First GERDA results on the neutrinoless double beta decay search of $^{76}\text{Ge}$

Nuno Barros on behalf of the GERDA Collaboration

Technische Universität Dresden, Germany

PASCOS 2013 - 25 Nov 2013 - Taipei, Taiwan
Probing the nature of neutrino with neutrinoless double-beta decay

**Neutrinoless double beta decay** $(0\nu\beta\beta)$

- $2\nu\beta\beta$ possible in isotopes where $\beta^-$ decay is energetically forbidden.
  - Continuous spectrum ending at Q-value.
  - $T_{1/2}^{2\nu} \sim 10^{19-21}$ yr.
  - For $^{76}$Ge: $T_{1/2}^{2\nu} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21}$ yr (GERDA)

- $0\nu\beta\beta$ prohibited by the S. M.
  - Lepton number violation.
  - Physics beyond the standard model.
  - Shed light on neutrino mass (and possibly hierarchy).

\[ \Delta L = 0 \Rightarrow \text{Predicted by the S.M.} \]

\[ \Delta L = 2 \Rightarrow \text{Prohibited by the S.M.} \]

Light Majorana neutrino exchange

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**Energy (keV)**

- **$2\nu\beta\beta$**
  - Ge-76: $Q_{\beta\beta} = 2039$ keV

First results on $0\nu\beta\beta$ from GERDA
Probing the nature of neutrino with neutrinoless double-beta decay

**Neutrinoless double beta decay (0νββ)**

- **Expected decay rate:**
  \[
  \left( T_{1/2}^{0ν} \right)^{-1} = G^{0ν} |M^{0ν}|^2 \frac{\langle m_{ββ} \rangle^2}{m_e^2}
  \]
  with:
  - \( G^{0ν} \): Phase space integral
  - \( |M^{0ν}|^2 \): Nuclear matrix element

- **Effective Majorana mass:**
  \[
  \langle m_{ββ} \rangle \equiv \left| \sum_i U_{ei}^2 m_i \right| = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{iφ_2} + |U_{e3}|^2 m_3 e^{iφ_3}
  \]

- **Signature:** Monoenergetic peak at
  \[
  Q_{ββ} = m(A, Z) - m(A, Z + 2)
  \]

**The Neutrinoless Double Beta Decay**

\( n \ p \ e \) \( en \ p \) \( 0νββ \)

**Theoretical aspects of 0νββ decay**

- **Lepton number is violated**
- **ν's are Majorana particles**
- **Physics beyond the Standard Model**

**Search of Neutrinoless Double Beta Decay with the GERDA Experiment**

Giovanni Benato for the GERDA Collaboration

\( ΔL = 2 \Rightarrow Prohibited by the S.M. \)

Light Majorana neutrino exchange

First results on 0νββ from GERDA
Probing the nature of neutrino with neutrinoless double-beta decay

**Experimental requirements for** \(0^\nu\beta\beta\)

<table>
<thead>
<tr>
<th>(\epsilon)</th>
<th>detection efficiency</th>
<th>(\geq 85%)</th>
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</thead>
<tbody>
<tr>
<td>(\varepsilon)</td>
<td>enrichment fraction</td>
<td>high natural or enrichment</td>
</tr>
<tr>
<td>(M)</td>
<td>active target mass</td>
<td></td>
</tr>
<tr>
<td>(T)</td>
<td>measuring time</td>
<td></td>
</tr>
<tr>
<td>(B)</td>
<td>background index (\frac{cts}{keV\cdot kg\cdot yr})</td>
<td>veto, select radio pure materials,...</td>
</tr>
<tr>
<td>(\Delta E)</td>
<td>Energy resolution</td>
<td>use high resolution spectroscopy</td>
</tr>
</tbody>
</table>

**GERDA technique:** Low background High-Purity Germanium Detectors

**Advantages:**
- Well established enrichment technique \((\varepsilon_{\text{76 Ge}} = 86\%)\)
- Very good resolution \((\text{FWHM } \Delta E \approx 0.1\% - 0.2\%)\)
- Very good detection efficiency \((\text{source } = \text{ detector } \Rightarrow \epsilon \approx 0.92)\)

**Disadvantages:**
- Low \(Q_{\beta\beta}\) value
  - Background from \(^{208}\text{Tl}\) and \(^{214}\text{Bi}\)
- Need enrichment from 7\% to 86\% (expensive)
Probing the nature of neutrino with neutrinoless double-beta decay

State of the art in $0\nu\beta\beta$

Ge-76:

- IGEX collaboration
  $T_{1/2}^{0\nu}(^{76}\text{Ge}) \geq 1.6 \cdot 10^{25}$ yr (90% C.L.)

