New data release GERDA Phase II: search for $0\nu\beta\beta$ of $^{76}$Ge

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on behalf of the GERDA Collaboration
The GERDA Collaboration

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

16 institutions
~110 members
**motivation for $0\nu\beta\beta$ decay searches:**

$$(A, Z) \rightarrow (A, Z+2)+2e^-$$

- would establish *lepton number violation* $\Delta L = 2$

$$(Z, A) \rightarrow (Z+2, A) + 2e^- ; \text{ half-life } > 10^{25}\text{ years}$$

other possibilities to test $LNV$:

$\mu^- + (Z, A) \rightarrow e^+ + (Z-2, A); \text{ exp. } Br \leq 10^{-12}$

$K^+ \rightarrow \mu^+\mu^+\pi^- ; \text{ exp. } Br \leq 1.1\times10^{-9}$

$\bar{\nu}_e$ emission from the Sun; exp. $Br \leq 10^{-4}$

- more *physics beyond standard model*
  - the process stands on equal footing with baryon number violation (i.e. $p$ decay)
  - important to understand the origin of the neutrino mass
motivation for $0\nu\beta\beta$ decay searches: 
$(A, Z) \rightarrow (A, Z+2)+2e^-$

- Possible interpretations of $0\nu\beta\beta$:
  
  - **Standard interpretation**: $0\nu\beta\beta$ decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution.
  
  - **Non-standard interpretations**: $0\nu\beta\beta$ decay is mediated by some other LNV physics (Higgs triplet, LR symmetric theories, SUSY theories, Majorons,...), and light and massive Majorana neutrinos (the ones which oscillate) potentially leading to $0\nu\beta\beta$ give negligible or no contribution.
motivation for $0\nu\beta\beta$ decay searches:

$$(A, Z) \rightarrow (A, Z+2)+2e^-$$

◆ Only way to determine if neutrino is its own antiparticle:

$$\nu = \bar{\nu} \Rightarrow \text{Majorana particle}$$

If YES:

◆ would provide access to absolute neutrino mass scale

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \quad \langle m_{ee}\rangle = \sum_i U_{ei}^2 m_i$$

◆ would provide important input to cosmology
GERDA physics goal

**Phase I:**
(completed in 2013)
- reached BI of $10^{-2}$ cts/(keV·kg·yr)
- exposure of 21.6 kg·yr → $T_{1/2}^{0ν} > 2.1 \times 10^{25}$ yr (90% C.L.)
- $<m_{ee}> \leq 0.2$ - 0.4 eV

**Phase II:**
(started at the end of 2015)
- reach background of $10^{-3}$ cts/(keV·kg·yr)
- reach an exposure of 100 kg·yr → $T_{1/2}^{0ν} > 1.3 \times 10^{26}$ yr (sensitivity)
- discovery potential up to $10^{26}$ yr (50% prob. chance for a 3σ signal)
- $<m_{ee}> \leq 0.09$-0.15 eV

**References**
- S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)
- Nature 544, 47 (2017)
- PRL 111, 122503 (2013)
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

a) overview
plastic scintillator panels
muon veto

lock system

clean room

590 m$^3$ ultra pure water
neutron moderator/absorber
muon Cherenkov veto

64 m$^3$ LAr cryostat
coolant, shielding

a) overview
b) liquid argon (LAr)
vetto instrumentation
plastic scintillator panels
muon veto

a) overview

590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto

64 m³ LAr cryostat
coolant, shielding

b) liquid argon (LAr)
veto instrumentation

c) detector array

lock system

low activity PMTs

wavelength shifting fibers with SiPM readout

Ge detector array

low activity electronics

clean room

a) overview
plastic scintillator panels
muon veto

lock system

clean room

590 m³ ultra pure water
neutron moderator/absorber
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64 m³ LAr cryostat
coolant, shielding

a) overview
b) liquid argon (LAr)
veto instrumentation
c) detector array
d) detector module
Background reduction tools

**Point-like (single-site) energy deposition inside one HP-Ge diode**

- **Anti-coincidence** with the **muon veto (MV)**
- **Anti-coincidence** between detectors (cuts multi site) (AC)
- **Active veto** using LAr scintillation (LAr Veto)
- **Pulse shape** discrimination (PSD)

**Multi-site energy deposition inside HP-Ge diode (Compton scattering), or surface events**
Status of Phase II data-taking

➢ Data taking in progress!
➢ Phase II exposure increased by x3 with respect to the Nature paper
➢ Valid exposure 34.4 kg·yr (18.2 BEGe + 16.2 Coax) up to Apr 15th (analysis cutoff)
➢ A few more kg·yr already in the bag (Apr-Jul) with blinded box of ± 25keV around \( Q_{\beta\beta} \)

