GERDA: results and future

Dušan Budjáš
Technische Universität München
for the GERDA collaboration
http://www.mpi-hd.mpg.de/GERDA
The **GERDA** collaboration

18 institutions

~100 members

www.mpi-hd.mpg.de/gerda

Dušan Budjáš (TUM)
Outline

1. Experimental approach and design
2. Data and analysis
3. Result: $0\nu\beta\beta$ $T_{1/2}$ limit
4. Future: GERDA Phase II
GERDA: 0νββ-decay experiment

GERDA aims to search for the half-life of 0νββ decay of $^{76}\text{Ge}$

Germanium detectors:
- ultra high purity material
- excellent energy resolution
- enrichment in $^{76}\text{Ge} \sim 86\%$

$Q_{\beta\beta} = 2039.01(5) \text{ keV}$

narrow peak $\Rightarrow$ good resolution is important

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Germanium detectors: historically most sensitive 0νββ probe

- IGEX: $T_{1/2}^{0ν} > 1.6$ (90% C.L.)
- Heidelberg-Moscow: $T_{1/2}^{0ν} > 1.9$ (90% C.L.)
- Klapdor-Kleingrothaus claim: $1.19^{+0.37}_{-0.23}$

Past approach (IGEX, HdM):

- Ge detector
- Pb shield
- Cu cryostat
- Cooling

GERDA approach (Gerd Heusser ‘95):

- Ultra-pure cryogenic liquid (cooling and shielding)
- Minimise nearby solid materials
- GERmanium Detector Array

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Design of GERDA

Laboratori Nazionali del Gran Sasso

Design of GERDA

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Design of GERDA

Clean room, data acquisition systems

Lock for detector insertion

Water tank

64m$^3$ LAr cryostat

Cu shield

Radon shroud

Detector array

PMT Cherenkov light read-out

228Th source

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Water Cherenkov PMT muon veto

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Low background challenge

Samples of all materials measured and selected for low radioactivity.

Variety of ultra-sensitive methods:

- Ge-detector spectrometry
- mass spectrometry
- neutron activation analysis
- radon emanation detection via proportional gas counters

proportional gas counter, GALLEX/GNO heritage

GeMPI spectrometer, evolution of Heidelberg-Moscow detector design
Low background challenge

$^{42}$Ar concentration in natural argon found much higher than expected.  
⇒ solved by installing protective Cu-foil “mini-shroud” around detectors
GERDA Phase I detectors

Enriched coaxial (17.67 kg):
5 from Heidelberg-Moscow
3 from IGEX

Enriched BEGe (3.63 kg):
5 new (Phase II design)
1 non-enriched coaxial

Deployment: November 2011
BEGe: July 2012
Data taking until: May 2013

Total exposure for $0\nu\beta\beta$ analysis: 21.6 kg⋅yr

3 data-sets: 17.9 kg⋅yr “golden”, 1.3 kg⋅yr “silver”, 2.4 kg⋅yr “BEGe”

ANG 1 and RG 3 stopped soon after deployment, RG 2 near the end.
GD35C excluded from analysis due to system instability
GERDA Phase I data analysis

Background data: blinded until all analysis procedures fixed

Analysis cuts:
muon-veto and Ge-array anti-coincidence: ~40% cut
signal quality: ~9% cut

Periodic calibration with $^{228}$Th sources.
Stability cross-check in final summed physics data on $^{42}$K background line:

FWHM only ~4% larger than expected
Background level improvement

**GERDA**

\[
T^{2\nu}_{1/2} = \left( 1.84^{+0.09}_{-0.08} \text{ fit } +0.11^{+0.11}_{-0.06} \text{ syst } \right) \times 10^{21}
\]


Average background at Qββ:

HdM: 0.16 cts/(keV·kg·y)

GERDA “golden”: 0.02 cts/(keV·kg·y)

Background γ-lines typically ~10× lower than HdM (except for $^{42}$K).

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Before unblinding: background model

“Gold” data allow good-statistics fit
Main background sources:

- $^{42}$K
- Th and U(or Ra) contamination in materials near detectors
- Ra and Po contamination of detector surfaces (including $\alpha$ decays)

Background near $Q_{\beta\beta}$ flat (no lines).

