Neutrinoless Double Beta Decay in GERDA

Mark Heisel for the collaboration

ICNFP2015
23-30 August 2015
Kolymbari, Greece
The collaboration

GERDA collaboration Meeting in Heidelberg, 2014

6 countries, 16 institutions, ~100 members
The collaboration

16 institutions
~100 members
GERDA at Gran Sasso, Italy

Underground site to reduce cosmic muon flux by ~1,000,000

GERDA in Hall A

3500 m w.e.
Double beta decay

\[ Q_{\beta\beta} = (2039.061 \pm 0.007) \text{ keV} \]

other ββ isotopes: \(^{48}\text{Ca},^{82}\text{Se},^{96}\text{Zr},^{100}\text{Mo},^{116}\text{Cd},^{128}\text{Te},^{130}\text{Te},^{136}\text{Xe},^{150}\text{Nd},^{238}\text{U}\]

Motivation for $0\nu\beta\beta$ decay searches

2 neutrino double beta decay

allowed by SM, $\Delta L = 0$

0 neutrino double beta decay

forbidden in SM, $\Delta L = 2$

- Majorana nature of neutrino
- lepton number violation $\Delta L=2$
- effective $\nu$ mass: $\langle m_{ee} \rangle = |\sum_i U_{ei}^2 m_i|$
- access to $\nu$ mass hierarchy

exchange of majorana neutrino
Neutrino hierarchy? Neutrino mass scale?

**Effective electron neutrino mass:**

\[
|m_{\beta\beta}| \equiv \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 s_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta} \right|
\]

- \(m_i\) = masses of n mass eigenstates,
- \(U_{ei}\) = elements of neutrino mixing matrix,
- \(e^{i\alpha,\beta}\) = Majorana CP phases

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**Plot Details:**

- Normal hierarchy
- Inverted hierarchy
- GERDA Phase I limit
- GERDA Phase II goal
- \(\Delta m_{23}^2 < 0\)
- \(\Delta m_{23}^2 > 0\)

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**References:**

Double Beta Decay detection in $^{76}$Ge

2 neutrino double beta decay

0 neutrino double beta decay

Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \left\langle m_{ee} \right\rangle^2$$

search for $0\nu\beta\beta$ peak at $Q_{\beta\beta} = 2039$ keV ($^{76}$Ge)

electron-energy spectrum

halflife, phase space integral, nuclear matrix element, effective neutrino mass
Double Beta Decay detection in GERDA

Sensitivity:

\[ T_{1/2}^{0\nu} \sim \epsilon_{\text{eff}} \sqrt{\frac{M \cdot t}{\Delta E \cdot B}} \]

- \( M \cdot t \) = exposure
- \( \epsilon_{\text{eff}} \) = detection efficiency
- \( \Delta E \) = energy resolution
- \( B \) = background index

Detector = Source

Detectors enriched to 86\% \(^{76}\)Ge

<table>
<thead>
<tr>
<th>Phase</th>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure [kg \cdot yr]</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>( Bg ) [counts/(keV\cdot kg\cdot yr)]</td>
<td>(10^{-2})</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>Upper limit ( m_{\beta\beta} ) [eV]</td>
<td>0.23-0.39</td>
<td>0.09-0.15</td>
</tr>
</tbody>
</table>

A. Smolnikov, P. Grabmayr PRC 81 028502(2010)
State of the art of $0\nu\beta\beta$ search in $^{76}\text{Ge}$

- HdM Collaboration
  \[T_{1/2} > 1.9 \times 10^{25} \text{ yr (90\% CL)}\]

- IGEX Collaboration
  [Phys.Rev.D65,092007 (2002)]
  \[T_{1/2} > 1.6 \times 10^{25} \text{ yr (90\% CL)}\]
  \[T_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25} \text{ yr}\]

- Klapdor-Kleingrothaus et al.

