Results and Perspectives of GERDA: on the way to Phase II

C.M. Cattadori INFN-Milano Bicocca
on behalf of the GERDA collaboration

NOW 2014
Conca Specchiulla 8-14 September 2014
GERDA Installations

Located in Hall A @ LNGS

8/09/2014
GERDA Installations

- Clean room with lock (old version) & clean bench
- Muon & cryogenic infrastructure
- Control rooms
- Water plant & radon monitor
- Ge-76 array (as shown)
- Detector = source
- LAr cryostat, Ø4m, with internal Cu shield
- Water tank, Ø10m, part of μ-veto detector
Pictures from GERDA
Data taking: Nov 2011-June 2013

Goal: Scrutinize claim
Demonstrate Bl

Exposure: 21.6 kg y
Observation of $2\nu\beta\beta$


$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08 \text{ fit}} +0.11^{+0.06}_{-0.06 \text{ syst}}) \times 10^{21}$ yr

- Exposure: 5kg·y
- 6 independent models for the 6 detectors (5 x 6=30 detector parameters)
- $T_{1/2}^{2\nu}$ common in 6 detectors
- Background from 3 sources: $^{42}K$, $^{40}K$, $^{214}Bi$ ($\gamma$-lines used for normalization)
  - $^{42}K$: homogeneously distributed
  - $^{40}K$ & $^{214}Bi$: close sources
- Detectors active masses and enr. factors are nuisance parameters in the fit.

$\beta\beta$ spectrum: 8796 events:
Model of the residual background: 80% $2\nu\beta\beta$, 14% $^{42}K$, 3.8% $^{214}Bi$, 2% $^{40}K$,
GERDA vs previous measurements of $T_{1/2}^{2\nu}$

\[ T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08 \text{ fit}} +0.11_{-0.06 \text{ syst}}) \times 10^{21} \text{ yr} = (1.84^{+0.14}_{-0.10}) \times 10^{21} \text{ yr} \]

- GERDA result consistent with HdM-B $T_{1/2}^{2\nu} = 1.78^{+0.07}_{-0.09} \times 10^{21}$
- Thanks to low BI reached comparable sensitivity with ~1/10 exposure
- 2$\nu\beta\beta$ results will improve with
  - New measurement of coax active volumes
  - Include larger statistics (already available)
$0
\nu \beta \beta$ Search – Blinded analysis:
events in $\pm 20$ keV around $Q_{\beta \beta}$ not reconstructed

$\Rightarrow$ FWHM @ $Q_{\beta \beta} = 4.8$ keV

$\Rightarrow$ FWHM @ $Q_{\beta \beta} = 3.2$ keV
Identification of Background Components

Main Contamination in COAX (with large variations among detectors):
- $\alpha$ contamination from $^{210}$Po.
- contamination at time of refurbishment mostly on thin p+ contact
- $^{210}$Po decaying away ($t_{1/2}=138$ d)
- BEGes much cleaner in $^{210}$Po (> factor 10) than COAX
Background model predictions vs data in 260 keV range around $Q_{\beta\beta}$

Minimal model

- The model reproduces a flat background around $Q_{\beta\beta}$ (data still blinded)
- No $\gamma$-lines visible in the 30 keV range around the $Q_{\beta\beta}$

Maximal model: Minimal +

spectra can be fitted with a flat background apart from $^{214}$Bi lines @ 2104 keV and 2119 keV

Pulse Shape Discrimination (PSD) to discriminate β-like (SSE) to γ-like (MSE) events

Different weighting potentials for Coax and BEGe

COAX: Artificial Neural Network (ANN) estimator used as PSD parameter

BEGe: Amplitude of Current/Amplitude of Charge Pulse (A/E) is the PSD parameter
PSD efficiencies

EPJC 73(2013) 2583

PSD Efficiencies experimentally determined @Q_{ββ} & for 2νββ events ( 1MeV < E < 1.5 MeV) from calibration (Double Escape Peak of 2.6 MeV line)