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arXiv:1306.5084
Before unblinding: pulse-shape discrimination

Signals recorded via FADC with 50 ns to 80 ns time resolution → analyse time-structure

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**Before unblinding:** pulse-shape discrimination

- measure **50 rise time variables** (1,3,5,…) 99%
- **Neural Network** (TMVA/TMIPANN) discriminates events

Trained on $^{228}$Th calibration data:
- MSE training sample: 1621 keV $\gamma$-line ($^{212}$Bi)
- SSE training sample: 1592 keV DEP of 2.6 MeV line ($^{208}$Tl)

DEP (double escape peak) events have similar spatial structure like $0\nu\beta\beta$

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**PSD for coaxial detectors:**
- measure **50 rise time variables** (1,3,5,…) 99%
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Before unblinding: pulse-shape discrimination

PSD for coaxial detectors

Neural Network response qualifier distribution:

![Graph showing neural network response qualifier distribution with terms SSE and MSE, and cutoffs for accepted and rejected.

PSD applied to $^{228}$Th calibration spectrum:

Cut is adjusted for each detector to 90% DEP survival.

arXiv:1307.2610
Before unblinding: pulse-shape discrimination

PSD for coaxial detectors

Determined Neural Network survival efficiency for $0\nu\beta\beta$: $0.90^{+0.05}_{-0.09}$

Furthermore, 2 alternative PSD methods were developed and their results support the validity of the Neural Network method.

Validity is cross-checked on $2\nu\beta\beta$ data: $0.85 \pm 0.02$

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arXiv:1307.2610
Before unblinding: pulse-shape discrimination

Separate analysis based on a single parameter used for BEGe detectors (more later).

Survival efficiency for $0\nu\beta\beta$: $0.92 \pm 0.02$

A/E parameter distribution:

2$\nu\beta\beta$ survival: $0.91 \pm 0.05$

Background at $Q_{\beta\beta}$:

$0.042^{+10}_{-8}\, \text{cts/(keV\cdot kg\cdot y)}$

$\Rightarrow 0.005^{+4}_{-3}\, \text{cts/(keV\cdot kg\cdot y)}$

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arXiv:1307.2610
Unblinding

14 June 2013, in Dubna, Russia

![Graph showing event count consistent with background](image)

<table>
<thead>
<tr>
<th>evt cnt in ±5 keV</th>
<th>golden</th>
<th>silver</th>
<th>BEGe</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>expt. w/o PSD</td>
<td>3.3</td>
<td>0.8</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>obs. w/o PSD</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>expt. w/ PSD</td>
<td>2.0</td>
<td>0.4</td>
<td>0.1</td>
<td>2.5</td>
</tr>
<tr>
<td>obs w/ PSD</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Event count consistent with background

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

Profile likelihood upper limit: $N^{0\nu} < 3.5$ cts @ 90% C.L.


“Neutrinoless Decays Are a No Show Again”

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Limit on $^{76}\text{Ge}$ half life

past claim $T_{1/2}^{0\nu} = 1.2 \cdot 10^{25} \text{ yr}$
present upper limit $\Rightarrow T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr}$ @ 90% C.L.

Combined with HdM and IGEX:
$T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{ yr}$

$<m_{\text{ee}}>/<m_{\text{ee}} > < 0.2\text{-}0.4 \text{ eV}$

$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{\text{enr}} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \epsilon_{fep} \cdot \epsilon_{psd}$$

<table>
<thead>
<tr>
<th>data set</th>
<th>$\mathcal{E}[\text{kg\cdot yr}]$</th>
<th>$\langle \epsilon \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>golden</td>
<td>17.9</td>
<td>$0.619^{+0.044}_{-0.070}$</td>
</tr>
<tr>
<td>silver</td>
<td>1.3</td>
<td>$0.619^{+0.044}_{-0.070}$</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>$0.663 \pm 0.022$</td>
</tr>
</tbody>
</table>