- GERDA Collaboration
  PRL 111, 122503 (2013)
  \[T_{1/2} > 2.1 \times 10^{25} \text{ yr (90\% CL)}\]

- GERDA + HdM + IGEX
  \[T_{1/2} > 3.0 \times 10^{25} \text{ yr (90\% CL)}\]
Germanium Detector Array

Clean room + lock system

Water tank/muon veto

LAr cryostat

Ge detector array

64 m$^3$ LAr

590 m$^3$ H$_2$O

Phase I detector configuration

- 3 + 1 detector strings
- 8 $^{\text{enr}}$Ge coaxial detectors (2 not considered in the analysis)
- 5 $^{\text{enr}}$Ge BEGe detectors (1 not considered in the analysis)
- 1 $^{\text{enr}}$Ge natural Ge detector

$^{\text{enr}}$Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)
Total exposure: 21.6 kg·yr
Phase I background

- Dominant background sources: $^{42}$Ar, $^{228}$Th and $^{226}$Ra in detector holder, $\alpha$ on detector surface

ROI at $Q_{\beta\beta} (2039 \pm 20)$ keV blinded since Jan 2012

Enriched coaxials, 16.70 kg × yr

Enriched BEGes, 1.80 kg × yr

- $^{39}$Ar $\beta^-$
- $2\nu\beta\beta$
- $^{226}$Ra
- $^{210}$Po
- $^{222}$Rn
- $^{218}$Po
- K-40 1461 keV
- K-42 1525 keV

Counts vs. (keV)
Background model & blinding

### Background in full energy range:
- fit combined Monte Carlo spectra to data in interval 570 keV – 7500 keV
- simulated known & observed background contributions
- different combinations of position & contribution tested (min/max model)

### Background in ROI (2039 keV):
- background is flat in 1930-2190 keV (excluding known peaks at 2104 and 2119 keV)
- partial unblinding \(Q_{\beta\beta} \pm 20\) keV after fixing calibration & background model
- \(Q_{\beta\beta} \pm 5\) keV remains blinded for 0νββ analysis

EPJC [arXiv:1306.5084]
GERDA Phase I result ($0\nu\beta\beta$)

7 events observed in blinded window

5.1 events expected from background

spectrum around $Q_{\beta\beta}$ (2039 keV) of full data set (21.6 kg·yr)
GERDA Phase I result ($0\nu\beta\beta$)

- **3** events observed w/ pulse shape discrimination (PSD)
- **2.5** events expected from background

→ B.I.: $\sim 1 \times 10^{-2} \text{ cts/(keV\cdot kg\cdot yr)}$

**spectrum around $Q_{\beta\beta}$ (2039 keV) of full data set (21.6 kg\cdot yr)**
GERDA Phase I result ($0\nu\beta\beta$)

3 events observed w/ PSD

2.5 events expected from background

→ BI: $\sim 1 \times 10^{-2}$ cts/(keV·kg·yr)

<3 events expected from $0\nu\beta\beta$ limit (best fit for $N^{0\nu}=0$)

→ profile likelihood fit for $0\nu\beta\beta$: $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr

GERDA Phase I result (0νββ)

3 events observed w/ PSD
2.5 events expected from background → BI: ~1 x 10^{-2} cts/(keV·kg·yr)
<3 events expected from 0νββ limit (best fit for N^{0v}=0) → profile likelihood fit for 0νββ: T^{0v}_{1/2} > 2.1 x 10^{25} yr
5.9 ± 1.4 events expected from claim (2004) → claim is rejected with 99% prob.

GERDA: 90% lower limit (T^{0v}_{1/2})
Claim: T^{1/2}_{1/2} = 1.19 x 10^{25} yr
**Combined $^{76}$Ge Results**

**GERDA + HDM$^1$ + IGEX$^2$:**

\[ T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{ yr (90\% C.L.)} \]

more detail in PRL 111, 122503 (2013)

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Comparison to results from $^{136}$Xe experiments:


GERDA Phase I result ($2\nu\beta\beta$)

- updated analysis using 20.3 kg·yr coaxial/BEGe detectors

- measured $2\nu\beta\beta$ half life: $T^{2\nu}_{1/2} = (1.926 \pm 0.095) \cdot 10^{21}$ yr

Results on Majoron emission

- search for $0\nu\beta\beta$ decay with Majoron(s) emission performed for spectral index $n = 1, 2, 3, 7$
- No signal found, limits of $O(10^{23})$ yr on half-lives
Phase II upgrade – commissioning since April '15

Additional 25 new BEGe detectors
~ 35 kg total mass
- enhanced energy resolution
- enhanced pulse shape discrimination

- new low-mass holders with reduced mass
- new front-end electronics
→ less radioactivity

- LAr veto light instrumentation w/ PMTs and SiPMs

7 detector string array
Background types & mitigation techniques

**Background types:**
- Single & multi site events from $\gamma$ background, e.g. $^{228}$Th, $^{226}$Ra, $^{60}$Co
- Surface events from $\alpha$ and $\beta$ background, e.g. $^{42}$K, $^{210}$Po
- Muons