<table>
<thead>
<tr>
<th></th>
<th>ε_{2νββ}</th>
<th>ε_{0νββ}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coax</td>
<td>0.85 ± 0.02</td>
<td>0.90 +0.05 -0.09</td>
</tr>
<tr>
<td>BEGe</td>
<td>0.91 ± 0.05</td>
<td>0.92 ± 0.02</td>
</tr>
</tbody>
</table>

EPS 2013
Unblinded counts & efficiencies

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

\[ \epsilon = \int_{76}^{Q_{\beta\beta}} \cdot \mathcal{E}_{ep} \cdot \mathcal{E}_{psd} \]

In 230 keV @\( Q_{\beta\beta} \) ± 5 keV

Expected bckgd only

<table>
<thead>
<tr>
<th>data set</th>
<th>( \mathcal{E}[\text{kg} \cdot \text{yr}] )</th>
<th>( \langle \epsilon \rangle )</th>
<th>bkg</th>
<th>BI (^\dagger)</th>
<th>cts</th>
</tr>
</thead>
<tbody>
<tr>
<td>without PSD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>golden</td>
<td>17.9</td>
<td>0.688 ± 0.031</td>
<td>76</td>
<td>18±2</td>
<td>5</td>
</tr>
<tr>
<td>silver</td>
<td>1.3</td>
<td>0.688 ± 0.031</td>
<td>19</td>
<td>63_{14}^{+16}</td>
<td>1</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>0.720 ± 0.018</td>
<td>23</td>
<td>42_{8}^{+10}</td>
<td>1</td>
</tr>
<tr>
<td>with PSD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>golden</td>
<td>17.9</td>
<td>0.619_{0.070}^{+0.044}</td>
<td>45</td>
<td>11±2</td>
<td>2</td>
</tr>
<tr>
<td>silver</td>
<td>1.3</td>
<td>0.619_{0.070}^{+0.044}</td>
<td>9</td>
<td>30_{9}^{+11}</td>
<td>1</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>0.663 ± 0.022</td>
<td>3</td>
<td>5_{3}^{+4}</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^\dagger\) in units of \( 10^{-3} \) cts/(keV·kg·yr).

Expected bckgrd Rej

Bckgrd Rej \(_{PSD}\) Coax ~ 43%

Bckgrd Rej \(_{PSD}\) BEGe ~ 87%

8/09/2014
Performed Profile Likelihood fit of the 3 data sets
• B+S: described by constant term + Gaus($Q_{\beta\beta}$, $\sigma_E$)
• 4 free parameters in the fit $B_{\text{gold}}$, $B_{\text{silv}}$, $B_{\text{BEGe}}$, $1/T_{1/2}^{0\nu}$
• Systematics folded in

**Frequentist approach**
Best fit: $N^{0\nu} = 0$
$N^{0\nu} < 3.5$ cts @ 90% C.L.
$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr @ 90% CL
Median sensitivity:
$T_{1/2}^{0\nu} > 2.4 \times 10^{25}$ yr

**Bayesian approach**
Flat prior for $1/T_{1/2}^{0\nu}$
Best fit: $N^{0\nu} = 0$
$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr @ 90% CI
Median sensitivity:
$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr
For $T_{1/2}^{0\nu} = 1.19 \times 10^{25} \text{ yr}$

- Expected Signal (after PSD): $5.9 \pm 1.4 \text{ cts in } \pm 2\sigma$
- Expected Bckgd (after PSD): $2.0 \pm 0.3 \text{ cts in } \pm 2\sigma$
- Observed: $3.0 \text{ (0 in } \pm 1\sigma)$

From profile likelihood
Assuming H1 true $\rightarrow$
$P(N^{0\nu}=0) = 1\%$

Comparing
H1: Claimed signal
H0: Background only
Bayes factor
$P(H1)/P(H0) = 0.024$
(uncertainties on claim included)

