Searching for neutrinoless double-beta decay with GERDA

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Searching for 0νββ of $^{76}\text{Ge}$

$^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^{-}$

- $\Delta L = 2$ → beyond Standard Model 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)

**Why high purity Ge detectors?**

- source = detector → high efficiency
- radio-pure → no intrinsic background
- high density → $e^{-}$ absorbed in 1-2 mm
- semiconductor → $\Delta E < 0.1\%$ at $Q_{\beta\beta}$
- enrichment up to 87% in $^{76}\text{Ge}$

**0νββ signature:**

- point-like energy deposition in detector bulk volume
- sharp energy peak at 2039 keV (FWHM = 3-4 keV)
The GERDA experiment

LNGS site: 3600 w.m.e

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

16 institutions ~110 members
Germanium detectors

p+ electrode (0 V)  n+ electrode (3/4 kV)

p-type Ge

25 – 50 mm  65 – 80 mm

HPGe detector signals:

➢ signal induced by drift of electron-hole clusters
➢ identification of events with multiple energy depositions
➢ identification of events on the surface
GERDA phase II setup

- Phase II

BEGe detector
GERDA phase II setup

- Phase II
GERDA phase II setup

- Phase II

BEGe detector

Ge detector array

wavelength shifting fibers with SiPM read-out

low activity PMTs
GERDA phase II setup

- Phase II

- BEGe detector

- Ge detector array

- wavelength shifting fibers with SiPM read-out

- clean room

- lock system

- plastic scintillator panels

- muon veto

- low activity PMTs

- 590 m³ ultra-pure water

- 64 m³ LAr cryostat
GERDA phase II setup

- 30 enrBEGe (20 kg)
- 7 enrCoax (16 kg)
- 3 natCoax (8 kg)
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GERDA phase II - UPGRADE

@ May 2018

- Improved electronics noise
- Increased LAr light collection
  (new fibers + new central module)
- Increased the enriched mass by 9.5 kg
  (remove nat. detectors → add inverted coax “IC”)

VCI 2019
Phase II: Dec 2015 → Apr 2018
- live time → 835 d
- duty cycle → 93%
- Exposure → 59 kg yr
  (82 kg yr considering Phase I + Phase II)

Phase II+: July 2018 → ongoing
- 6.6 kg yr exposure validated

GOAL: exposure 100 kg yr
Energy reconstruction / resolution

- Weekly calibrations with $^{228}\text{Th}$ sources
- Stability monitored online with Test Pulses, injected every 20 s

- Fluctuations between calibrations <1 keV
- Resolution at $Q_{bb}$ better than 0.1%
  (FWHM@$Q_{bb}$: 3.0(1) keV (BEGe), 3.6(1) keV (Coax))
Background modeling before analysis cuts

Full GERDA setup is reproduced in GEANT4

Bayesian fit of multiple datasets (BEGe, coaxial, multiplicity=2, $^{40}\text{K}/^{42}\text{K}$ tracking) with Monte Carlo PDFs, screening measurements as priors

Background@Q_{\beta\beta}:
- $\alpha$ from $^{210}\text{Po}/^{222}\text{Ra}$
- $\beta$ from $^{42}\text{K}$
- $\gamma$ from $^{208}\text{TI}/^{214}\text{Bi}$
Active background suppression

Discriminate point like (single site) $\beta\beta$ topology from:

- multi-detector interactions
- interactions with coincident energy deposition in surroundings
- multi-site/surface interactions
Pulse shape discrimination for BEGe’s

- normalized to single-site events
- cut value determined from calibration data (low cut @ 90% DEP acceptance, high cut @ 4σ)

$0
\nu
\beta
\beta$ acceptance BEGe $(87.6\pm2.5)\%$
Pulse shape discrimination for Coaxials

- Artificial neural network (ANN) trained on $^{208}\text{Tl}$ DEP (signal) and $^{212}\text{Bi}$ SEP (background)
- acceptance from pulse shape simulations, cross-checked with $2\nu\beta\beta$ events
- additional $\alpha$ rejection based on (fast) signal rise time, tuned after ANN MSE rejection