**Mitigation techniques:**
- Detector anti-coincidence (AC)
- Pulse shape discrimination (PSD)
- Argon scintillation veto (LAr veto)
- Nylon 'mini shroud' (NMS)
- Water Cerenkov muon veto
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**BEGe pulse shape discrimination**

- well established cut parameter $A/E = \text{current pulse} / \text{charge pulse}$
- $0\nu\beta\beta$ efficiency = 92±2 %
  - determined from DEP efficiency & simulation
- $2\nu\beta\beta$ efficiency = 91±5 %
  - in good agreement to DEP efficiency
- reject > 80% of background

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Single-site event (signal like):

[EPJ C73 (2013) 2583]
BEGe pulse shape discrimination

- well established cut parameter
  \( \frac{A}{E} = \text{current pulse / charge pulse} \)
- \( 0\nu\beta\beta \) efficiency = 92\( \pm \)2 \% determined from DEP efficiency & simulation
- \( 2\nu\beta\beta \) efficiency = 91\( \pm \)5 \% in good agreement to DEP efficiency
- reject > 80% of background

Multi-site event (background like):

\[ \text{[EPJ C73 (2013) 2583]} \]
LAr veto – light instrumentation

16 low background 3“ PMTs Ham RG11065-10/20 MOD

810 scintillating fibres coupled to 90 KETEK SiPMs
LAr veto – light instrumentation

100 µm Cu shrouds w/ wavelength shifting TETRATEX foil

810 scintillating fibres coupled to 90 KETEK SiPMs
Phase II commissioning – \(^{228}\text{Th}\) source

**GERDA preliminary May 2015**

**counts/5 keV**

- anti-coincidence cut (AC)
- AC + PSD
- AC + LAr veto
- AC + LAr veto + PSD

**228\text{Th} calibration run**

Detectors:
- 4/C, 1/D, 79C, 02B, 35B
Phase II commissioning – $^{228}$Th source

- Double escape peak of the $^{208}$Tl 2.6 MeV line → signal-like events
- Full energy peaks of the $^{212}$Bi 1.6 MeV line → background events

→ In case of discovery PSD + LAr veto will show if $\gamma$ or $0\nu\beta\beta$ line
Phase II commissioning – $^{226}$Ra source

GERDA preliminary June 2015

2$^{26}$Ra calibration run
- anti-coincidence cut (AC)
- AC + PSD
- AC + LAr veto
- AC + LAr veto + PSD

detectors: 4/C, 1/D, 79C, 02B, 35B
Phase II sensitivity projection

- MC realization of data sets w/ profile likelihood analysis of each set
  → global analysis including Phase I & Phase II

- Phase II input/goal:
  mass: $37 \text{ kg}^{76}\text{Ge}$
  backgr.: $1 \times 10^{-3} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)}$

- median sensitivity after two years of data taking:
  $T_{1/2}^{0\nu} > 1 \times 10^{26} \text{ yr}$
  $|m_{ee}| < 100 \text{ meV}$
Conclusion

► Neutrinoless double beta decay promises exiting physics beyond the standard model!

► GERDA Phase I set new limit on $0\nu\beta\beta$ in $^{76}\text{Ge}$: $T^{1/2} > 2.1 \times 10^{25}$ yr

► GERDA Phase II has started, goal is to improve sensitivity by factor 10

Corno Grande: GERDA's passive shielding @ LNGS
backup slides
LArGe test bench

at Gran Sasso

... suppression at region of interest

<table>
<thead>
<tr>
<th>source</th>
<th>position</th>
<th>suppression factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LAr veto</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>int</td>
<td>27 ± 1.7</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>ext</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>int</td>
<td>4.6 ± 0.2</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>ext</td>
<td>25 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>int</td>
<td>1180 ± 250</td>
</tr>
</tbody>
</table>

e.g. close-by Th-228 source

without veto
with LAr veto
with PSD cut
with veto & PSD

counts [#]

energy [keV]

10^4

10^3

10^2

10^1

10^0

0

500

1000

1500

2000

2500

3000

counts [#]

energy [keV]

10^4

10^3

10^2

10^1

10^0

1950

2000

2050

2100
Detectors in Phase I & II

**Phase I:**
- Use 8 refurbished semi-coaxial diodes from HdM & IGEX (total mass 17.67 kg)
- Use pulse shape discrimination (PSD) based on artificial neural network
- Also use 5 $^{enr}$BEGe detectors (3.63 kg)