- HdM collaboration
  $T_{1/2}^{0\nu}(^{76}\text{Ge}) \geq 1.9 \cdot 10^{25}$ yr (90% C.L.)

- Klapdor-Kleingrothaus et al.
  $T_{1/2}^{0\nu}(^{76}\text{Ge}) = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

Xe-136:

- EXO collaboration
  $T_{1/2}^{0\nu}(^{136}\text{Xe}) > 1.6 \cdot 10^{25}$ yr (90% C.L.)

- KamLAND-Zen collaboration
  $T_{1/2}^{0\nu}(^{136}\text{Xe}) > 1.9 \cdot 10^{25}$ yr (90% C.L.)
The GERDA experiment

The GERDA collaboration

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

16 institutions
~100 members
The GERDA experiment

Located at Hall A of LNGS.

- 3800 m.w.e.

**Phase I (Nov 2011 - May 2013):**

- 15 – 20 kg of target mass (87% $^{76}$Ge)
- bkg $\sim 10^{-2}$ cts/(keV·kg·yr) at $Q_{\beta\beta}$
- exposure 21.6 kg·yr
- sensitivity to scrutinize KK claim

**Phase II (migration ongoing):**

- new custom-produced BEGe detectors (additional 20 kg, 87% $^{76}$Ge)
- bkg $\lesssim 10^{-3}$ cts/(keV·kg·yr) at $Q_{\beta\beta}$ (active techniques for bkg suppression)
- exposure $\gtrsim 100$ kg·yr
- start exploring $T_{1/2}^{0\nu}$ in the $10^{26}$ yr range

[Phys.Rev.D75, 092003 (2006)]

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First results on $0\nu\beta\beta$ from GERDA
Background sources:
- natural radioactivity ($^{232}$Th and $^{238}$U chains):
  - $\gamma$-rays (e.g. $^{208}$Tl, $^{214}$Bi)
  - $\alpha$-emitting isotopes from surface contamination (e.g. $^{210}$Po) or $^{222}$Rn in LAr
- cosmogenic isotopes in Ge decaying inside the detectors ($^{68}$Ge, $^{60}$Co)
- long-lived cosmogenic Ar isotopes ($^{39}$Ar, $^{42}$Ar)

Mitigation strategy:
- Gran Sasso suppression $\mu$ flux ($10^6$)
- Muon veto
- detector anti-coincidence
- time-coincidence (Bi-Po or $^{68}$Ge)
- pulse shape analysis (bulk localized energy deposition)
- LAr-scintillation (in Phase II)
The GERDA Experiment: detector design

**GERDA: detector apparatus**

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H$_2$O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)

GERDA collaboration, EPJ C 73 2330 (2013), arXiV: 1212.3210
The GERDA Experiment: detector design

Detector array assembly

- 3 + 1 strings
- 8 enr Ge coaxial detectors: 14.6 kg working mass
  (2 not considered in the analysis due to high leakage current)
- 3 nat Ge coaxial detectors: 3.0 kg
- 5 enr Ge BEGe detectors: 3.0 kg working mass
  (testing Phase II concept in the real environment)

enr Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)
The GERDA Experiment: Data taking

Overview of the data taking

- data taking Nov11 - May13 (492 d)
- total exposure 21.6 kg·yr
- (bi)weekly calibration with Th-228
- BEGe detectors from June 2012

Blinding

- All events within $Q_{\beta\beta} \pm 20\text{keV}$ are not reconstructed.
- Dataset unblinded only after freezing analysis procedure and background model.

