Search of Neutrinoless Double Beta Decay with the GERDA Experiment

From Majorana to LHC: Workshop on the Origin of Neutrino Mass

Giovanni Benato for the GERDA Collaboration

University of Zurich

ICTP, Trieste, 3 October 2013
The GERDA Collaboration

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

16 institutions
~100 members
The Double Beta Decay

- If $\beta$-decay energetically forbidden $\rightarrow 2\nu2\beta$ decay might be possible.
- $2\nu2\beta$ decay introduced by Maria Goeppert-Mayer in 1935.
- The experimental spectrum is a continuum ending at the Q-value.
- $T_{1/2}^{2\nu}$ usually of order of $10^{19-21}$ years.
- For $^{76}\text{Ge}$: $T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr

The Neutrinoless Double Beta Decay

If $0\nu2\beta$ decay is discovered:

- Lepton number is violated ($\Delta L = 2$)
- Neutrinos are Majorana particles
- Physics beyond the Standard Model

Theoretical aspects of $0\nu2\beta$ decay

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

  $G^{0\nu}(Q, Z) =$ Phase Space integral
  $|M^{0\nu}|^2 =$ nuclear matrix element
  $\langle m_{ee} \rangle^2 = \sum_i U_{ei}^2 m_i =$ effective $\nu$ mass
  $U_{ei} =$ elements of the PMNS mixing matrix

- Experimental signature: peak at
  $$Q_{\beta\beta} = m(A, Z) - m(A, Z - 2) - 2m_e$$
  (2039 keV for $^{76}\text{Ge}$)
Number of signal events:

\[ N_{\text{sig}}^{0\nu} = \frac{f_{76} \cdot N_A}{m_A} \frac{\ln 2}{T_{1/2}^{0\nu}} \varepsilon \cdot M \cdot t \]

Number of background events:

\[ N_{\text{bkg}} = M \cdot t \cdot BI \cdot \Delta E \]

Experimental sensitivity:

\[ T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2 \cdot N_A}{n_\sigma \sqrt{2}} \frac{f_{76} \cdot \varepsilon}{A} \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}} \]

- \( f_{76} \) = enrichment fraction
- \( N_A \) = Avogadro number
- \( m_A \) = atomic mass
- \( \varepsilon \) = efficiency
- \( M \) = detector mass
- \( t \) = livetime
- \( M \cdot t \) = exposure
- \( BI \) = Background Index
- \( \Delta E \) = energy resolution
- \( n_\sigma \) = Confidence Level

Advantages of Ge

Disadvantages of Ge
The GERDA Experiment

Experiment structure

- 590 m³ Water Tank to absorb neutrons and veto cosmic muons
- 64 m³ Liquid Argon (LAr) for cooling and shielding (and vetoing)
- Plastic scintillators above the cryostat to further veto cosmic

- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden
- Array of bare enriched Ge detectors in liquid argon (LAr)
- Minimal amount of material in proximity of the diodes
The GERDA Experiment

The two phases of GERDA (from the Proposal to LNGS):

<table>
<thead>
<tr>
<th></th>
<th>Mass [kg]</th>
<th>BI [counts/(keV·kg·yr)]</th>
<th>Livetime [yr]</th>
<th>Expected $T_{1/2}^{0\nu}$ Sensitivity [yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>15</td>
<td>$10^{-2}$</td>
<td>1</td>
<td>$2.2 \cdot 10^{25}$</td>
</tr>
<tr>
<td>Phase II</td>
<td>35</td>
<td>$10^{-3}$</td>
<td>3</td>
<td>$2 \cdot 10^{26}$</td>
</tr>
</tbody>
</table>

The time-line of GERDA:

- Mar. 2008: cryostat installation
- May 2008: water tank construction
- Feb. 2009: clean room installation
- May 2010: start of commissioning
- 10 Nov. 2010: inauguration
- Nov. 2011 - May 2013: Phase I data taking
- Summer/autumn 2013: preparing Phase II...
The GERDA Detectors

Coaxial detectors

- \(\sim 86\%\) isotopically enriched in \(^{76}\text{Ge}\)
- 5 enr-Ge (“ANG”) detectors from Heidelberg-Moscow (HdM), 3 enr-Ge (“RG”) from IGEX, 3 nat-Ge from Genius Test Facility (GTF)
- Detectors reprocessed at Canberra before being used
- \(\sim 2\%\) FWHM at 2.6 MeV
- Total enriched mass: 17.7 kg
- Two detectors turned off because of high leakage current
  \(\rightarrow\) total enriched mass 14.6 kg

