First results from Phase II of the neutrinoless double beta decay experiment GERDA

Werner Maneschg for the GERDA Collaboration

Max-Planck-Institut für Kernphysik

TeV Particle Astrophysics 2016
September 12-16, 2016, CERN, Geneva
Double beta decay: Theory and observation

Double beta decay: $2\nu\beta\beta$ versus $0\nu\beta\beta$

1. $2\nu\beta\beta$ decay: Allowed by SM
   
   $(A,Z) \rightarrow (A,Z+2) + 2\ e^- + 2\ \bar{\nu}_e (\Delta L = 0)$
   
   → Signature: β-like spectrum
   
   → Observed in 12 candidates: $O(T_{1/2}) = 10^{18}-10^{24}$ yr

2. $0\nu\beta\beta$ decay: Forbidden by SM
   
   $(A,Z) \rightarrow (A,Z+2) + 2\ e^- (\Delta L = 2)$
   
   → Signature: Full energy peak at $Q_{\beta\beta}$

Signature from $2\nu\beta\beta$ and $0\nu\beta\beta$:

Observable: half-life

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

- $T_{1/2} \propto \begin{cases} a \cdot \epsilon \cdot M \cdot T, & \text{background-free} \\ a \cdot \epsilon \cdot \sqrt{M \cdot T \Delta E \cdot B}, & \text{w background} \end{cases}$
The GERDA experiment

Location:
Laboratori Nazionali del Gran Sasso, Assergi, Italy

Setup and background reduction:

- **1.4 km overburden**
  → Reduction of cosmic muon flux by 6 orders of magnitude (PB)

- **Water tank and plastic scintillator**
  → neutron moderator/absorber (PB)
  → muon Cherenkov veto (AB)

- **Liquid argon (LAr) cryostat**
  → cooling medium for diodes (80 K)
  → attenuation of external radiation (PB)
  → LAr scintillation light used for bg rejection (AB)

- **GERmanium Detector Array**
  - Operate bare diodes in LAr with low-mass, ultra-radiopure copper holders (PB)
  - Detectors enriched in $^{76}\text{Ge}$:
    $Q_{\beta\beta}$ of $^{76}\text{Ge} = 2039$ keV
  - **Concept**: DBD source = Detector
  - Coincidence modus between Ge diodes and auxiliary systems (AB)
  - Particle identification via pulse shape (AB)

Legend:

PB = passive background rejection
AB = active background rejection
GERDA Phase I (2011-2013)

String with coaxial Ge diodes

String with Broad Energy Ge diodes

Results from GERDA Phase I

- **Physics goal fullfilled**: 21.6 kg·yr with $B \approx 0.01 \text{ cts/(kg·yr·keV)}$ at $Q_{\beta\beta}$ incl. pulse shape discrimination (PSD) cuts (unprecedented !)
- **Detector performance**: excellent energy resolution at 0.2%, energy scale very stable
- **Data analysis**: fully blinded (unprecedented !)
- **Physics results**:
  - No evidence for peak, $\rightarrow T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr (90% C.L.)
  - combined Ge experiments: $T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr (90% C.L.)
  - $\rightarrow$ Combined Ge experiments (HdM + IGEX + GERDA): $\langle m_{\beta\beta} \rangle < (0.2-0.4) \text{ eV}$
**Strategy:** improve $T_{1/2}$ sensitivity by applying modifications *inside* the LAr cryostat

