Status of the GERDA experiment: on the way to Phase II

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\( \beta\beta \)-decay

\[ \text{(A,Z)} \xrightarrow{\beta} \text{(A,Z+1)} \]

\[ \text{(A,Z)} \xrightarrow{\beta\beta} \text{(A,Z+2)} \]

- allowed in the SM
- conserves lepton number
- already observed

\[ 2\nu\beta\beta \]

\[ 0\nu\beta\beta \]

- forbidden in the SM
- violates lepton number
- only if \( \nu \) has Majorana mass component or other new \( \Delta L = 2 \) operators exist
0νββ-decay

- Natural decay mechanism: exchange of massive Majorana neutrinos:

\[
\frac{1}{T_{1/2}} = \frac{G(Q,Z)}{2} \left| M_{\text{nucl}} \right|^2 \langle m_{ee} \rangle^2
\]

0νββ decay rate

- Phase space factor
- Matrix element
- Effective Majorana neutrino mass

\[
\left| \sum_i U_{ei}^2 m_i \right|
\]

Neutrino is massive, but absolute mass scale and hierarchy still unknown
$0\nu\beta\beta$-decay – signature

Signature: sharp peak at Q-value of the decay

- 2 neutrinos escape the detector undetected: continuous spectrum
- Total energy of decay is deposited within detector: sharp peak
$0\nu\beta\beta$-decay:

HPGe detectors enriched in $^{76}\text{Ge}$

- 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
GERDA experiment at LNGS

- bare HPGe detectors in LAr
- water and LAr – shield against external radiation
- deep underground – Hall A of LNGS, Italy (3400 m.w.e)
GERDA: the Collaboration

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

16 institutions
≈120 members
GERDA: Phase I

Coaxial detectors (from HdM, IGEX)
- Enriched 86% in $^{76}\text{Ge}$
- Total mass 17.66 kg
- Reprocessed by Canberra
- Average FWHM 4.8 keV at $Q_{\beta\beta}$

New Phase II BEGe detectors
- Enriched 86% in $^{76}\text{Ge}$
- Better pulse shape discrimination capability and FWHM (Phase I average: 3.2 keV at $Q_{\beta\beta}$)
Phase I results: $0\nu\beta\beta$

Total exposure: 21.6 kg yr between Nov 2011 and May 2013 (492.3 live days, 88.1% duty factor)

Prominent analysis feature: blind analysis!

- Events in a 40 keV range around $Q_{\beta\beta}$ are blinded
- Develop and validate the background model and the PSD cuts before the unblinding

Background after PSD: $10^{-2}$ counts / (keV kg yr)

- design goal reached!

Limit on the half-life:

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


$T_{1/2}^{0\nu} = 2.1 \times 10^{25}$ yr

$H_1$: $T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr (*) vs. $H_0$: background only

Expected Signal (w/ PSD): (5.9 $\pm$ 1.4) cts in $\pm 2\sigma$

Expected Bckgd (w/ PSD): (2.0 $\pm$ 0.3) cts in $\pm 2\sigma$

Observed: 3.0 in $\pm 2\sigma$ (0 in $\pm 1\sigma$)

PRL 111 (2013) 122503
New Phase I results: $0\nu\beta\beta\chi$(Majoron) $G \sim (Q_{\beta\beta} - K)^n$

- Alternative mechanism of $0\nu\beta\beta$:
  - Majoron(s) emission
    - Many models/candidates available: $\beta\beta\chi$, $\beta\beta\chi\chi$
    - Continuous spectra, but different shape than $2\nu\beta\beta$ decay ($n=5$)
    - **Global fit** of the energy spectrum

  for $n = 1$: $T^{0\nu\chi}_{1/2} > 4.2 \times 10^{23}$ yr (90% CL)

Most stringent limits for $^{76}\text{Ge}$, improvement by a **factor > 6**

arXiv:1501.02345 (in print at EPJC)
New Phase I results:

$2\nu\beta\beta$

Old GERDA result (5 kg yr):

$T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \times 10^{21}$ yr


New:

- exposure 17.9 kg yr
- uncertainties on background model reduced

New result:

$T_{1/2}^{2\nu} = (1.926 \pm 0.095) \times 10^{21}$ yr

arXiv:1501.02345 (in print at EPJC)
New Phase I results:
2νββ to excited states

- (2ν)ββ of 76Ge can occur into excited states of 76Se
  - Not observed by now.
  - Previous limits for $T_{1/2}$ in the range of few $10^{21}$ yr.
  - Most probable: $0^+_1$ level at 1122 keV.
  - Predictions $10^{21}$-$10^{24}$ yr for $T_{1/2}$
  - Benchmark for NME calculations

- Search for coincidence of ββ-decay in one detector and 560 keV γ-ray in another
  - NO evidence found
  - Limits improved by ~100
  - For $0^+_1$ level:
    $T_{1/2} > 3.7 \times 10^{23}$ yr (90% CL)