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First results on $0\nu\beta\beta$ from GERDA
The GERDA Experiment: Data taking

Calibration of the GERDA data

- Spectra calibrated weekly with $^{228}\text{Th}$ sources and pulser with 0.05 Hz
- Calibration data also useful for monitor energy resolution and gain stability over time
- FWHM at $Q_{\beta\beta}$: 4.8 keV for coaxial detectors, 3.2 keV for BEGe’s

![Graph showing calibration data with peaks at various energies](image.png)
The GERDA Experiment: Data taking

Time stability

<table>
<thead>
<tr>
<th>detector</th>
<th>FWHM [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaxial</td>
<td></td>
</tr>
<tr>
<td>ANG2</td>
<td>5.8 (3)</td>
</tr>
<tr>
<td>ANG3</td>
<td>4.5 (1)</td>
</tr>
<tr>
<td>ANG4</td>
<td>4.9 (3)</td>
</tr>
<tr>
<td>ANG5</td>
<td>4.2 (1)</td>
</tr>
<tr>
<td>RG1</td>
<td>4.5 (3)</td>
</tr>
<tr>
<td>RG2</td>
<td>4.9 (3)</td>
</tr>
<tr>
<td>mean coax</td>
<td>4.8 (2)</td>
</tr>
<tr>
<td>BEGe</td>
<td></td>
</tr>
<tr>
<td>GD32B</td>
<td>2.6 (1)</td>
</tr>
<tr>
<td>GD32C</td>
<td>2.6 (1)</td>
</tr>
<tr>
<td>GD32D</td>
<td>3.7 (5)</td>
</tr>
<tr>
<td>GD35B</td>
<td>4.0 (1)</td>
</tr>
<tr>
<td>mean BEGe</td>
<td>3.2 (2)</td>
</tr>
</tbody>
</table>

$0\nu\beta\beta$ data set:

- peak position within 0.3 keV at correct position
- resolution 4% larger than in calibration runs
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):
  - coax $\rightarrow$ 4.8±0.2 keV
  - BEGe $\rightarrow$ 3.2±0.2 keV

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First results on $0\nu\beta\beta$ from GERDA
The GERDA Experiment: Data taking

**Energy spectra**

**Golden coax:** Data from coaxial detectors

**Silver coax:** Data from coaxial detectors during BEGe deployment (higher BI)

**BEGe:** Data from BEGe detectors

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- **Data split in 3 data sets:**
  - **dataset** | **exposure**
    - coaxial (golden) | 17.9 kg·yr
    - coaxial (silver) | 1.3 kg·yr
    - BEGe | 2.4 kg·yr

- **Background level:**
  - **energy** | **BI** [cts/(keV kg yr)]
    - 2614 | 1.1 ± 0.3
    - 1764 | 3.3 ± 0.5
    - 2039 (Q\(\beta\beta\)) | 0.018 ± 0.002

- **Events in Q\(\beta\beta\) ±20 keV blinded**
The GERDA Experiment: Data taking

The background model of GERDA Phase I


- Simulation of known and observed backgrounds
- Fit combination of MC spectra to data from 570 keV to 7500 keV
- Different combinations of positions and contributions tested

Main contributions from sources close by: $^{228}$Th and $^{226}$Ra in holders, $^{42}$Ar, $\alpha$ on detector surface

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First results on $0\nu\beta\beta$ from GERDA
The GERDA Experiment: Data taking

The background model @ $Q_{\beta\beta}$


Minimum model (all known contributions)

- No line expected in the blinded window
- Background flat between 1930 and 2190 keV
- $2140 \pm 5$ keV and $2119 \pm 5$ keV excluded

Maximum model (many possible contributions added)

Interpolated BI in ROI:

- **Golden coax:** $BI = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}$ cts/(keV kg yr)
- **BEGe's:** $BI = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}$ cts/(keV kg yr)
Motivation:
- $0\nu\beta\beta$ signals are contained in small region $\rightarrow$ Single site event (SSE)
  - 1 MeV electron drifts $\approx$ 1 mm in Ge
- $\gamma$ events generate multiple energy depositions $\rightarrow$ Multi site event (MSE)