**Phase II:**
- Use 30 $^{enr}$BEGe detectors (20.5 kg) (in addition to semi-coaxial ones)
- Small 'point-like' contact allows for superior PSD & $\Delta E$
- Already tested in Phase I
BEGe pulse shape discrimination

single site events: $\beta\beta$, DEP (signal like)

multi site events: Compton (background like)

- $0\nu\beta\beta$ efficiency = 92±2 % determined from DEP efficiency & simulation
- $2\nu\beta\beta$ efficiency = 91±5 % in good agreement to DEP efficiency
- reject > 80% of background events

well established cut parameter $A/E = \text{current pulse} / \text{charge pulse}$

[EPJ C73 (2013) 2583]
Front end electronics

**Phase II:** very front end electronics are very close to detector!

**Phase I:** distance was > 30 cm

- custom made feed back resistor (~GΩ)
- JFET - bare die SF291
- printed trace capacitors (feed back, test, ~pF)
- bond pad
- signal cable to cryogenic preamp > 50 cm away
- HV cable
- wire bonds 25 μm Al
Front end electronics

**CC3: 4 Channel Charge Sensitive Preamplifier**
- upgrade of CC2 preamplifier of GERDA Phase I, based on commercially available op-amps

- **low-noise:**
  - 0.7 keV FWHM pulser resolution
  - 2.6 keV FWHM at 2.6 MeV with BEGe detector
  - 20 MHz bandwidth allows PSD (A/E)

- **cryogenic:**
  - suitable for operation in liquid Argon (50 mW/channel)

- **radio-pure electronics:**
  - ≈ 50 µBq/channel (including pins) expected
42K background

42Ar activity used for proposal: <41 µBq/kg @90% CL [Barabash et al., 2002]
measured in GERDA: (93.0 ± 6.4) µBq/kg (preliminary result)

► background enhanced by collection of 42K ions via E-field
► therefore: E-field & convection free configuration in 'mini-shroud'

42K line
@1525 keV

without mini-shroud

with mini-shroud
'Mini-shroud' against $^{42}$K $\beta$-background

**Phase II:**
suppression of $^{42}$K background by three orders of magnitude at $Q_{\beta\beta}$ using LAr veto /w nylon mini-shroud and PSD:

measurement in LArGe test bench spiked with $^{42}$Ar statistics corresponding to $\sim 17$ kg$\times$yr in natural argon.
### 76Ge $0\nu\beta\beta$ search before GERDA

#### Heidelberg-Moscow


<table>
<thead>
<tr>
<th>Exposure</th>
<th>Result $T_{1/2}^{0\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.9 kg·yr</td>
<td>$&gt; 1.3 \times 10^{25}$ yr (no PSD)</td>
</tr>
<tr>
<td>35.5 kg·yr</td>
<td>$&gt; 1.9 \times 10^{25}$ yr (90% C.L.)</td>
</tr>
</tbody>
</table>

#### IGEX


<table>
<thead>
<tr>
<th>Exposure</th>
<th>Result $T_{1/2}^{0\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.8 kg·yr:</td>
<td>$&gt; 1.6 \times 10^{25}$ yr (90% C.L.)</td>
</tr>
</tbody>
</table>
Klapdor-Kleingrothaus et al. (2004)


- **Claim:** 4.2σ evidence for $0
\nu\beta\beta$

  \[ T_{1/2} = 1.19 \times 10^{25} \text{ yr} \]

- **Exposure:** 71.7 kg·yr,
- **Background:** 0.17 / (kg·yr·keV)
- **Events:** 28.75 ± 6.87 (bgd: ~60)

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Klapdor-Kleingrothaus et al. (2006)

[Mod. Phys. Lett. A 21, 1547 (2006)]

- **Claim:** $T_{1/2} = 2.23 \times 10^{25} \text{ yr} (~6\sigma)$

- **not considered by us, because:**

  1. reported half-life can be reconstructed* only with $\epsilon_{\text{psd}} = 1$ (previous similar analysis $\epsilon_{\text{psd}} \approx 0.6$)
  2. $\epsilon_{\text{fep}} = 1$ (also used in result from 2004),
     GERDA value for same detectors is $\epsilon_{\text{fep}} = 0.9$

New detectors: from raw material to diode production

Energy resolution of GERDA BEGe detectors

FWHM [keV] at 1332 keV

1.74 ± 0.06 keV