Claim poorly credible
### Status of experimental searches

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T^{2\nu}_{1/2}$ $(10^{19}$ y)</th>
<th>$T^{0\nu}_{1/2}$ $(10^{24}$ y)</th>
<th>$&lt;m_{\beta\beta}&gt;$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.4 ± 0.5(stat) ± 0.4(syst)</td>
<td>&gt;0.058</td>
<td>3515-14133</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>1.78 $^{+0.07}_{-0.09}$</td>
<td>22.3 $^{+4.4}_{-3.1}$</td>
<td>400</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>184 ±90 (stat) ±11(syst)</td>
<td>&gt;21.0</td>
<td>&gt; 30 GERDA&amp;IGEX&amp;HdM</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>9.6±0.1(stat) ±1.0(syst)</td>
<td>&gt;0.32</td>
<td>884-2631</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>2.35 ± 0.14 (stat) ± 0.16 (syst)</td>
<td>&gt;0.0092</td>
<td>4207-15139</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>0.716 ± 0.001 (stat) ± 0.054 (syst)</td>
<td>&gt; 1.0</td>
<td>334-946</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.88 ± 0.04 (stat) ± 0.16 (syst)</td>
<td>&gt; 0.17</td>
<td>1300-2440</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>70 ± 9 ±(stat) 11 (syst)</td>
<td>&gt; 2.8</td>
<td>296 – 773</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>217.2 ± 1.7 (stat) ± 6 (syst)</td>
<td>&gt;26</td>
<td>140-280</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>0.911 ± 0.025 (stat) ± 0.063 (syst)</td>
<td>&gt; 0.018</td>
<td>2622-5678</td>
</tr>
</tbody>
</table>
GERDA II Expected Sensitivity

Assumed $\Delta E = 4$ keV

- KK Claim: 440 meV
- GERDA I lower limit range: 200-400 meV
- Expected GERDA II lower limit range: 90 meV

From Dell’Oro, Marcocci, Vissani, hep-ph/1404.2616v1

- Reach a $B|_{\sim} 10^{-3}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$ (±200 keV ROI)

- Reach $T^{0\nu}_{1/2} \sim 1.5 \cdot 10^{26}$ yr (120 kgy exposure) $\Rightarrow <m_{\beta\beta}> \leq 0.09-0.15$ eV

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GERDA Strategy to improve $T_{1/2}$ limits

- Increase $^{enr}$Ge mass (~40 kg in total) 21 kg in form of Ge-BEGe detectors
- → enhanced PSD to pinpoint $\beta\beta$ events (Single Site) vs residual $\gamma$ events (Multi Site)

- Reduce radioactivity of Ge holders and mechanical structures
- New Ge readout electronics with closer FE devices in die for improved FWHM
- LAr as active media (active detector) and not only as passive shield
- $^{42}$K bkgd: Transparent Nylon Mini Shroud (NMS) coated with WLS (instead of Cu opaque) surrounding each BEGe detector string.

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Phase I: 13 kg of enrGe COAX Detectors
3 kg of enrBEGe Detectors w. enhanced PSD

Phase II: 18 kg of enrGe COAX Detectors
21 kg of enrGe BEGe Detectors w. enhanced PSD
Readout of Liquid Argon Scintillation Light

Strategy:
- Wide angle eye: 16 PMTs
- Closer eye: Fiber Shroud readout by SiPMs

Expected: Suppression factor $\sim 10$ for $^{214}$Bi and $>> 10$ for $^{232}$Th events.
$^{42}$K backgrd mitigation by 
Nylon Mini Shroud and LAr veto

$^{232}$Th bckgrd reduction by 
LAr veto & PSD

Measured $^{42}$K bckgrd reduction: 
1BEGe in Nylon Mini Shroud 
(NMS)& PMTs & PSD

$10^2$-$10^3$
Ge detectors holders and Front End (FE) Electronics

- Holders: Si plates instead of Cu (improved radiopurity)
- Upgraded Circuit (based on commercial CMOS selected for cryogenic applications.
- Phase II FE: FE Devices (JFET in die Feedback R and C) onto the Si Plate
- Phase I FE: On CSA PCBs at 80 cm distance from bottom detector

Achieved in Phase II Tests
- FWHM: 2.6 keV @ 2.6 MeV
- Electronic Noise: 0.9 keV
- FWHM of PSD Parameter: ~ 1%
- Survival Fraction of Compton Continuum @Q_{ββ} after PSD Cut ~ 50%
What Next GERDA II?