$0\nu\beta\beta$ acceptance Coaxial

$(84\pm5)\% \times (85\pm1)\%$
Liquid Argon Veto

- Channelwise (PMT/SiPM) anti-coincidence condition
- Thresholds at ~0.5 P.E.
- Compton suppression by LAr veto -> almost pure $2\nu\beta\beta$ continuum

$0\nu\beta\beta$ acceptance BEGe $97.7(1)\%$

Dead Time 2%
Active background suppression

Blinded region ±25 keV @ $Q_{\beta\beta}$
Active background suppression – LAr veto
Active background suppression – PSD
Active background suppression – PSD&LAr veto
Active background suppression – PSD&LAr veto
ROI: [1930,2190] keV, excl. ±5 keV around $^{208}$Tl (SEP), $^{214}$Bi (FEP) and $Q_{\beta\beta}$

Enriched coaxial: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)

Enriched BEGe: $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)
Statistical analysis

Frequentist:

Best fit $N^{0\nu} = 0$

$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.}$

Median Sensitivity

$T^{0\nu}_{1/2} > 1.1 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.}$

Bayesian:

$T^{0\nu}_{1/2} > 0.8 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.I.}$

Median Sensitivity:

$T^{0\nu}_{1/2} > 0.8 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.I.}$
Conclusion and outlook

- GERDA Phase II goals
  
  background $\sim 10^{-3}$ cts/(keV·kg·yr) ✔
  
  sensitivity $T^{0}\nu_{1/2} \gtrsim 10^{26}$ yr ✔
  
  exposure $\simeq 100$ kg·yr → data taking still on-going after last upgrade (May 2018)

- GERDA performs a high resolution background-free $0\nu\beta\beta$ decay search approaching $T^{0}\nu_{1/2} \gtrsim 10^{26}$ yr

- Upper limit on $m_{\beta\beta} < (0.11-0.26)$ eV [NME range from [Rept.Prog.Phys. 80 (2017) no.4, 046301]

- **LEGEND-200** is in preparation to reach $T^{0}\nu_{1/2} \gtrsim 10^{27}$ yr

VCI 2019
Calibration Phase II+
### Summary

<table>
<thead>
<tr>
<th>Exposure [kg*yr]</th>
<th>FWHM [keV]</th>
<th>Total Efficiency</th>
<th>Background Index [cts/(keV<em>kg</em>yr)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I golden</td>
<td>17.9</td>
<td>4.3(1)</td>
<td>0.57(3)</td>
</tr>
<tr>
<td>Phase I silver</td>
<td>1.3</td>
<td>4.3(1)</td>
<td>0.57(3)</td>
</tr>
<tr>
<td>Phase I BEGe</td>
<td>2.4</td>
<td>2.7(2)</td>
<td>0.66(2)</td>
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<tr>
<td>Phase I extra</td>
<td>1.9</td>
<td>4.2(2)</td>
<td>0.58(4)</td>
</tr>
<tr>
<td>Phase II EnrCoax</td>
<td>5.0</td>
<td>3.57(1)</td>
<td>0.52(4)</td>
</tr>
<tr>
<td><strong>Phase II EnrCoax_2</strong></td>
<td><strong>23.1</strong></td>
<td><strong>3.57(1)</strong></td>
<td><strong>0.48(4)</strong></td>
</tr>
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<td>Phase II EnrBEGe</td>
<td>30.8</td>
<td>2.96(1)</td>
<td>0.60(2)</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>82.4</strong></td>
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</tr>
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</table>

Combined unbinned maximum likelihood fit (flat background + gaussian signal)

- **Frequentist**: test statistics and method à la [Nature 544, 47 (2017)]
- **Bayesian**: flat prior on $1/T^{1/2}$ between 0 and $10^{-24}$ yr$^{-1}$
- Systematic uncertainties folded as pull terms by Monte Carlo