**Starting point:** $T_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$, assuming non-zero background

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{M}(^{76}\text{Ge enr.})$</td>
<td>6 coax: 14.6 kg</td>
<td>7 coax: 15.2 kg</td>
</tr>
<tr>
<td>(all operational channels)</td>
<td>4 BEGe: 3.0 kg</td>
<td>30 BEGe: 20.0 kg</td>
</tr>
<tr>
<td>$M \cdot T$</td>
<td>Goal: 20 kg·yr</td>
<td>Goal: 100 kg·yr</td>
</tr>
<tr>
<td></td>
<td>Achieved: 21.6 kg·yr</td>
<td></td>
</tr>
<tr>
<td>$\Delta E$ at $Q_{\beta\beta}$</td>
<td>coax: 4.2-5.7 keV</td>
<td>Goal: as good as in P I or</td>
</tr>
<tr>
<td>(full-width at half-maximum)</td>
<td>BEGe: 2.6-4.0 keV</td>
<td>improve via new filters</td>
</tr>
<tr>
<td>$B$ at $Q_{\beta\beta}$</td>
<td>Goal: $10^{-2}$ cts/( kg·keV·yr)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Achieved (incl. PSD):</td>
<td>Goal: $10^{-3}$ cts/( kg·keV·yr)</td>
</tr>
<tr>
<td></td>
<td>coax: 1.1-3.0·$10^{-2}$ cts/( kg·keV·yr)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BEGe: 0.5·$10^{-2}$ cts/( kg·keV·yr)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* PSD: reduced for coax</td>
<td>* PSD: enhanced for BEGe</td>
</tr>
<tr>
<td></td>
<td>* Signal contact: mech. spring</td>
<td>* Signal contact: bonding</td>
</tr>
<tr>
<td></td>
<td>* FE electronics + preampl.</td>
<td>* New development</td>
</tr>
<tr>
<td></td>
<td>* Copper mini-shroud</td>
<td>* Nylon mini-shroud</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>* LAr scintillation light:</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>- PMTs</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>- Glass fibers with SiPMs</td>
</tr>
</tbody>
</table>

* PSD: reduced for coax
* Signal contact: mech. spring
* FE electronics + preampl.
* Copper mini-shroud
* LAr scintillation light:
- PMTs
- Glass fibers with SiPMs
GERDA Phase II upgrade: New detector components

String with 8 BEGe detectors

**Background mitigation:**

- Pulse shape discrimination and Ge detector anti-coincidence:
  - Single-site event (SSE) → signal like
  - Multi-site event (MSE)
  - Multi-detector event
  - Surface event

- Low mass holder of low activity + new contacting / electronics
GERDA Phase II upgrade: LAr scintillation light instrumentation

Background mitigation:

- Ge detectors in anti-coincidence with LAr scintillation light read-out:
  - Single-site event (SSE) → signal like
  - 128 nm LAr scintillation

Hybrid design:

1. 16 x 3" low background PMTs Ham RG11065-10/20 MOD
2. 810 x scintillating fibers coupled to 90 KETEK SiPMs
3. 100 µm Cu shrouds with wavelength shift TETRATEX foil
GERDA Phase II upgrade: A special barrier against $^{42}\text{Ar}$

**$^{42}\text{Ar}$ background mitigation:**

- **Mechanical barrier** against $^{42}\text{Ar}$ ions attracted by high E field (GERDA Phase I: copper shroud)
- **Requirements** to GERDA Phase II shroud:
  1. transparent for LAr scintillation light $\lambda=128$ nm → use nylon
  2. match PMT and SiPM sensitivity → use nylon coated with wavelength shifter
  3. mech. robustness, no ageing, low intrinsic contamination

**Proof of principle in LArGe test stand**
Calibration with external sources:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>LAr Veto</th>
<th>LAr Veto + det. anti-coincidence + pulse shape discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{228}$Th</td>
<td>$85\pm 3$</td>
<td>$390\pm 28$</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>$5.1\pm 0.2$</td>
<td>$25\pm 2.2$</td>
</tr>
</tbody>
</table>

- **Suppression factors** depend on isotopes, source location & detector configuration
- **For external $\gamma$’s:** LAr veto more efficient than pulse shape discrimination (PSD)

In case of peak discovery at $\approx Q_{\beta\beta}$ possibility to check if event has:

a) multi-site energy dep. $\rightarrow$ bg-like
b) single energy dep. $\rightarrow$ $0\nu\beta\beta$-like

Strength of PSD:
GERDA Phase II: Data collection

Data collection start: December 15, 2015
All 7 strings mounted & all Ge detectors + LAr veto working!

