after 5 years
- LEGEND-1000 > $10^{28}$ yr (hosting lab under investigation)

LEGEND-200 phase:
- Up to 200 kg of $^{76}$Ge
- Modification of existing GERDA infrastructure at LNGS
- Improved background index
- Data start in 2021

NEWS:
- Most of funding already secured
- First isotopes from both ECP/URENCO have arrived!
Hardware improvements

- **New Inverted Coaxial Point-Contact Ge detector technology**
  - Large active mass up to 3 kg (R&D for 6 kg!)
  - Characterization campaign starting in a few months
  - **Reduced background due to smaller number of channels**

- **Low Mass Front End (LMFE) electronics**
  - Experience from MAJORANA
  - Reduce the signal noise w.r.t. GERDA situation
  - Ongoing R&D in test stand
  - **Better energy resolution + pulse shape discrimination**

- **LAr veto**
  - Experience from GERDA
  - Design studies ongoing
  - **Optimization of light collection to better tag bkg**
Summary

• $0\nu\beta\beta$ decay, if discovered, has far reaching consequences in particle physics! $\nu = \bar{\nu} / \text{LNV} / \text{interplay with cosmology}$ (many isotopes needed!)

• $^{76}\text{Ge}$ isotope offers excellent properties especially for signal discovery
  - Energy resolution, background-free regime, high detection efficiency
  - Possibility to reach $T_{1/2}^{0\nu} > 10^{28}$ yr sensitivity
  - “the new physics is at any corner!” therefore we should continue measuring in all directions, regardless of physics models

• GERDA and MAJORANA DEMONSTRATOR best technologies provide the path to next generation experiment
  - First time to surpass the $10^{26}$ yr sensitivity: $1.1 \times 10^{26}$ yr (90% CL)
  - LEGEND-200 phase has secured funding
    Ongoing efforts to start in 2021!
Phase II physics data modeling before cuts

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Phase II PSD cut topology

- **Strong suppression of** $^{40}\text{K}$ and $^{42}\text{K}$ gamma lines (MSE) [1450-1530] keV
- **Suppression of almost all** $\alpha$ events (p+ contact) [> 3000] keV

Rise time cut for coax
Energy calibration

3 weak $^{228}$Th sources lowered every ~ week

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Graph showing energy calibration data with three weak $^{228}$Th sources.}
\end{figure}

\begin{itemize}
\item 3.6(1) keV FWHM
\item 3.0(1) keV FWHM
\item GERDA 18-06
\end{itemize}

\begin{itemize}
\item 583 keV
\item 763 keV
\item 861 keV
\item 1079 keV
\item 1513 keV
\item 1621 keV
\end{itemize}

\begin{itemize}
\item TI-208 Bi-212
\item 2 years of calibrations!
\end{itemize}

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Alpha background decay

\[ f(t) = C + N \exp\left(\frac{-\ln(2) t}{T_{1/2}}\right) \]

C = (1.1 \pm 0.1) cts / day
N = (5.7 \pm 0.3) cts / day
T_{1/2} (^{210}\text{Po}) = (138.4 \pm 0.2) \text{ days}
Since May 2018 #3

Restart of the data taking

- Already 6.6 kg.yr exposure validated
- Improved energy resolution in BEGe strings
- No sign of significant alpha re-contamination
- Run until we reach 100 kg.yr

Energy resolution

Alpha count rate

\[ Q_{\beta\beta} \]

\[ f(t) = C + N \exp\left(\frac{-\ln(2) \cdot t}{T_{1/2}}\right) \]

- \( C = (0.8 \pm 0.1) \text{ cts/day} \)
- \( N = (1.0 \pm 0.2) \text{ cts/day} \)
- \( T_{1/2} = (138.4 \pm 0.2) \text{ days} \)

\[ C_{\text{IC}} = (1.2 \pm 0.1) \text{ cts/day} \]
### GERDA datasets

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Exposure [kg.yr]</th>
<th>FWHM [keV]</th>
<th>$\varepsilon$ [10^{-3} cts/kev.kg.yr]</th>
<th>BI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I golden</td>
<td>17.9</td>
<td>4.3 ± 0.1</td>
<td>0.57 ± 0.03</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>Phase I silver</td>
<td>1.3</td>
<td>4.3 ± 0.1</td>
<td>0.57 ± 0.03</td>
<td>30 ± 10</td>
</tr>
<tr>
<td>Phase I BEGe</td>
<td>2.4</td>
<td>2.7 ± 0.1</td>
<td>0.66 ± 0.02</td>
<td>$5^{+4}_{-3}$</td>
</tr>
<tr>
<td>Phase I extra</td>
<td>1.9</td>
<td>4.2 ± 0.1</td>
<td>0.58 ± 0.04</td>
<td>$5^{+4}_{-3}$</td>
</tr>
<tr>
<td>Phase II coax-1</td>
<td>5.0</td>
<td>3.6 ± 0.1</td>
<td>0.52 ± 0.04</td>
<td>$3.5^{+2.1}_{-1.5}$</td>
</tr>
<tr>
<td>Phase II coax-2</td>
<td>23.1</td>
<td>3.6 ± 0.1</td>
<td>0.48 ± 0.04</td>
<td>$0.6^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>Phase II BEGe</td>
<td>30.8</td>
<td>3.0 ± 0.1</td>
<td>0.60 ± 0.02</td>
<td>$0.6^{+0.4}_{-0.3}$</td>
</tr>
</tbody>
</table>
« Background-free » regime

\( <\text{FWHM}>: \)

\[ 3.25 \text{ keV} \]

Exposure:

\[ 58.9 \text{ – } 100 \text{ kg yr} \]

\( <\text{Background index}>: \)

\[ 8.1 \times 10^{-4} \text{ cts/(keV kg yr)} \]

Counts in \( Q_{\beta\beta} \pm \text{FWHM}: \)

\[ 0.32 \text{ – } 0.52 \]
« Background-free » regime

\[ <\text{FWHM}>: \quad 3.25 \text{ keV} \]

Exposure:
\[ 58.9 \text{ – 100 kg} \cdot \text{yr} \]

\[ <\text{Background index}>: \quad 8.1 \times 10^{-4} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)} \]

Counts in \( Q_{\beta\beta} \pm \text{FWHM}: \quad 0.32 \text{ – 0.52} \]