New Data Release

➢ Box opened for BEGe dataset only (12.4 kg·yr)
➢ New enrCoax data still in the box
  • confident to improve background by better rejection of \( \alpha \) events from the groove
  • Rejection a posteriori would spoil the blinding concept
  • Even worse in case of signal
➢ Total unblinded exposure: 23.2 kg·yr from Phase II

Phase II a: 10.8 kg·yr already published in Nature 544, 47–52
Phase IIa results

- new limit on $T_{0^{\nu}}^{1/2}$ (Phase I + Phase IIa)
  
  $T_{0^{\nu}}^{1/2} > 5.3 \cdot 10^{25} \text{ yr (90\% CL)}$ (median sensitivity $4.0 \cdot 10^{25} \text{ yr}$)

- Background Index (BI):
  
  Coax: $3.5^{+2.1 \, -1.5} \cdot 10^{-3} \text{ cts/(keV\cdot kg \cdot yr)}$; FWHM: $4.0(2) \text{ keV}$
  
  BEGe: $0.7^{+1.1 \, -0.5} \cdot 10^{-3} \text{ cts/(keV\cdot kg \cdot yr)}$; FWHM: $3.0(2) \text{ keV}$

- $\text{BI/}\epsilon = 3.5 \text{ cts/( ROI\cdot ton\cdot yr)}$ using BEGe
  
  ROI: ± 0.5 FWHM
since 2010: 7 PMTs in water tank dead (no effect on eff.), >99% $\mu$ identification
~0.1% dead time; very reliable and stable
LAr Veto

read out all channel if Ge triggers
→ offline veto
- all channels working
- gain stable with time

low noise → veto cut ~0.5 p.e.

reject ~ 2.3% of pulser events
LAr Veto

PMTs

- stability of the amplitude vs. time
- stability of the trigger position vs. time

![Graphs showing stability of amplitude and trigger position over time.](image)
SIPMs

- stability of the amplitude vs. time
- stability of the trigger position vs. time
tested with $^{228}\text{Th}$ and $^{226}\text{Ra}$ sources

- Suppression factor higher with $^{228}\text{Th}$ (98(4)) than with $^{226}\text{Ra}$ (5.7(2)) source due to more energy available for deposition in the LAr
- Combining with PSD & anticoincidence the overall supp. factors become:
  - 345 (25) for $^{228}\text{Th}$
  - 29 (3) for $^{226}\text{Ra}$
LAr veto background suppression

- $^{40}\text{K}/^{42}\text{K}$ Compton continuum fully suppressed
- LAr veto generates 2.3% dead time
- $T_{\frac{1}{2}}^{2\nu} = 1.9 \cdot 10^{21}$ yr taken from Phase I
  
  $[\text{EPJC 75 (2015) 416}]$

$\gamma$-lines from:

- $^{40}\text{K} \rightarrow ^{40}\text{Ar} + \gamma \ (1.4 \text{ MeV}) \ [\text{EC}]$
- $^{42}\text{K} \rightarrow ^{42}\text{Ca} + \gamma \ (1.5 \text{ MeV})$
  
  + e- (up to 2 MeV)

$^{40}\text{K(\beta^-)}$

$^{42}\text{K(\beta^-)}$

$\beta^-$ in LAr

no energy in LAr
**Ge detectors**

- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

→ **35.8 kg of enr detectors**

3 diodes lost (burn-out JFET)
Ge detectors: leakage current

➢ Leakage currents rather stable
➢ In the first months temporary increase of LC during calibration for some detectors.
Effect now almost disappeared.
**Ge detectors: energy calibration**

- FWHM resolution curves from calibration and physics data
- @\(Q_{\beta\beta}\): FWHM(BEGe) = \(2.9 \pm 0.1\) keV
- FWHM(Coax) = \(4.0 \pm 0.2\) keV (add correction due to diff. calib - physics)

**Procedure:**
- weekly \(^{228}\)Th calibrations
- comparison with \(^{42}\)K, \(^{40}\)K peaks in physics data
- stability btw. calib: every 20 s pulser injected into FE
- ZAC filter for E reconstruction

[EPJC 75 (2015) 255]
Ge detectors: energy shift

- shifts @ $^{208}$Tl line very limited (within 1 keV); sufficient to allow the merger of the data from all periods
- data with energy shift greater than 1 keV are not used in the analysis
Pulse Shape Discrimination: BEGe

- Event classification using the ratio: Current/Energy i.e. A/E variable

- A/E<1 → MSE and n+ surface events
- A/E~1 → SSE
- A/E>1 → p+ surface events
A/E resolution of DEP events versus detector

- **Phase II**: strong dependence on position in string
- **Phase I**: FWHM 1.5-2%, little dependence on position in string