Data set of GERDA Phase II used for 1. data release:

- From Run 53: First event: UTC Fri Dec 25 00:45:09 2015
- To Run 64: Last event: UTC Wed Jun 1 07:43:10 2016
- Live time: $130.67 \text{ d} = 0.358 \text{ yr}$ (→ Duty cycle: 82.0%)
BEGe

**Blinded region:**
$$Q_{\beta\beta} \pm 25 \text{ keV}$$

- **LAr veto cut:** → For $^{40}\text{K}$: fully accepted; $^{42}\text{K}$: SF~5
  → Below 2 MeV: basically only $2\nu\beta\beta$ spectrum
  → In 1839-2239 keV: survival fraction $= \sim 1/3$

- **Pulse shape:** → Events in ROI: signal accep. 87.3±0.9 %, Bg reject. 80%
  → $\alpha$ events: very efficient rejection
GERDA Phase II: Background suppression of coaxial detectors

**Coax**

**Blinded region:** $Q_{\beta\beta} \pm 25$ keV

- **LAr veto cut:** → In 1839-2239 keV: survival fraction $\sim 1/2$
- **Pulse shape:**
  - Multi-site events: rejected via artificial neural network (ANN) + projective Likelihood: $\epsilon_{mse} = (80 \pm 9)\%$ $0\nu\beta\beta$ acceptance
  - $\alpha$ events: rejected via ANN: $\epsilon_{\alpha} = (96 \pm 1)\%$ $0\nu\beta\beta$ acceptance
  - Total eff.: $\epsilon_{psd} = \epsilon_{mse} \cdot \epsilon_{\alpha} = (77 \pm 9)\%$, while bg. rejected at 65%
GERDA Phase II: background model

Global fit prior application of LAr veto and PSD cut

**BEGe:** $p$-value = 0.3

Fit $[570,5300]$ keV with 30 keV binning

Well understood bg composition

Expect flat bg in ROI at $Q_{\beta\beta}$

Bg model still preliminary!

**Coax:** $p$-value = 0.6

Fit predicts again flat bg in ROI

Main components before LAr veto and PSD cut similar to Phase 1:

- $\alpha$ from $^{210}$Po and $^{226}$Ra
- $\beta$ from $^{42}$K
- $\gamma$ from $^{214}$Bi and $^{208}$Tl
Final steps prior unblinding the $Q_{\beta\beta} \pm 25$ keV window:

- Freeze analysis cuts (energy reconstruction, quality cuts, flags...)
- Freeze data periods from Phase 1 and 2
- Freeze background model
- Freeze LAr veto and PSD cuts for BEGe and Coax
- Fix and agree on statistical methods ... →
GERDA Phase II: Unblinding of first data set

**BEGe:** Exposure = 5.8 kg·yr

**Coax:** Exposure = 5.0 kg·yr

<table>
<thead>
<tr>
<th>Counts</th>
<th>Region</th>
<th>BEGe</th>
<th>Coax</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected, w PSD</td>
<td>$Q_{\beta\beta} \pm 25$ keV</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1930-2190 keV</td>
<td>1.2</td>
<td>3.6</td>
</tr>
<tr>
<td>observed, w PSD</td>
<td>$Q_{\beta\beta} \pm 25$ keV</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1930-2190 keV</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

→ Like in Phase I, no hint for $\gamma$-line at $Q_{\beta\beta}$!
Background is flat.
**List of used data sets and of relevant quantities**