- Majorana Demonstrator at SURF (Sanford Underground Facility) is in advanced stage of construction. Operation of the First String is expected soon.
- It consists of 40 kg of Ge BEGe/PIN Point Detectors 30 kg are $\text{enrGe}$.
- The goal of the demonstrator is to show that the chosen technique (operate detectors in cryostat made of Cu electroformed underground) can achieve a BI of 1 cts/(t·y) in a 4 keV ROI @ $Q_{\beta\beta}$ (i.e. < $10^{-3}$ cts/(keV·kg·y))
- At the completion of GERDA II and Majorana Demonstrator physics program, Gerda & Majorana projects could merge data & detectors, pinpointing the best technique.
Summary

• GERDA I collected 21.6 kg·y exposure in the time period 2011-2013, with
  • B1 10^{-2} cts/(keV · kg · y) and
  • FWHM ~ 4.8 keV (for COAX detectors)
  • FWHM ~ 3.2 keV (for BEGe detectors)
  • Pulse Shape Discrimination with 90% acceptance for efficiency for single site events
• No excess count has been found over the expected background
  After PSD: 3 cts found vs 2.5 expected
  Best fit: N^{0\nu} = 0
  N^{0\nu} < 3.5 cts @ 90% C.L.
  T^{0\nu}_{1/2} > 2.1 \times 10^{25} \text{ yr} @ 90\% \text{ CL}
• The 0\nu\beta\beta claim has not been confirmed
• Since 2013 GERDA is upgrading to complete Phase II of the foreseen experimental program
  • 21 kg of BEGe detectors w. Enhanced PSD capabilities + 18 kg COAX detectors
  • LAr will be readout and will act as veto
  • FWHM expected <3 keV for BEGe detectors
• The expected sensitivity
  \[ T^{0\nu}_{1/2} > 1.5 \times 10^{26} \text{ yr} @ 90\% \text{ CL for an exposure of } 120 \text{ kg} \cdot \text{y} \ \rightarrow \ m_{ee} < 90 \text{ meV} \]
Comparison of **forthcoming** Ge vs Xe & Te projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Total Mass of isotope [kg]</th>
<th>Expected/Achieved BI [cts/keV·kg·y]</th>
<th>Expected/Achieved FWHM [keV]</th>
<th>Exposure [kg·y]</th>
<th>$T_{1/2}$ Sensitivity (90%CL) [y]</th>
<th>$m_{ee}$ Sensitivity (90%CL) [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerda II</td>
<td>39</td>
<td>10^{-3}</td>
<td>&lt; 4</td>
<td>120</td>
<td>1.5 \cdot 10^{26}</td>
<td>90-150</td>
</tr>
<tr>
<td>Gerda I</td>
<td>18</td>
<td>10^{-2}</td>
<td>4.5</td>
<td>21.6</td>
<td>2.1 \cdot 10^{25}</td>
<td>200-400</td>
</tr>
<tr>
<td>Majorana</td>
<td>30</td>
<td>&lt;10^{-3}</td>
<td>&lt; 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuore</td>
<td>206</td>
<td>10^{-2}</td>
<td>5</td>
<td>1000</td>
<td>9.5 \cdot 10^{25}</td>
<td>51-133</td>
</tr>
<tr>
<td>Cuore 0</td>
<td>10.9</td>
<td>0.6 \cdot 10^{-2}</td>
<td>5.1</td>
<td>18.1</td>
<td>2.8 \cdot 10^{24}</td>
<td>0.3 – 0.7</td>
</tr>
<tr>
<td>Cuoricino</td>
<td>11.6</td>
<td>15.3 \cdot 10^{-2}</td>
<td>6.3</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-EXO</td>
<td>5000</td>
<td>1.7 \cdot 10^{-3}</td>
<td>73</td>
<td>112</td>
<td>1.1 \cdot 10^{25}</td>
<td>down to 8</td>
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<tr>
<td>EXO 200 ult.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50</td>
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<tr>
<td>EXO 200</td>
<td>200</td>
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<td></td>
<td></td>
<td></td>
<td>190-450</td>
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<tr>
<td>KZ ultimate</td>
<td>600-800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
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<tr>
<td>KZ comb.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>140 -280</td>
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<tr>
<td>Kam-Zen II</td>
<td>348</td>
<td>6.0 \cdot 10^{-4}</td>
<td>284</td>
<td>130</td>
<td>2.6 \cdot 10^{25}</td>
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<tr>
<td>Kam-Zen I</td>
<td>320</td>
<td></td>
<td>284</td>
<td>29.6</td>
<td>1.3 \cdot 10^{25}</td>
<td></td>
</tr>
</tbody>
</table>