**PSD: BEGe**

- DEP events
- Compton at $Q_{\beta\beta}$
- FEP @ 2614 keV
- FEP 1620 keV, SEP
Pulse Shape Discrimination: BEGe

- Event by event selection
- Acceptance for $0\nu\beta\beta$ events: $(87.4 \pm 2.6)\%$
  - estimated from $^{208}\text{Tl}$ DEP
  - double checked at low energy with $2\nu\beta\beta$ events (after LAr cut)
Pulse Shape Discrimination: Coax

- PSD for Coax detectors less effective than for BEGes
- Artificial Neural Network (ANN) as in Phase I:
  - Trained on signal (SSE): $^{208}$Tl (2614 keV) DEP at 1592 keV
  - Background (MSE): $^{212}$Bi @ 1620 keV γ-line
  - Acceptance for $0\nu\beta\beta$ events ($85\pm5$)%
    - Double check with Compton edge and $2\nu\beta\beta$ events
    - MC simulation of waveforms
- New ingredient in PhaseII: dedicated ANN for $\alpha$
  - Test/train from data
  - Acceptance for $0\nu\beta\beta$ events ($93\pm1$)%
- Combined acceptance: ($79\pm5$)%

Current Pulses for SSE
Most prominent feature: $^{39}\text{Ar }\beta$ (< 500 keV), 2$\nu$$\beta$$\beta$, $^{42}\text{K}$ and $^{40}\text{K }\gamma$ lines, $\alpha$

PSD of BEGe clears completely the $\alpha$ region

LAr and PSD highly effective cuts

Final background at $Q_{\beta\beta}$ $\mathcal{O}(10^{-3}$ counts/keV·kg·yr)


Alpha rate

➢ Alpha rate different among detectors
  • Higher for Coax detectors
  • BEGE/coax same order if normalized according to the detector surface

➢ Part of the $\alpha$ component is decaying away ($^{210}\text{Po, } T_{1/2} = 138 \text{ days}$)

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GERDA

July 2017
Background Model

- Similar approach as in Phase I
  - EPJ C 74 (2014) 2764
  - Mostly same components considered
  - Fit range: 565 - 5320 keV

- Also same problem: difficult to disentangle components, also due to the low statistics

- The spectra are considered before LAr and PSD cuts
  - work in progress to have a full combined fit including LAr, PSD and multi-detectors events
  - PDF derived by MC
  - screening measurements included

- Observed $\gamma$-lines from $^{42}$K, $^{40}$K, Th chain ($^{228}$Ac, $^{208}$Tl), U chain ($^{214}$Bi, $^{214}$Pb)
Background Model

➢ The background model confirms the flatness of the background around the ROI and inside the blinding window as in Phase I
➢ The expected spectrum is roughly composed as follows: ~ 30% of events from $\alpha$, 30% $e^-$ from $^{42}$K and 30% from $\gamma$ coming from $^{212}$Bi + $^{208}$Tl and $^{214}$Bi + $^{214}$Pb as in Phase I
➢ Use the same analysis window as in Phase I
   ● 1930 – 2190 keV excluding the interval 2104 ±5 keV and 2119 ±5 keV of known peaks
Unblinding at Krakow

GERDA collaboration meeting at Krakow, 30 June: unblinding of ± 25 keV around $Q_{\beta\beta}$
Spectra in the ROI

**BI for Coax:**
7 cts (+2 known in blinded box)
$2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV·kg·yr)

**BI for BEGe:**
2 cts
$0.5^{+0.5}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg·yr)

**enrCoax**
16.2 kg·yr
(after all cuts)

**enrBEGe**
18.2 kg·yr
(after all cuts)
Spectra in the ROI

**BI for Coax:**
7 cts (+2 known in blinded box)
\[ 2.7^{+1.0}_{-0.8} \cdot 10^{-3} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)} \]

\[ \text{enr Coax} \]
16.2 kg·yr
(all cuts)
Previously unblinded:
5.0 kg·yr

\[ \text{enr BEGe} \]
18.2 kg·yr
(after all cuts)

**BI for BEGe:**
2 cts + 2 new (> 10σ from \( Q_{\beta\beta} \))
\[ 1.0^{+0.6}_{-0.4} \cdot 10^{-3} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)} \]
**Statistical Analysis**