BEGe detectors (design for Phase II)

- BEGe = Broad Energy Germanium
- \(\sim 1\%\) FWHM at 2.6 MeV
- Enhanced Pulse Shape Discrimination (PSD)
- \(\sim 20\) kg of BEGe’s successfully produced and tested in 2012
- 5 BEGe’s inserted in GERDA in July 2012
GERDA Phase I Data Processing and Selection

Data processing framework: GELATIO

- Read-out and signal structure:
  - JINST 6 (2011) P08013

- Digital signal processing to extract energy, rise time, ...
GERDA Phase I Data Taking

- Total Phase I exposure: 21.6 kg·yr between 9\textsuperscript{th} Nov 2011 and 21\textsuperscript{st} May 2013
- Total livetime of 492.3 days with 88\% duty factor
- 5\% of data not used due to temperature-related instability of the electronics
- Used for analysis: 6 enr-Ge coaxial detectors (14.6 kg) and 4 BEGe (3.0 kg)

- Spikes: (Bi)-weekly calibration runs
- Flat parts: BEGe's insertion (June 2012), maintenance operations
- Dataset for background model: Nov 2011 - March 2013
- Dataset for 0\nu 2\beta analysis: Nov 2011 - May 2013
Calibration of the GERDA Data

- Spectra calibrated (bi)-weekly with $^{228}\text{Th}$ sources
- Data useful also for monitoring the resolution and gain stability over time
- FWHM at $Q_{\beta\beta}$: 4.8 keV for the coaxial detectors, 3.2 keV for the BEGe’s (space for $\sim$ 10% improvement with better filtering).

![Graph showing energy spectra for different detectors with peaks at various keV values.](image-url)
Time Stability and Energy Resolution

- If needed, correction term applied to FWHM to account for instabilities

<table>
<thead>
<tr>
<th>detector</th>
<th>FWHM [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUM-coax</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>SUM-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>

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Blinding of the Region of Interest

Energy & pulse of events $\in [2019-2059] \text{ keV}$ automatically removed from data flow

Tasks to be fulfilled before the unblinding

- Reach 20 kg⋅yr of exposure
- Reach sensitivity of $2 \cdot 10^{25} \text{ yr}$ on $T_{1/2}^{0\nu}$
- Have (and publish: arXiv:1306.5084) a good enough background model
- Be able to predict a reliable BI at $Q_{\beta\beta}$ (intensity and shape)
- Fix the data selection and the partition
- Fix the data processing procedure (quality cuts, calibration, ...)
- Fix (and publish: arXiv:1307.2610) the PSD methods and cuts
- Fix the statistical analysis

Unblinding procedure

- Once the background model is fixed, open 15keV side-bands
- If no surprise is found, proceed as stated above. And good luck!
2ν2β Measurement

- Measured by GERDA with 5.04 kg·yr exposure
- Very simple background model due to high signal-to-background ratio
- $T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr
The Background of GERDA Phase I

▶ Split coaxial data in two sets, according to the BI
▶ Golden: all the coax data, but July 2012
▶ Silver: coax data taken in June and July 2012 (removal of two nat-coaxial and insertion of BEGe's)
▶ BEGe data kept separated, due to different resolution and background

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Exposure [kg·yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden</td>
<td>17.90</td>
</tr>
<tr>
<td>Silver</td>
<td>1.30</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.40</td>
</tr>
</tbody>
</table>
The Background Model at High Energy

- Duty-factor corrected time distribution of events in the 3.5-5.3 MeV compatible with $^{210}$Po half-life ($T_{1/2} = 138$ d)
- Contribution from $^{226}$Ra and daughters also visible
- $\alpha$-emitter mostly located on $p^+$ surface (also confirmed by PSD)
- $\alpha$ events account for $\sim 10\%$ of the BI at $Q_{\beta\beta}$ for coaxial detectors and $\sim 5\%$ for BEGe’s.
The Background Model of GERDA Phase I

Minimum model for Golden dataset

- Only known and visible contributions considered
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- No hint for any different behavior in the last 3 months of data taking
- Official result found with 30 keV binning, crosschecks performed with thinner binnings
- Background Model published: arXiv:1306.5084v1
No surprise found when comparing the complete Phase I spectrum and the (scaled) background model with 2 keV bins.

Maximum model with several combinations of contributions and positions → no unique determination.

No surprise in comparison between lines intensity predicted by the background model(s) and the spectral fit on data.

Same approach for BEGe’s.

