Searches for neutrinoless double beta decay – results from phase I of the GERDA experiment

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on behalf of the GERDA Collaboration
• Double beta decay
• Design and goals of GERDA
• Phase I results
• Conclusions
In a number of even-even nuclei, $\beta$ decay is energetically forbidden, while double beta decay from a nucleus of $(A,Z)$ to $(A, Z+2)$, is energetically allowed.

\[ Q = 2039 \text{ keV} \]

\[ \beta \beta \]

\[ 48^{\text{Ca}}, 76^{\text{Ge}}, 82^{\text{Se}}, 96^{\text{Zr}}, 100^{\text{Mo}}, 116^{\text{Cd}}, 128^{\text{Te}}, 130^{\text{Te}}, 136^{\text{Xe}}, 150^{\text{Nd}} \]
Double beta decay modes

$2\nu\beta\beta$

$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\Delta L = 0$

$T_{1/2} \sim 10^{18} - 10^{21}$ y

$0\nu\beta\beta$

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

$\Delta L = 2$

$T_{1/2} \sim 10^{26} - 10^{27}$ y

$T_{1/2}^{\exp} > 2 \times 10^{25}$ y

Phase I results

GERDA D&G

Conclusions

GERDA

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Double beta decay modes

ββ decay

GERDA D&G

Phase I results

Conclusions
Neutrinoless $\beta\beta$ beta decay (0$\nu\beta\beta$)

$$T_{1/2}(90\%\ CL) > \frac{\ln 2 \ N_A}{1.64 \ \frac{A}{A}} \ \epsilon \cdot a \ \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

- $\epsilon$ – detection efficiency
- $A$ – isotope molar mass
- $a$ – isotope mass fraction
- $M$ – active mass
- $T$ – measurement time
- $B$ – background rate
- $\Delta E$ – energy resolution
- $M \cdot T$ – exposure
If $0\nu\beta\beta$ observed:

- Neutrino is a Majorana particle (its own antiparticle)
- Lepton number is not conserved
- Dealing with physics beyond the Standard Model
- Absolute neutrino mass scale
- Neutrino mass hierarchy
- CP violation in the lepton sector

**Significant contribution to Particle Physics, Astrophysics and Cosmology**
Observation claim


- 71.7 kg year - bgd 0.16 / (keV×kg×yr)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0ν} = (1.19^{+0.37}_{-0.23}) \times 10^{25}$ yr

N.B. Half-life $T_{1/2}^{0ν} = 2.23 \times 10^{25}$ yr; $T_{1/2}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006)) is not considered because it misses efficiencies (i.e. $\epsilon_{PSD} \sim 0.5$).
GERDA

• GERDA (GERmanium Detector Array) has been designed to investigate neutrinoless double beta decay of $^{76}\text{Ge}$ ($Q_{\beta\beta} = 2039$ keV)
  - Ge mono-crystals are very pure
  - Ge detectors have excellent energy resolution
  - Detector = source ($\varepsilon \approx 1$)
  - Enrichment required ($7.4\% \rightarrow 86\%$)

• Background (index) around $Q_{\beta\beta}$:
  $10^{-2} - 10^{-3}$ cts/(keV×kg×yr); 10 – 100 times lower compared to previous experiments (HdM/IGEX)
GERDA Detector Design

ββ decay

GERDA D&G

Phase I results

Conclusions

Water tank + µ veto

Cryostat

Cryo-lab

Control room

222Rn monitor

Clean room

Lock

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GERDA Phase I detectors
Realization in phases

Phase I:
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV×kg×yr)
Sensitivity after 20 kg×yr

Phase II:
Add new enr. BEGe detectors (~20 kg)
BI ≈ 0.001 cts / (keV×kg×yr)
Sensitivity after 100 kg×yr

ββ decay
GERDA D&G
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Conclusions
The GERDA Collaboration

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

ßß decay
GERDA D&G
Phase I results
Conclusions
GERDA in LNGS

ββ decay
GERDA D&G
Phase I results
Conclusions

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GERDA milestones

• 2004 – 2005: The collaboration was formed
• 2005 – 2010: GERDA funded, designed and constructed in LNGS Hall A
• June 2010: Commissioning started. One string (3 natGe detectors, 7.6 kg) deployed for the first time. Checking the detector’s performance
• June 2010 – June 2011: Detailed investigation of background sources with natGe (42Ar, 228Th, cosmogenics)
• June 2011: Deployment of the first string of enrGe (3 detectors, 6.7 kg)
• 01.11.2011: Start data taking with all 8 Phase I enrGe crystals (17.8 kg) and 1 natGe crystal (from GTF)
• June 2012 5 Phase II enr. BEGe detectors inserted into the cryostat (3.6 kg)
• Phase I data: 09.11.11 – 09.05.13 (21.6 kg×yr acquired)
GERDA data analysis