Phase I/II: Improvement in energy resolution

Zero Area Cusp (ZAC) filter: a novel filter for enhanced energy resolution

<table>
<thead>
<tr>
<th>Detector</th>
<th>FWHM at 2614.5 keV (keV)</th>
<th>Improvement (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gaussian</td>
<td>ZAC</td>
</tr>
<tr>
<td>ANG2</td>
<td>4.712 (3)</td>
<td>4.314 (3)</td>
</tr>
<tr>
<td>ANG3</td>
<td>4.658 (3)</td>
<td>4.390 (3)</td>
</tr>
<tr>
<td>ANG4</td>
<td>4.458 (3)</td>
<td>4.151 (3)</td>
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<tr>
<td>ANG5</td>
<td>4.323 (3)</td>
<td>4.022 (3)</td>
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<tr>
<td>RG1</td>
<td>4.595 (4)</td>
<td>4.365 (4)</td>
</tr>
<tr>
<td>RG2</td>
<td>5.036 (5)</td>
<td>4.707 (4)</td>
</tr>
<tr>
<td>GD32B</td>
<td>2.816 (4)</td>
<td>2.699 (3)</td>
</tr>
<tr>
<td>GD32C</td>
<td>2.833 (3)</td>
<td>2.702 (3)</td>
</tr>
<tr>
<td>GD32D</td>
<td>2.959 (4)</td>
<td>2.807 (3)</td>
</tr>
<tr>
<td>GD35B</td>
<td>3.700 (5)</td>
<td>2.836 (3)</td>
</tr>
</tbody>
</table>

ZAC filter:
- Better low frequency rejection
- The energy reconstruction for Phase I/II can be improved (for both coaxial and BEGe detectors)
GERDA: on the way to Phase II

**Phase I:**
Use refurbished HdM & IGEX (18 kg)

\[
BI \approx 0.01 \text{ cts / (keV kg yr)}
\]

Sensitivity after 20 kg yr

**Phase II:**
Add new BEGe detectors (20 kg)

\[
BI \approx 0.001 \text{ cts / (keV kg yr)}
\]

Sensitivity after 100 kg yr
GERDA: on the way to Phase II

- 30 new BEGe detectors (produced and tested)
- We have to reduce background by one order of magnitude!
  - New low mass holder
  - New front end readout close to detectors & new front end cabling
  - New HV and signal cabling
  - Pulse shape discrimination (PSD) with BEGes
    (more details in the poster from Bjoern Lehnert)
  - Liquid argon veto instrumentation
Phase II: new holders for new detectors

- 28 out of 30 BEGe detectors mounted in Phase II holders and tested in LAr/LN$_2$
Phase II: new front-end readout

GERDA CC3 preamplifier

- Used at the beginning of Phase II commissioning:
  - High mortality of jFETs found

- decision: \textbf{start} with Phase I like readout (VFE at CC3 level (> 40 cm from detectors))
  - Tested with 5 BEGes during Phase I
  - FWHM was fine (≤ 3 keV at Q_{ββ})
  - PSD was also acceptable

Resistive feedback circuit of FE electronics (very front-end, VFE)

situated on the Si plate close (~1 cm) to the detector
Phase II: detector array

- 7 strings of detectors
- 15 pairs of BEGe detectors mounted back-to-back
- 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)
Phase II: LAr veto

3” PMTs

Fibers (coated with WLS) coupled to SiPMs

Cu cylinders with WLS foil

Holes for calibration sources
Phase II: commissioning 1\textsuperscript{st} step (pilot string)
Phase II: commissioning 1\textsuperscript{st} step (pilot string) – $^{228}\text{Th}$

detectors: 4/C, 1/D, 79C, 02B, 35B

GERDA preliminary May 2015

$^{228}\text{Th}$ calibration run
- anti-coincidence cut (AC)
- AC + PSD
- AC + LAr veto
- AC + LAr veto + PSD

Preliminary!!!
Phase II: commissioning 1\textsuperscript{st} step (pilot string) – $^{226}\text{Ra}$
Phase II: commissioning 2nd step (5 string assembly)
Phase II: commissioning 2nd step (5 string assembly)

Calibration with $^{228}$Th

FWHM at 2.6 MeV: BEGes $\sim$ 3 keV
Coaxes $\sim$ 4 keV
Phase II: commissioning 2\textsuperscript{nd} step (5 string assembly)

Phase II commissioning (~ 1 kg yr)

![Graph showing energy distribution with Preliminary!!! note]
GERDA status

• Phase I finished in 2013 but still providing new results:
  • Most stringent limit for Majoron(s) emission in $^{76}$Ge
  • New analysis for $2\nu\beta\beta$ of $^{76}$Ge: $T_{1/2}^{2\nu} = (1.926 \pm 0.095) \times 10^{21}\text{yr}$
  • New limits for $2\nu\beta\beta$ to excited states (improvement ~ 100)

• Phase II commissioning is ongoing:
  • LAr veto fully installed and operational
  • 27 out of 40 detectors installed
  • Unexpected problem with LC for some detectors found
    ✓ will be solved soon by producer
  • Working diodes show stable behaviour
  • Energy resolutions of working diodes are good (as in Phase I)
    ✓ Phase I like readout is fine to start physic data taking
  • bkg run with 1 kg yr exposure: background fits our expectation

Final Phase II installation will require more steps

• Fall 2015: full array in GERDA
Additional slides
GERDA:  
$^{42}$Ar concentration

Limit < 41 μBq/kg (90% CL)  
(Ashitkov et al., arXiv:nucl-ex/0309001)  
NOT compatible with our data

Intensity of 1525 keV line in $E$-field free setup indicates $^{42}$Ar activity is significantly higher than the limit above

Evidence that charge $^{42}$K ions drift in electric field of HPGe detectors.

GERDA/LArGe measurement: 70-90 μBq/kg