PSD for BEGe’s: A/E parameter
- $A = $ Pulse amplitude ; $E = $ Energy
- A/E range defined from $^{208}$Tl ($E_\gamma = 2614$ keV ) DEP ($E_{DEP} = 1592$ keV) from $^{228}$Th calibrations
- Rejects 80% of background-like events
- $92 \pm 2\%$ efficiency for $0\nu\beta\beta$

PSD for Coaxial: Artificial Neural Network (ANN)
- Trained on signal SSE: $^{208}$Tl DEP ($E_{DEP} = 1592$ keV)
- Rejects 45% of background like events
- $90^{+5}_{-9}\%$ efficiency for $0\nu\beta\beta$
Phase I – $0\nu\beta\beta$ analysis

Energy spectra around $Q_{\beta\beta}$

Analysis cuts applied:
1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)
5) PSD

Survival fraction around $Q_{\beta\beta}$:

- $1 \sim 99\%$
- $2+3 \sim 60\%$
- $4 \sim 100\%$
- $5 \sim 50\%$

<table>
<thead>
<tr>
<th>data set</th>
<th>exposure [kg · 10yr]</th>
<th>background $10^{-2}$ cts/(keV · kg · yr)</th>
<th>expected cts ($Q_{\beta\beta} \pm 5$ keV)</th>
<th>observed cts ($Q_{\beta\beta} \pm 5$ keV)</th>
</tr>
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<tbody>
<tr>
<td>w/o PSD</td>
<td>golden</td>
<td>1.8</td>
<td>3.3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>silver</td>
<td>6.3</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>BEGe</td>
<td>3.6</td>
<td>1.0</td>
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First results on $0\nu\beta\beta$ from GERDA
Phase I – $0\nu\beta\beta$ analysis

Energy spectra around $Q_{\beta\beta}$

Analysis cuts applied:
1) signals quality cuts
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Survival fraction around $Q_{\beta\beta}$:

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<tr>
<td>1</td>
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<th>background $10^{-2}$ cts/(keV·kg·yr)</th>
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<td>0.8</td>
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<td>BEGe</td>
<td>2.4</td>
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<td>w/ PSD</td>
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First results on $0\nu\beta\beta$ from GERDA
Phase I – $0\nu\beta\beta$ analysis

Statistical analysis

GERDA collaboration, PRL 111, 122503 (2013), arXiv:1307.4720

Baseline analysis (profile likelihood):

- maximum likelihood spectral fit (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $\left[T_{1/2}^{0\nu}\right]^{-1}$)
- $\left(T_{1/2}^{0\nu}\right)^{-1} \geq 0$ (coverage tested)

Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

Results (GERDA + IGEX [1] + HdM [2]):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (90% C.L.)
Phase I – $0\nu\beta\beta$ analysis


Hypothesis test: $H_1 \left( T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25} \text{ yr} + \text{ bkg} \right)$ vs $H_0 \left( \text{bkg only} \right)$

\[ T_{1/2}^{0\nu} = 1.19e25 \text{ yr} \]
\[ T_{1/2}^{0\nu} = 2.1e25 \text{ yr} \]

GERDA only:
- PL $P(N_{0\nu\beta\beta} = 0|H_1) = 0.01$
- Bayes factor $P(H_1)/P(H_0) = 2.4 \cdot 10^{-2}$

GERDA+IGEX+HdM:
- Bayes factor $P(H_1)/P(H_0) = 2 \cdot 10^{-4}$

$\Rightarrow$ claim strongly disfavoured

$T_{1/2}^{0\nu}$ from Mod. Phys. Lett. A 21 (2006) 1547 is not considered because of inconsistencies (i.e. missing efficiency factors, problem in the conversion from counts to $T_{1/2}^{0\nu}$) pointed out in Ann. Phys. 525 (2013) 269.