Past claim strongly disfavoured

**H1:** signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

**H0:** background only

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>$P(H_1)/P(H_0)$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>$^{76}\text{Ge}$</td>
<td>0.024</td>
</tr>
<tr>
<td>GERDA+H</td>
<td>$^{76}\text{Ge}$</td>
<td>0.0002</td>
</tr>
<tr>
<td>dM+IGEX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KamLAND-Zen*</td>
<td>$^{136}\text{Xe}$</td>
<td>0.40</td>
</tr>
<tr>
<td>EXO-200*</td>
<td>$^{136}\text{Xe}$</td>
<td>0.23</td>
</tr>
<tr>
<td>GERDA+KL</td>
<td>$^{76}\text{Ge} + ^{136}\text{Xe}$</td>
<td>0.002</td>
</tr>
</tbody>
</table>

* with conservative (smallest) NME ratio $M_{0\nu}(^{136}\text{Xe})/M_{0\nu}(^{76}\text{Ge}) \approx 0.4$ from:


$T_{1/2}^{0\nu}$ claim from Mod. Phys. Lett. A 21 (2006) 1547 **not** considered because of the inconsistencies (efficiency factors not taken into account $\Rightarrow T_{1/2}^{0\nu}$ calculation incorrect)


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Physics goals of GERDA

\( ^{76}\text{Ge} \) 0νββ decay \( T_{1/2} \) detection limit goals:

\[ 2 \cdot 10^{27} \text{ y} \star \]

\[ 2 \cdot 10^{26} \text{ y} \star \]

\[ 3 \cdot 10^{25} \text{ y} \star \]

Claim (Klapdor Kleingrothaus)

neutrino mass scale:

\[ < 24 - 41 \text{ meV} \] \( \dagger \)

\[ < 75 - 129 \text{ meV} \] \( \dagger \)

\( \dagger |m_{ee}| \) assuming \( |M_{0\nu}| = 2.99 - 8.99 \)

[Smolnikov & Grabmayr PRC 81 (2010) 028502]

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**Background requirement (in ~6 keV wide ROI):**

**\( ^{76}\text{Ge} \) exposure:**

state-of-art (HdM) 0.16 counts/(kg·y·keV) 72 kg·y (HdM)

GERDA Phase 1 <0.01 counts/(kg·y·keV) 21 kg·y (HdM+IGEX+new detectors)

GERDA Phase 2 <0.001 counts/(kg·y·keV) 100 kg·y (old + new detectors)

GERDA 3 & Majorana ‡ <0.0001 counts/(kg·y·keV) 1000 kg·y ‡

‡ GERDA-Majorana LoI: intention to merge for a 1 t experiment, not yet funded

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GERDA Phase II

- Increase mass: additional 30 enriched BEGe detectors (~ 20 kg)
- new front end readout in close proximity (2 cm) to detectors (noise reduction)
- radiopurity improvements (new cables, detector supports)
- PSA discrimination with the BEGe's
- Liquid argon veto instrumentation
Phase II tools: Modified Broad-Energy Ge detectors

GERDA Phase I: semi-coaxial Ge detector

GERDA Phase 2: modified BEGe detectors

n$^+$ electrode

(≤ mm thick)

(HV contact

p$^+$ electrode

(< μm thick)

read-out contact

BEGe advantages:

1) smaller p$^+$ electrode $\Rightarrow$ less capacitance $\Rightarrow$ **less noise** $\Rightarrow$ better energy resolution

2) favourable internal electric field distribution $\Rightarrow$ **powerful PSD capability**

- narrow peak in current signal
- signal shape independent of interaction position (same final trajectory)
- current amplitude depends only on energy of interaction (~95% of volume)

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[D. Budjáš et al., JINST 4:P10007,2009]  
[M. Agostini et al., JINST 6:P03005, 2011]
Phase II tools: LAr instrumentation

PMT option (Ø500 mm)
- new big lock
- low-background PMTs on top & bottom
- copper shroud
- reflector foil coated with wavelength shifter
- approach validated in LArGe*
- PMTs available
- on-going testing in LAr
- mechanical mock-up in preparation

SiPM & scintillating fiber option
- scintillating fibers form cylinder around Ge array (light detection inside & outside)
- read-out by KETEK SiPMs
- fits in present lock (Ø250 mm)
- approach tested on small scale
- fibers and SiPMs available
- test set-up in preparation

* [M. Heisel, Dissertation, University of Heidelberg (2011)]

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Phase II tools: Background identification