Crosschecked with nat-Ge detectors, too.
Background prediction at $Q_{\beta\beta}$

- Both min and max model predict a flat bkg at $Q_{\beta\beta} \rightarrow$ unblind side-bands!
- BI predicted form bkg models and fitted from data are in agreement

**BI before PSD interpolated in the Region of Interest:**

<table>
<thead>
<tr>
<th></th>
<th>GOLD-coax</th>
<th>SUM-BEGe</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI in ROI before PSD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10 keV for coaxial, 8 keV for BEGe)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[10^{-3} \text{cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>interpolation</td>
<td>17.5[15.1, 20.1]</td>
<td>36.1[26.4, 49.3]</td>
</tr>
<tr>
<td>minimum</td>
<td>18.5[17.6, 19.3]</td>
<td>38.1[37.5, 38.7]</td>
</tr>
<tr>
<td>maximum</td>
<td>21.9[20.7, 23.8]</td>
<td>-</td>
</tr>
</tbody>
</table>

Analysis recipe: fit with Gaussian peak and flat background in the 1930-2190 keV region, excluding known gamma peaks at 2104 ($^{208}$Tl SEP) and 2119 keV ($^{214}$Bi).
Pulse Shape Discrimination: arXiv:1307.2610

- PSD: distinguish between \((0\nu2\beta)\) signal-like events (SSE) and background-like events (MSE, \(p^+\))
- Different PSD needed for coaxial and BEGe detectors

Simulated current pulse in coaxial detector

Simulated current pulse in BEGe
Pulse Shape Discrimination for BEGe

PSD discrimination parameter: A/E

- \( A = \) amplitude of current pulse
- \( E = \) energy
- High capability of distinguishing SSE from MSE, \( p^+ \) and \( n^+ \) events
- Well tested and documented method*

![Graphs showing PSD discrimination](image)

- Acceptance for \( 2\nu2\beta \): \( 0.91 \pm 0.05 \)
- Acceptance for \( 0\nu2\beta \): \( 0.92 \pm 0.02 \)


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Pulse Shape Discrimination for coaxial detectors

PSD discrimination method: Artificial Neural Network (ANN)

- ANN analysis of 50 rise-time info (1,3,5,...,99%) with TMVA/TMIPANN
- SSE training with signal-like $^{208}\text{TI}$ DEP at 1592 keV
- MSE training with background-like $^{212}\text{Bi}$ FEP at 1621 keV
- Cut adjusted for each detector to have 90% survival probability on DEP

*arXiv:1307.2610

Search of Neutrinoless Double Beta Decay with the GERDA Experiment

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Pulse Shape Discrimination for coaxial detectors

PSD selection in $2\nu2\beta$ and $0\nu2\beta$ energy ranges

- For $2\nu2\beta$ data and model are in good agreement
- $2\nu2\beta$ survival fraction: $0.85 \pm 0.02$

- Estimated survival fraction for $0\nu2\beta$ event: $0.90^{+0.05}_{-0.09}$

*arXiv:1307.2610

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**0ν2β Decay Analysis**

From counts to half-life

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

\[ \varepsilon = f_{76} \cdot f_{AV} \cdot \varepsilon_{FEP} \cdot \varepsilon_{PSD} \]

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Exposure M·t [kg·y]</th>
<th>( f_{76} )</th>
<th>( f_{AV} )</th>
<th>( \varepsilon_{FEP} )</th>
<th>( \varepsilon_{PSD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden</td>
<td>17.9</td>
<td>0.86</td>
<td>0.87</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>Silver</td>
<td>1.3</td>
<td>0.86</td>
<td>0.87</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>0.88</td>
<td>0.92</td>
<td>0.90</td>
<td>0.92</td>
</tr>
</tbody>
</table>

- \( N_A \) = Avogadro number
- \( m_{enr} \) = molar mass of enr-Ge
- \( N^{0\nu} \) = signal counts/limit
- \( t \) = livetime
- \( f_{76} \) = enrichment fraction
- \( f_{AV} \) = active volume fraction
- \( \varepsilon_{FEP} \) = FEP efficiency for 0ν2β
- \( \varepsilon_{PSD} \) = signal acceptance

**Fitting method**

- Fit 3 datasets with Gaussian over flat background
- 4 parameters: 3 bkg levels and \( T_{1/2}^{0\nu} \) with the constraint \( 1/T_{1/2}^{0\nu} > 0 \)
- Fixed parameters: \( \mu = 2039.07 \pm 0.007 \) keV and \( \sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1) \) keV for coaxial/BEGe
- Systematic uncertainties on \( f, \varepsilon, \mu, \sigma \): MC sampling and averaging
Unblinding of GERDA Phase I Data