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Extra Slides
The Energy Scale: COAX


FWHM of COAX @ 2039 keV from calibrations

Energy:
From semi-gaussian DSP of the acquired waveforms

DAQ facts:
14 bit, 100 MHz continuos running ADC.
TRG thrsd: 40-100 keV

C.Cattadori - EPS 2013
FWHM @ 2039 keV
From calibrations

1\textsuperscript{enr}BEGe not used in the 0νββ data sets because of instabilities
Data quality:

Events accepted by the analysis cut

Very high quality:
- more than 90% of events accepted

Thanks to superior setup
- Ultra-low background
- Low Electronic noise

Pulser to check stability
GERDA BI vs. HdM (both no PSA)
BI Reduction factor ~ 10

enriched coaxials, 13.65 kg \times yr
natural coaxials, 4.69 kg \times yr
Cuoricino Calibration spectrum

GERDA BI vs. Cuoricino:

BI Reduction factor ~ 30 @ 2040 keV

enriched coaxials, 13.65 kg × yr
natural coaxials, 4.69 kg × yr
The $0\nu\beta\beta$ observation claim

- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for $0\nu\beta\beta$
- reported $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

N.B. Half-life $T_{1/2}^{0\nu} = 2.23 \times 10^{25}$ yr $T_{1/2}^{\nu}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:
- reported half-life can be reconstructed only (Ref. 1) with $\epsilon_{psd} = 1$ (previous similar analysis $\epsilon_{psd} \approx 0.6$)
- $\epsilon_{fep} = 1$ (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: $\epsilon_{fep} = 0.9$)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):
Combining Gerda+Xe

- Present Sensitivity on $m_{ee}$ according to the Ge+Xe combined limit for
  - different quenching scenarios for $g_A$
  - NME from QRPA. No error on relative ratio of $NME_{Xe}/NME_{Ge}$
- Bands from phase space & NME uncertainties

From Dell’Oro, Marcocci, Vissani, hep-ph/1404.2616v1
Combining GERDA, HdM, IGEX & Xe

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

**H0:** background only

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$P(H_1)/P(H_0)$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>76Ge</td>
<td>0.024 Model independent</td>
</tr>
<tr>
<td>GERDA +HdM+IGEX</td>
<td>76Ge</td>
<td>0.0002 Model independent</td>
</tr>
<tr>
<td>KamLAND-Zen*</td>
<td>136Xe</td>
<td>0.40 Model dependent: NME, leading term</td>
</tr>
<tr>
<td>EXO-200*</td>
<td>136Xe</td>
<td>0.23 Model dependent: NME, leading term</td>
</tr>
<tr>
<td>GERDA+KLZ* +EXO*</td>
<td>76Ge + 136Xe</td>
<td>0.002 Model dependent: NME, leading term</td>
</tr>
</tbody>
</table>

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

3 GERDA Data sets, 1 HdM, 1 IGEX
Profile likelihood function w. 5 independent bckgds

$T_{1/2}^{0ν} > 3.0 \times 10^{25}$ yr @ 90% CL

NME from

8/09/2014