<table>
<thead>
<tr>
<th>dataset</th>
<th>exposure [kg·yr]</th>
<th>FWHM [keV]</th>
<th>$\epsilon$</th>
<th>BI [10(^{-3})cts/(kev·kgyr)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI golden</td>
<td>17.9</td>
<td>4.3(1)</td>
<td>0.57(3)</td>
<td>11±2</td>
</tr>
<tr>
<td>PI silver</td>
<td>1.3</td>
<td>4.3(1)</td>
<td>0.57(3)</td>
<td>30±10</td>
</tr>
<tr>
<td>PI BEGe</td>
<td>2.4</td>
<td>2.7(2)</td>
<td>0.66(2)</td>
<td>5(^{+4}_{-3})</td>
</tr>
<tr>
<td>PI extra</td>
<td>1.9</td>
<td>4.2(2)</td>
<td>0.58(4)</td>
<td>5(^{+4}_{-3})</td>
</tr>
<tr>
<td>PIIa coaxial</td>
<td>5.0</td>
<td>4.0(2)</td>
<td>0.53(5)</td>
<td>3.5(^{+2.1}_{-1.5})</td>
</tr>
<tr>
<td>PIIb BEGe</td>
<td>18.2</td>
<td>2.9(1)</td>
<td>0.60(2)</td>
<td>1.0(^{+0.6}_{-0.4})</td>
</tr>
</tbody>
</table>

**Total exp. 46.7 kg**

- **Combined unbinned maximum likelihood** fit (flat background + gaussian signal) of the 6 spectra:
  - **Frequentist**: test statistics and method as in Cowan et al., EPJC 71 (2011)1554 (2 side-test statistics)
  - **Bayesian**: flat prior on $1/T_{0.5}^{0v}$ between 0 and $10^{-24}$ yr\(^{-1}\)
  - Systematic uncertainties folded as pull terms or by Monte Carlo

same as in Nature 544 (2017) 47
Statistical Analysis

➢ **Frequentist (preliminary results):**
Best fit $N^{0v} = 0$

$T^{0v}_{1/2} > 8.0 \cdot 10^{25}$ yr @ 90% C.L.

It was $5.3 \cdot 10^{25}$ yr in Phase IIa

Median Sensitivity (NO Signal)

$T^{0v}_{1/2} > 5.8 \cdot 10^{25}$ yr @ 90% C.L.

30% of MC realizations yield limit stronger than data

➢ upper limit on

$m_{\beta\beta} < 0.12 - 0.27$ eV

➢ **Bayesian (preliminary results):**

$T^{0v}_{1/2} > 5.1 \cdot 10^{25}$ yr @ 90% C.I.

Median Sensitivity:

$T^{0v}_{1/2} > 4.5 \cdot 10^{25}$ yr @ 90% C.I.
Future ...

➢ Phase I: (23.5 kg·yr)
  - Sensitivity: $2.4 \times 10^{25}$ yr
  - Limit: $T_{1/2}^{0v} > 2.1 \times 10^{25}$ yr (90% CL)

➢ Phase IIa: (Phase I + 10.8 kg·yr)
  - Sensitivity: $4.0 \times 10^{25}$ yr
  - Limit: $T_{1/2}^{0v} > 5.3 \times 10^{25}$ yr (90% CL)

➢ This release (Phase IIa + 12.4 kg·yr)
  - Sensitivity: $5.8 \times 10^{25}$ yr
  - Limit: $T_{1/2}^{0v} > 8.0 \times 10^{25}$ yr (90% CL)

➢ Already available:
  - $11.2$ kg·yr of validated coax data
  - $\sim 5$ kg·yr of data (Coax & BEGe) taken after Apr 15th

➢ The sensitivity of $10^{26}$ yr will be reached in the middle of 2018

➢ Final goals:
  - $100$ kg·yr @ $BI = 10^{-3}$ cts/(keV·kg·yr)
  - Sensitivity: $1.3 \times 10^{26}$ yr
  - Discovery potential up to $10^{26}$ yr (50% prob. chance for a $3\sigma$ signal)
Conclusions

➢ GERDA is **running smoothly** and with **high efficiency**
➢ We have collected **more than 35 kg·yr** of really good data: i.e. more than 1/3 of Phase II exposure (100 kg·yr)
➢ With the present release we have obtained:
  - Limit on $T_{1/2}^{0v} > 8.0 \times 10^{25}$ yr (90% CL)
  - Median Sensitivity: $5.8 \times 10^{25}$ yr (better than KamLand-Zen)
  - BI($^{enr}$ Coax): $2.7^{+1.0}_{-0.8} \times 10^{-3}$ cts/(keV·kg·yr)
    - BI($^{enr}$ BEGe): $1.0^{+0.6}_{-0.4} \times 10^{-3}$ cts/(keV·kg·yr)
  - $m_{\beta\beta} < 0.12 – 0.27$ eV
➢ With more data we confirm to have reached our **background index goal**
➢ **Lowest bkg** (~10x) in ROI respect to experiment using other isotopes
➢ Next year we are ready to break the wall of $10^{26}$ yr in **median sensitivity**
➢ This result suggests future Ge experiments with 200 kg and beyond