Golden dataset

Silver dataset

BEGe dataset

All datasets

<table>
<thead>
<tr>
<th>data set</th>
<th>detector</th>
<th>energy [keV]</th>
<th>date</th>
<th>PSD passed</th>
</tr>
</thead>
<tbody>
<tr>
<td>golden</td>
<td>ANG5</td>
<td>2041.8</td>
<td>18-Nov-2011 22:52</td>
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</tr>
<tr>
<td>silver</td>
<td>ANG5</td>
<td>2036.9</td>
<td>23-Jun-2012 23:02</td>
<td>yes</td>
</tr>
<tr>
<td>golden</td>
<td>RG2</td>
<td>2041.3</td>
<td>16-Dec-2012 00:09</td>
<td>yes</td>
</tr>
<tr>
<td>BEGe</td>
<td>GD32B</td>
<td>2036.6</td>
<td>28-Dec-2012 09:50</td>
<td>no</td>
</tr>
<tr>
<td>golden</td>
<td>RG1</td>
<td>2035.5</td>
<td>29-Jan-2013 03:35</td>
<td>yes</td>
</tr>
<tr>
<td>golden</td>
<td>ANG3</td>
<td>2037.4</td>
<td>02-Mar-2013 08:08</td>
<td>no</td>
</tr>
<tr>
<td>golden</td>
<td>RG1</td>
<td>2041.7</td>
<td>27-Apr-2013 22:21</td>
<td>no</td>
</tr>
</tbody>
</table>
**GERDA Phase I Results**

**Events at $Q_{\beta\beta} \pm 5$ keV**

<table>
<thead>
<tr>
<th>PSD</th>
<th>Dataset</th>
<th>Obs.</th>
<th>Exp. bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>Golden</td>
<td>5</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>BEGe</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>yes</td>
<td>Golden</td>
<td>2</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>BEGe</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Profile Likelihood Method**

- best fit $N^{0\nu} = 0$
- No excess of signal over bkg
- 90% C.L. lower limit:
  \[ T^{0\nu}_{1/2} > 2.1 \cdot 10^{25} \text{ yr} \]

**Bayesian Approach**

- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}] \text{ yr}^{-1}$
- best fit $N^{0\nu} = 0$
- 90% credibility interval:
  \[ T^{0\nu}_{1/2} > 1.9 \cdot 10^{25} \text{ yr} \]

Combination with HdM 2001 and IGEX

Previous limits

- **HdM 2001:**
  \[ T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ yr (90\% C.L.)} \]
  - EPJ A12 (2001) 147-154

- **IGEX 2002:**
  \[ T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ yr (90\% C.L.)} \]

Combining the limits

- Same result with Profile Likelihood and Bayesian approach

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

- Phys. Lett. B 586 198 (2004): $T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr
- Expected $5.9 \pm 1.4$ signal events over $2.0 \pm 0.3$ bkg events in a $\pm 2\sigma$ region
- Found 3 counts in $\pm 2\sigma$ region (0 in $\pm 1\sigma$)

Hypothesis comparison

- $H_1$: claimed signal ($5.9 \pm 1.4$)
- $H_0$: background only
- Bayes factor: $P(H_1)/P(H_0) = 0.024$
- P-value from profile likelihood: $P(N_{0\nu}^0 = 0|H_1) = 0.01$
- Bayes factor lowered to $2 \cdot 10^{-4}$ when combining with IGEX and HdM 2001
- Comparison independent of NME and physical mechanism generating $0\nu2\beta$

Claim strongly disfavored
Conclusion and Outlook

Summary of the results

▶ Best fit gives 0 counts both for PL and BA: no excess is visible.
▶ $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
▶ 2004 claim predicted $5.9 \pm 1.4$ signal events over $2.0 \pm 0.3$ bkg events in $Q_{\beta\beta} \pm 2\sigma$.
▶ 3 events are observed in $Q_{\beta\beta} \pm 2\sigma$, 0 in $Q_{\beta\beta} \pm \sigma$.
▶ Claim disfavoured with high probability.

Combination with other experiments

▶ Combining with HdM 2001 and IGEX 2002:
  $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (90%) C.L. (same with Bayesian approach).
▶ Limit on effective Majorana neutrino mass:
  $m_{ee} < 0.2$-0.4 eV

Outlook

▶ Work is ongoing with the preparation of GERDA Phase II...