Status of the search for neutrinoless double-beta decay with GERDA

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Motivation

Neutrinoless double beta ($0\nu\beta\beta$) decay experiments are a good way to search for the physics beyond the Standard Model. The observation of such a decay would prove that lepton number is not conserved. Lepton number (L) is accidentally conserved in Standard Model $\rightarrow$ L number violation is expected. Most of the SM extension predict $\nu = \bar{\nu}$.

Searching for $0\nu\beta\beta$ helps to understand:
- Nature of $\nu$ (Dirac or Majorana)
- Neutrino mass scale
- Neutrino hierarchy
- Some fields in particle physics including cosmology

Other types of $0\nu\beta\beta$ decay are also considered
$0\nu\beta\beta$ decay

$2\nu\beta\beta$ decay has been observed already in more than ten isotopes, but $0\nu\beta\beta$ not found yet.

For $0\nu\beta\beta$ mediated by light Majorana neutrinos:

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto G^{0\nu}(Q, Z) \cdot \left| M^{0\nu} \right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$G^{0\nu}$ – phase space factor $\sim Q^5$
$M^{0\nu}$ – nuclear matrix element
$\left\langle m_{\beta\beta} \right\rangle$ – effective Majorana mass

\begin{equation}
\left\langle m_{\beta\beta} \right\rangle = \sum_i U_{ei}^2 m_i
\end{equation}
Experimental sensitivity expressed:

If background $<< 1$:

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot M \cdot t$$

If background $>> 1$:

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

- $\varepsilon$ Efficiency
- $M \cdot t$ Mass-Time = Exposure
- $a$ Abundance
- $\Delta E$ Energy resolution
- $BI$ Background Index

To maximize sensitivity:
- As low background as possible
- Very good energy resolution
- Large isotope mass and time of the measurement
- High detector efficiency
- Enriched material with high abundance
The GERDA Collaboration

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

16 institutions
~110 members
GERDA experimental setup located at LNGS underground laboratory of INFN (Italy). The rock overburden is equivalent to **3500 m w.e.** This allows to reduce $\mu$ ($\sim 10^6$ times) and neutron flux induced by cosmic radiation.
The search is performed with High Purity Ge detectors enriched up to 88% in $^{76}$Ge. They are submerged into liquid argon (LAr). LAr shields from the radiation and cools down the germanium detectors.

- $Q_{\beta\beta} = 2039$ keV
- Detector = source
- Intrinsically pure material
- Excellent energy resolution $\sim 3$ keV (FWHM) @ $Q_{\beta\beta}$
- Powerful Pulse Shape Discrimination (PSD) allows to suppress different backgrounds
Examples of the pulses from BEGe detector.

**Single-site event (SSE):**
- Constant $I_{\text{max}}/E$
- Multi-site event (MSE):
  - Reduced $I_{\text{max}}/E$
  - Amplified $I_{\text{max}}/E$

**n+ surface pulse (NSP):**
- Reduced $I_{\text{max}}/E$

**p+ contact pulse (PCP):**
- Amplified $I_{\text{max}}/E$

More details:
- EPJC 75 (2015) 39
- EPJC 73 (2013) 2583
- JINST, 8 (2013) P104018
- NIMA 891 (2018) 106-110

For coaxial detectors use Artificial Neural Network + risetime cut.
Detector array

To minimize contamination from the detector’s surrounding GERDA uses:
• Low mass holder made from copper and silicon plates.
• Low radioactive electronics and cables
LAr light instrumentation

LAr scintillation veto works in the coincidence with Ge detectors allowing to suppress background events which deposit energy in LAr.

PMTs readout consist of 16 3” PMTs

Scintillation fibers and SiPM readout
General concept of GERDA

- plastic scintillator panels
- muon veto
- clean room
- lock system
- 590 m³ ultra-pure water neutron moderator/absorber muon Cherenkov veto
- 64 m³ LAr cryostat coolant, shielding
- low acitivity PMTs
- wavelength shifting fibers with SiPM read-out
- low mass detector holder
- low-mass, low-activity electronics
- Ge detector array
- HPGe detector
In Phase I mini-shroud made from a copper foil placed around the detectors was used to decrease a collection of $^{42}\text{K}$ ions towards the detector. For GERDA Phase II copper MS would block the scintillation light → decrease efficiency of LAr veto significantly. Transparent **Nylon Mini-Shroud (NMS)** covered with wavelength shifter is used for Phase II.

Thanks to Princeton for providing such clean nylon foils (which was developed for Borexino).