- Identification and discrimination of events by PSD and LAr veto:
  - $\beta\beta$-decay: $\beta$ range in Ge ~mm
  - $\gamma$-ray backgrounds: range in Ge ~cm

- Single-site event (SSE) vs multi-site event (MSE)
  - Single-site event: constant $I_{max}/E$
  - Multi-site event: reduced $I_{max}/E$

- Rejection of background events (e.g., $^{210}$Po $\alpha$, $^{42}$K $\beta$, $^{210}$Po $\beta$, LAr veto signal)

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Performance studies: PSD and LAr veto in LArGe

Low background test facility GERDA-LArGe at LNGS:

BEGe           LAr            PMTs
reflecting foil with wavelength shifter

228\text{Th near} and 228\text{Th far}:

226\text{Ra near} and 60\text{Co near}:

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[M. Heisel, Dissertation, University of Heidelberg (2011)]
Performance studies: $^{241}\text{Am} \ p^+ \ \text{contact} \ \alpha \ \text{events}$

**Table:**

<table>
<thead>
<tr>
<th>surface</th>
<th>p+ contact</th>
<th>groove inner</th>
<th>groove bottom</th>
<th>groove outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>survival fraction*</td>
<td>&lt; 1.1%</td>
<td>&lt; 12%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.2%</td>
</tr>
</tbody>
</table>

* 90% confidence-level upper limits
results limited by background in test setup; improved measurement analysis under way
Performance studies: surface $^{42}$K with BEGe in LArGe

MC cut set to 0.1% survival of $\beta$-like events and 20% survival of $\gamma$-like events. LAr veto with 100 keV threshold.

Expected survival at $Q_{\beta\beta}$:
- PSD only: $1.2 \times 10^{-3}$
- PSD+LAr veto: $0.8 \times 10^{-3}$

$^{42}$K measurement in LArGe

Veto + “standard” PSD cut:
- $0\nu\beta\beta$ survival: 85%
- $^{42}$K survival at $Q_{\beta\beta}$ (2 events): $< 11 \times 10^{-3}$ (90% c.l.)
  (noise limiting PSD performance)

Veto + “strong” PSD cut:
- $0\nu\beta\beta$ survival: 71%
- $^{42}$K survival at $Q_{\beta\beta}$ (0 events): $< 5 \times 10^{-3}$ (90% c.l.)
  (limited by available statistics)
Production of $^{enr}\text{Ge}$ Phase II detectors

Transports in shielded container, storage underground

→ 5 working HP$^{enr}\text{Ge}$ detectors mounted in GERDA
Phase II background summary: $Q_{\beta\beta}$

Background goal: $< 10^{-3}$ cts/(keV·kg·yr)  

<table>
<thead>
<tr>
<th>background</th>
<th>without cuts $\text{[cts/(keV·kg·yr)]}$</th>
<th>PSD survival</th>
<th>LAr veto survival</th>
<th>after cuts $\text{[cts/(keV·kg·yr)]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}$Tl</td>
<td>$\leq 0.01$</td>
<td>0.4</td>
<td>$4 \cdot 10^{-3}$</td>
<td>$\leq 1.6 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$^{214}$Bi</td>
<td>$\leq 0.01$</td>
<td>0.25</td>
<td>0.3</td>
<td>$\leq 7.5 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>$\leq 4 \cdot 10^{-4}$</td>
<td>0.01</td>
<td>0.02</td>
<td>$\leq 8 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$^{60}$Co (in Ge)</td>
<td>$\leq 4 \cdot 10^{-4}$</td>
<td>0.01</td>
<td>0.02</td>
<td>$\leq 8 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$^{68}$Ga (in Ge)</td>
<td>$\leq 0.015$</td>
<td>0.05</td>
<td>0.2</td>
<td>$\leq 3 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$^{226}$Ra ($\alpha$ on p+)</td>
<td>$\leq 1.5 \cdot 10^{-3}$</td>
<td>$&lt; 0.03$</td>
<td>–</td>
<td>$&lt; 3 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$^{42}$K ($\beta$ on n+)</td>
<td>$\sim 0.2$</td>
<td>$&lt; 0.05$</td>
<td>0.68</td>
<td>$&lt; 0.86 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

PSD and veto combined acceptance of $0\nu\beta\beta$-decay events is $\sim 86\%$