Probing Majorana neutrinos via double-$\beta$ decay with GERDA

11 July 2019
R. Hiller for the GERDA collaboration
Double beta decay

• \((Z,N) \rightarrow (Z+2,N) + 2e^- + 2\bar{\nu}_e\)
• SM, second order weak process
• \(\times\) \(\beta\)-decay, \(\checkmark\) \(\beta\beta\)-decay
• \(^{76}\text{Ge}\) \(1.926 \pm 0.095 \times 10^{21}\) yr


- Hypothetical, \(\Delta L = 2\)
- Dirac vs. Majorana fermion
- Potentially sensitive to other \(\nu\) properties

\(2\nu\beta\beta\)

\(0\nu\beta\beta\)
Detection of $0\nu\beta\beta$

- Peak signature at $Q_{\beta\beta}$ in $e^-$-spectrum
- $\mathcal{O}(10)$ experimentally relevant isotopes
- No clear favorite from nuclear physics + phase space
- Sensitivity $\sim \sqrt{\frac{\mathcal{E}}{BI \cdot \Delta E}}$; $\mathcal{E}$=exposure, $BI$=background index, $\Delta E$=energy resolution
- $^{76}\text{Ge}$: detector tech. (purity, efficiency, enrichment), energy resolution

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance</th>
<th>$Q_{\beta\beta}$ (keV)</th>
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<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>0.2%</td>
<td>4263</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.6%</td>
<td>2039</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>9.2%</td>
<td>2998</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>2.8%</td>
<td>3348</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>9.6%</td>
<td>3035</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>7.6%</td>
<td>2813</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>34.1%</td>
<td>2527</td>
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<tr>
<td>$^{136}\text{Xe}$</td>
<td>8.9%</td>
<td>2459</td>
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<tr>
<td>$^{150}\text{Nd}$</td>
<td>5.6%</td>
<td>3371</td>
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The GERDA collaboration

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

16 institutions
~110 members
GERmanium Detector Array

- Low background electronics
- Detector strings
- WLS coated nylon shrouds
- Low mass detector holders
  - ~87% enr. $^{76}$Ge
- Copper cylinder
- Fiber read out (SiPM)
- Fiber curtain (wave length shifter coated)
- Ge detectors
- Low background
  - 3'' PMTs
- Plastic scintillator panels
- Ge detector array
- Steel cryostat 64m$^3$ LAr
- Copper shield
- Clean room
- Water tank 590m$^3$
- WCD muon veto
The GERDA experiment (until 2018)

• LNGS, Italy, 3500 m.w.e, Muon flux 1 per m² h
• Coaxial + BEGe detectors (FWHM 3.6(1)/3.0(1) keV)
• 36 kg Ge, enriched in $^{76}\text{Ge}$ to 88% ($Q_{\beta\beta} = 2039$ keV)
• $\sim 10^{-3} \frac{\text{cts}}{\text{keV kg yr}} + 100 \text{ kg yr} \rightarrow $ sensitivity $\sim 10^{26}$ yr
• Demonstrate LAr concept

arXiv:1801.00587
Data taking

Phase II a-c (Dec. 2015-June 2018):

- Blind analysis: Events at 2039±25 keV released after analysis frozen
- Latest release June 2018, total 82.4 kg yr
- 35.7 kg freshly released (Phase IIc)
  + 23.2 kg yr (Phase II a+b) + 23.5 kg yr Phase I (2011-2013)

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<tr>
<th>Date (year/month)</th>
<th>Live time fraction</th>
<th>Exposure (kg yr)</th>
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<td>2016/01</td>
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GERDA 18-06

June 2016
10.8 kg yr
Nature 554, 47

June 2017
23.2 kg yr
PRL 120, 132503

June 2018
58.9 kg yr

R. Hiller
GERDA experiment
Background model

- Sources simulated with GEANT4, fit to background data
- Input from screening measurements (via priors)
- Dominating backgrounds at $Q_{\beta\beta}$:
  - degraded $\alpha$
  - $\beta$ from $^{42}\text{K}$
  - $\gamma$ from U/Th chains
Background reduction

Signal signature = a point-like ($\sim \text{mm}$) E-deposition in single detector

Pulse shape discrimination vs. multi-site and surface events

LAr scintillation light from external sources

Muon veto via Cherenkov radiation

Detector anti-coincidence

Water tank

LAr cryostat

Ge

$^{42}\text{K}$

$^{2}$

$^{2}$

$^{2}$

$^{2}$
Pulse shape discrimination

- Charge drift time $\rightarrow$ pulse shape
- Discrimination SSE/MSE, surface:
  - Amplitude/Energy for BEGe (IC)
  - Multivar. analysis (ANN) for coax. MSE
  - Risetime for coaxial alpha

![Diagrams showing pulse shape discrimination results](image-url)
Energy spectrum after cuts

- After LAr veto and PSD cuts background rate in ROI (1930 keV-2130 keV)
  
  \[ 0.6 \cdot 10^{-3} \text{ cts/(keV kg yr)} \]

- \(~95\%\) background rejection at \(~86/70\%\) efficiency BEGe/Coax (only LAr veto, PSD)
Statistical analysis in the ROI

Combined unbinned maximum likelihood fit (7 datasets PI + PII)
(Methods in Agostini et al., Nature 544, 47-52, 2017)

- Data up to mid 2018
- 1st event in ROI
  (> 2σ away from $Q_{\beta\beta}$)
- Best fit for no signal
- Half-life lower limit
  $0.9 \cdot 10^{26}$ yr (90% CL)
- Median sensitivity
  $1.1 \cdot 10^{26}$ yr
GERDA upgrade-I

- Following data release ~2 month interruption
- Replace natural Ge detectors with 5 new Inverted Coaxial type (~9 kg)
GERDA upgrade-II

- Install denser fiber curtain and middle string curtain
- Repair electronics and maintain a few detectors
- Replace cables to reduce radioactivity and crosstalk
GERDA post upgrade

- GERDA back online with additional mass
- Acquired already $\sim 25$ kg yr
- Approaching 100 kg yr ($\sim$Nov.)
- IC detectors perform well (FWHM$\sim 2.8$ keV)

Preliminary
GERDA plans

- Last unblinding ($0\nu\beta\beta$) planned for mid 2020
- Analysis of $2\nu\beta\beta$ spectrum and distortions (e.g. Majorons)
- $2\nu\beta\beta$ to excited states (via coincidences)
- Search for keV dark matter

![2$\nu\beta\beta$ spectrum](image)

**Coincidence spectrum**

![Coincidence spectrum](image)

**Peak rate sensitivity**

![Peak rate sensitivity](image)
Conclusion

- GERDA surpassed sensitivity of $10^{26}$ yr
- Effectively background-free + exposure of 82.4 kg yr
- After upgrade mass at 44kg, approaching target 100 kg yr
- Data taking planned until end of 2019, afterwards continue with LEGEND-200 at LNGS