In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):
- expected $5.9\pm1.4$ signal cts
- expected $2.0\pm0.3$ bkg cts
- observed 3 cts

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First results on $0\nu\beta\beta$ from GERDA
Conclusions

- GERDA collected 21.6 kg·yr of exposure between 11.2011 and 05.2013
- Background an order of magnitude lower than previous Ge experiments:
  - $\sim 0.01$ cts/(keV·kg·yr) at $Q_{\beta\beta}$ (after PSD)
- 3 events observed while $2.5 \pm 0.3$ expected in $Q_{\beta\beta} \pm 2\sigma$
  - No events in $Q_{\beta\beta} \pm \sigma$
- GERDA limit:
  - $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr at 90% C.L. (GERDA only)
  - $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr at 90% C.L. (GERDA+IGEX+HdM)
- Previous claim refuted by GERDA at 99% C.L.
The GERDA Collaboration

GERDA Collaboration Meeting in Dubna, Russia
June 2013

First results on $0\nu\beta\beta$ from GERDA
Phase II detector design and performance

- Broad Energy Ge (BEGe) detectors:
  - commercial product (Canberra)
  - excellent spectroscopic performance (resolution, low threshold, low noise)
  - pulse shape discrimination (PSD)
- >30 BEGe detectors produced and tested

\[ f(x) = a + bx^{1/2} \]

\[
\begin{align*}
  a &= 0.180 (10) \\
  b &= 0.0395 (4)
\end{align*}
\]
Detection of LAr scintillation

LAr-scintillation (combined design):

- low-background photo-multipliers
- WLS fibers read-out with Si photo-multipliers

Top/bottom: PMTs

Central cylinder: SiPM/Fiber readout
Use of PSD and LAr scintillation signal

Pulse shape analysis combined with LAr-scintillation (in LArGe setup): measured suppression factor of \((5.2 \pm 1.3) \cdot 10^3\) at \(Q_{\beta\beta}\) for close Th-228
Background model – $2\nu\beta\beta$ half-life

- Binned maximum likelihood (5 kg·yr)
- Nuisance parameters:
  - Active detector masses (6+1)
  - Ge-76 fractions (6)
  - Background contributions (3x6)
- $T^{2\nu}_{1/2}$ common to all detectors
- After marginalizing:
  \[ T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08} \text{ fit} +0.11_{-0.06} \text{ syst}) \cdot 10^{21} \]

Comparison with $^{136}$Xe experiments

- GERDA provides a model-independent test of the signal claim
- comparison with $^{136}$Xe experiments possible only through:
  - assumptions on the leading channel (e.g. exchange of light Majorana neutrinos)
  - matrix element computations (selection used in the plot is taken from arXiv:1305.0056)

GERDA + EXO + KamLAND-Zen:
Bayes factor $P(H_1)/P(H_0) = 2.2 \cdot 10^{-3}$
(computed for the smallest NME ratio Xe/Ge)
Why GERDA does not use KK 2006 result?


Entire data set: 71.7 kg·yr (active mass)
- $28.75 \pm 6.86$ signal events
- $T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr

Data for PSD analysis: 51.4 kg·yr
- $19.58 \pm 5.41$ signal events
- $T_{1/2}^{0\nu} = (1.25^{+0.49}_{-0.27}) \cdot 10^{25}$ yr

With PSD applied
- $12.36 \pm 3.72$ events
- DEP survival fraction $\sim 62$
- $T_{1/2}^{0\nu} = 1.23 \cdot 10^{25}$ yr

Without efficiency correction:
- $T_{1/2}^{0\nu} = 1.98 \cdot 10^{25}$ yr

No efficiency correction is applied in any publication!
Why GERDA does not use KK 2006 result?

b) 2006 publication : Mod Phys Lett A21 p. 1547-1566

- Fit to the data yields $11.32 \pm 1.75$ signal events
  \[ T_{1/2}^{0\text{nu}} = \left(2.23^{0.44}_{-0.31}\right) \cdot 10^{25} \text{ yr}\]
- error on signal count not correct
  - smaller than Poisson error

PSD based on 3 previous methods (2 neural networks + pulse boardness) & library of SSE pulses: Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks. NO event overlap between the 2 sets!?

Statement from publication:
- "multi site events are suppressed by 100%"
- $0\nu\beta\beta$ efficiency = 1 used for $T_{1/2}^{0\nu}$

Efficiency factor not considered:
- Calculation of $T_{1/2}^{0\nu}$ not correct
- GERDA does not use this result