- Data around $Q_{\beta\beta}$ (±20/5 keV) were blinded
- Background analyzed in a wider window of $Q_{\beta\beta} \pm 200$ keV
- PSD procedures (for coax and BEGe detectors) developed and documented (internally) in advance
- Discussion and freezing of all parameters and methods prior to unblinding
- Unblinding at Dubna Collaboration meeting (22-24 June 2013)
228\textsubscript{Th} calibration once every one to two weeks; stability continuously monitored with pulser.
Stability of detectors

Peak position stability of 2614.5 keV calibration line: coax: 1.5 keV / BEGe: 1.0 keV (FWHM)

Mean energy resolution at $Q_{\beta\beta} = 2039$ keV:
- Coax: 4.8 keV (FWHM)
- BEGe: 3.2 keV (FWHM)
Half life for $2\nu\beta\beta$

$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}) \times 10^{21}$ yr

Background model: arXiv:1306.5084
submitted to EPJC

Half life for $2\nu\beta\beta$

$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}) \times 10^{21} \text{ yr}$$
**After data unblinding**


<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>Counts/(2 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>2</td>
</tr>
<tr>
<td>1950</td>
<td>3</td>
</tr>
<tr>
<td>2000</td>
<td>4</td>
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<tr>
<td>2050</td>
<td>5</td>
</tr>
<tr>
<td>2100</td>
<td>6</td>
</tr>
<tr>
<td>2150</td>
<td>7</td>
</tr>
<tr>
<td>2200</td>
<td>8</td>
</tr>
</tbody>
</table>

- **1930 keV**
- **2039 keV** $Q_{\beta\beta}$
- **2190 keV**
- **2204 keV** $^{214}\text{Bi}$

**Total counts in BW (10 keV)**

<table>
<thead>
<tr>
<th></th>
<th>Expected (bgd only)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>without PSD</td>
<td>5.1</td>
<td>7</td>
</tr>
<tr>
<td>with PSD</td>
<td>2.5</td>
<td>3</td>
</tr>
</tbody>
</table>

**PSD methods for coaxial and BEGe’s:** arXiv:1307.2610
(submitted to EPJC)

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• 90% lower limit derived from profile likelihood (Frequentist limit, flat bgd)
• BW = 10 keV
• Best fit: $N^{0
\nu} = 0$
• No excess of signal counts above the background
• Limit on half-life corresponds to $N^{0
\nu} < 3.5$ cts
Expected for claimed $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr: $5.9 \pm 1.4$ signal over $2.0 \pm 0.3$ bgd in $\pm 2\sigma$ energy window to be compared with 3 cts (0 in $\pm 1\sigma$)

**H1:** claimed signal: $5.9 \pm 1.4$ cts

**H0:** background only

**Bayes factor:** $P(H1)/P(H0) = 0.024$

**p-value** from profile likelihood

$P(N^{0\nu} = 0|H1) = 0.01$

→ Claim refuted with high probability

**Combining available Ge data:**


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

$P(H1)/P(H0) = 2 \times 10^{-4}$ strongly disfavors the claim: Comparison is independent of NME and of physical mechanism which generates $0\nu\beta\beta$
Conclusions

• GERDA Phase I design goals reached:
  • Background index after PSD: 0.01 cts / (keV×kg×yr)
  • Exposure 21.6 kg×yr

• No 0νββ-signal observed at $Q_{\beta\beta} = 2039$ keV; best fit: $N^{0\nu} = 0$
  • Background-only hypothesis $H_0$ strongly favored
  • Claim strongly disfavored (independent of NME and of leading term)

• Limit on half-life:
  GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)
  GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.)
  $<m_{ee}> < 0.2 - 0.4$ eV

• Results reached after only 21.6 kg×yr exposure because of unprecedented low background: bgd counts in ±2σ after analysis cuts:
  0.01 cts / (mol×yr) (EXO: 0.07, KL: 0.67)

• GERDA Phase II will start in late 2013
Backup slides
Ge / Xe combined results

![Graph showing combined results for Ge and Xe in a diagram with various theoretical and experimental data points.](Image)
Effective neutrino mass

\[ |m_{ee}| \text{ in eV} \]

- 90% CL (1 dof)
- \( \Delta m_{23}^2 > 0 \)
- \( \Delta m_{23}^2 < 0 \)
- disfavoured by cosmology
- claim of evidence