Configuration from December 2015 to May 2018:
- 7 enriched (semi-)coaxial (15.6 kg)
- 30 enriched BEGe (20.0 kg)
- 3 natural semi-coaxial (7.6 kg)
Calibration and stability check

- Weekly calibrations with three weak $^{228}$Th sources
- Test pulses generated to additionally check stability
Energy region $Q_{\beta\beta} \pm 5$keV is blinded until analysis is fixed. Background index (BI) in energy region of [1930,2190] keV:

- For enriched coaxial: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)
- For enriched BEGe: $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

“Background free” regime achieved - sensitivity scales linearly with exposure!
Requirements to the BI were achieved even for coax detectors! Duty cycle: 92.9%. Data quality: 80.4%. Total exposure including Phase I is \(82.4\ \text{kg}\cdot\text{yr}\).
**Frequentist** analysis:
- Best fit → no signal.
- $T_{1/2} > 0.9 \cdot 10^{26}$ yr (median sensitivity for limit $1.1 \cdot 10^{26}$ yr ) @ 90% C.L.

**Bayesian** analysis:
- Best fit → no signal. Bayes factor = 0.054
- $T_{1/2} > 0.8 \cdot 10^{26}$ yr (median sensitivity for limit $0.8 \cdot 10^{26}$ yr ) @ 90% C.I.

The median limit on effective Majorana mass is $< (0.11-0.26)$ eV NME range from [Rept.Prog.Phys. 80 (2017) no.4, 046301]
GERDA upgrade 2018

Major upgrade of the experimental setup (May 2018):

- New 5 enriched inverted coaxial (9.5 kg) installed instead of natural
- Improved LAr veto: new fibers + central fiber shroud
- Improved electronic noise
- Cleaner materials (cables and electronics)

- Data taking now
- Phase II goal (exposure of 100 kg·yr) will be reached soon!
Beyond GERDA: LEGEND

**LEGEND collaboration:**
- GERDA + MAJORANA + external contributions
- 52 institutes
- ~250 members

**Staged approach:**
- **LEGEND 200:** up to 200 kg of $^{76}$Ge in the existing GERDA cryostat at LNGS. Sensitivity $\sim 10^{27}$ yr.
- **LEGEND 1000:** 1 ton detector mass, proposal for the future, location is under discussion. Sensitivity $\sim 10^{28}$ yr
LEGEND-200

• Increased detector mass up to 200 kg
• Funding basically secure
• Inverted coaxial point contact HPGe detectors with mass up to 3 kg
• New Low Mass Front End (LMFE) electronics with reduced noise → better resolution and PSA
• Optimization of LAr veto using GERDA experience
• Radiopure detector surrounding
• Ultra-pure electroformed copper
• BI goal: 0.6 cts/(FWHM·t·yr) – factor of 3 better than now in GERDA.

Anticipated schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>Jan 2018</td>
<td>First LEGEND-200 enriched material purchase</td>
</tr>
<tr>
<td>2019 / 2020 / 2021</td>
<td>LEGEND-200 Detectors production</td>
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<tr>
<td>Nov 2020</td>
<td>Start installation of detectors</td>
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<tr>
<td>July 2021</td>
<td>Data taking with LEGEND-200</td>
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Summary

• Lowest background per ROI ever achieved in $0\nu\beta\beta$ experiments. Background Index:
  – for coaxial detectors: $5.7 \cdot 10^{-4}$ cts/(kg·keV·yr)
  – for BEGe detectors $5.6 \cdot 10^{-4}$ cts/(kg·keV·yr)

• Excellent energy resolution and “background free” regime offer very good conditions for discovery of $0\nu\beta\beta$ decay. More results with higher sensitivity are expected in coming years.

• No $0\nu\beta\beta$ signal is observed so far.

• The obtained limit is $T_{1/2}^{0\nu} > 0.9 \cdot 10^{26}$ yr (90% C.L.).

• GERDA keeps taking data.

• Preparations for LEGEND-200 are ongoing. Most of the funding for LEGEND-200 is secured.

• Data taking in LEGEND-200 is planning to start in 2021.
Thank you!
42Ar background mitigation

In measurements in LArGe test facility with spiked 42Ar it was shown that with NMS after applying all the cuts (PSD+PMT) it is possible to dramatically decrease 42K background: suppression factor of more than 1000 was obtained in the measurements.

Surface beta events are efficiently suppressed by PSD.

42Ar spectra taken with bare BEGe detector in LArGe

<table>
<thead>
<tr>
<th>Without NMS (scaled)</th>
<th>With NMS</th>
<th>After PMT cut</th>
<th>88% PSD + PMT cuts</th>
<th>73% PSD + PMT cuts</th>
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Expectations for bare BEGe without NMS

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WIN2019, A.Lubashevskiy