- 10^{25} \text{ y (GD I)}
- 10^{26} \text{ y (GD II)}
- 10^{27} \text{ y (GD III)}
- 10^{28} \text{ y (Future)}

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From counts to half life

\[
T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{\text{enr}} \cdot N_{0\nu}} \cdot \varepsilon \cdot \varepsilon
\]

\[
\varepsilon = f_{76} \cdot f_{\text{av}} \cdot \varepsilon_{\text{fep}} \cdot \varepsilon_{\text{psd}}
\]

**Data set** | **Exposure (kg yr)**
--- | ---
Golden-coax | 17.9
Silver-coax | 1.3
BEGe | 2.4

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<table>
<thead>
<tr>
<th></th>
<th>(&lt;f_{76}&gt;)</th>
<th>(&lt;f_{\text{av}}&gt;)</th>
<th>(&lt;\varepsilon_{\text{fep}}&gt;)</th>
<th>(&lt;\varepsilon_{\text{psd}}&gt;)</th>
<th>(&lt;\varepsilon&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coax</td>
<td>0.86</td>
<td>0.87</td>
<td>0.92</td>
<td>0.90 ±0.05/ -0.09</td>
<td>0.619 ±0.044/-0.070</td>
</tr>
<tr>
<td>BEGe</td>
<td>0.88</td>
<td>0.92</td>
<td>0.90</td>
<td>0.92 ± 0.02</td>
<td>0.663 ± 0.022</td>
</tr>
</tbody>
</table>

**Symbols:**

- \(N_A\): Avogadro number
- \(E\): exposure
- \(\varepsilon\): exposure averaged efficiency
- \(m_{\text{enr}}\): molar mass of enriched Ge
- \(N_{0\nu}\): signal counts / limit
- \(f_{76}\): enrichment fraction
- \(f_{\text{av}}\): fraction of active detector volume
- \(\varepsilon_{\text{fep}}\): full energy peak efficiency for \(0\nu\beta\beta\)
- \(\varepsilon_{\text{psd}}\): signal acceptance
Min. model Gold-coax data (17.9 kg·yr)

\[(870 - 1170) \text{ keV in 2 keV bins} \rightarrow (1170-870)/2 = 150 \text{ data points}\]

116 out of 150 points (77\%) are inside the green band (expected 68\%)

143 out of 150 points (95\%) are inside the yellow band (expected 95\%)

150 out of 150 points (100\%) are inside the red band (expected 99.9\%)
Min. model Gold-coax data (17.9 kg·yr)

(2070 – 2570) keV in 5 keV bins → (2570-2070)/5 = 100 data points

81 out of 100 points (81%) are inside the green band (expected 68%)

97 out of 100 points (97%) are inside the yellow band (expected 95%)

100 out of 100 points (100%) are inside the red band (expected 99.9%)
Neutrinoless $\beta\beta$ beta decay

$$T_{1/2}(90\% \text{ CL}) > \frac{\ln 2}{1.64} \frac{N_A}{A} \varepsilon \cdot \gamma \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{\tau} = G(Q, Z) \cdot |M_{nuc}|^2 \cdot <m_{ee}>^2$$

- Space factor
- Nuclear matrix element
- Effective neutrino mass

$$<m_{ee}> = \left| \sum_j m_j U_{ej}^2 \right|$$
„Super” isotope for $0\nu\beta\beta$

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

Figure adopted from Robertson.

~ factor 4

**QRPA**
(Simkovic et al. PRC 77, 2008)

- 1/A
- phase space
- matrix element
- rate per mass

**Ratio to $^{76}\text{Ge}$**

$$^{76}\text{Ge} \quad ^{82}\text{Se} \quad ^{100}\text{Mo} \quad ^{116}\text{Cd} \quad ^{130}\text{Te} \quad ^{136}\text{Xe}$$

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Spectra $^{\text{n}}\text{atGe}$ vs $^{\text{en}}\text{rGe}$

- $^{\text{en}}\text{rGe}$: 3.8 kg·y
- $^{\text{n}}\text{atGe}$: 2.0 kg·y

Energy (keV)

Counts/(keV·kg·y)
HdM spectrum

$T_{1/2}^{2\nu\beta\beta} = 1.74 \cdot 10^{21}$ y
Neutrino masses

$0\nu\beta\beta$ decay:  \[ < m_{ee} > = \left| \sum_j m_j U_{ej}^2 \right| \]

$\beta$ decay:  \[ \langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} \]

Cosmology:  \[ \sum = \sum m_i \]