<table>
<thead>
<tr>
<th>Data set</th>
<th>Exposure [kg·yr]</th>
<th>Signal eff. [cts/(keV·kg·yr)]</th>
<th>Background [cts/(keV·kg·yr)]</th>
<th>Resolution FWHM [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I, coax golden</td>
<td>17.9</td>
<td>0.57(3)</td>
<td>11±2 · 10^{-3}</td>
<td>4.3(1)</td>
</tr>
<tr>
<td>Phase I, coax silver</td>
<td>1.3</td>
<td>0.57(3)</td>
<td>30±10 · 10^{-3}</td>
<td>4.3(1)</td>
</tr>
<tr>
<td>Phase I, BEGe</td>
<td>2.4</td>
<td>0.66(2)</td>
<td>5^{+4}_{-3} · 10^{-3}</td>
<td>2.7(2)</td>
</tr>
<tr>
<td>Phase I, extra</td>
<td>1.9</td>
<td>0.58(4)</td>
<td>5^{+4}_{-3} · 10^{-3}</td>
<td>4.2(2)</td>
</tr>
<tr>
<td>Phase II, coax</td>
<td>5.0</td>
<td>0.51(7)</td>
<td>3.5^{+2.1}_{-1.5} · 10^{-3}</td>
<td>4.0(2)</td>
</tr>
<tr>
<td>Phase II, BEGe</td>
<td>5.8</td>
<td>0.60(2)</td>
<td>0.7^{+1.1}_{-0.5} · 10^{-3}</td>
<td>3.0(2)</td>
</tr>
</tbody>
</table>

**Analyses based on two methods:**

<table>
<thead>
<tr>
<th></th>
<th>unbinned profile likelihood</th>
<th>Bayesian</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-side test-stat</td>
<td>flat prior on cts</td>
</tr>
<tr>
<td>$0\nu\beta\beta$ cts best fit value</td>
<td>0 cts</td>
<td>0 cts</td>
</tr>
<tr>
<td>$T^{0\nu}_{1/2}$ lower limit</td>
<td>&gt;5.2 · 10^{25} yr (90% CL)</td>
<td>&gt;3.5 · 10^{25} yr (90% CI)</td>
</tr>
<tr>
<td>$T^{0\nu}_{1/2}$ median sensitivity</td>
<td>4.0 · 10^{25} yr (90% CL)</td>
<td>3.0 · 10^{25} yr (90% CI)</td>
</tr>
</tbody>
</table>
Result from Phase I + first Phase II period:
- Sensitivity: $T_{1/2}^{0\nu} > 4.0 \cdot 10^{25} \text{ yr (90\% CL)}$
- No $0\nu\beta\beta$ signal found
  $\rightarrow T_{1/2}^{0\nu} > 5.2 \cdot 10^{25} \text{ yr (90\% CL)}$
  $\rightarrow m_{\text{eff}} < (0.15-0.33) \text{ eV}$

Goal for Phase II (next 3-4 yr):
- Exposure of 100 kg\cdot yr
- Only a fraction of bg event in ROI expected
  $\rightarrow$ first bg free experiment

Discovery potential:
- Find $\gamma$-line at $Q_{\beta\beta}$
  $\leftarrow$ very good energy res. and low bg
- Identify origin of $\gamma$-line at $Q_{\beta\beta}$
  $\leftarrow$ capability to distinguish $\beta\beta$ from other bg events on event-by-event basis
THANK YOU FOR YOUR ATTENTION!
SPARE SLIDES

GERDA and some general remarks about $\beta\beta$-decay search
GERDA: Active background suppression via pulse shape discrimination

Particle identification:

- **0νββ events**: free path of 1 MeV electrons in Ge is ≈1 mm. So, only one single energy deposition → single site event (SSE).
- **Gamma-rays**: free path of 1 MeV of γ-rays in Ge is > 10× larger, Compton scattering. So, charge pulse consists of several time-spread energy depositions → multi-site events (MSE)
- **Surface events**: peculiar behavior distinguishable from SSE (fast/slow risetime)

Example: Charge and current signal for a BEGe

Survival vs. rejection fraction:

- BEGe: SSE survival: (92±2)%, bkgr. rej.: >80%
- coax: SSE survival: (90^{+5}_{-9})%, bkgr. rej.: >45%
**GERDA Phase II upgrade: detector production and characterisation**

- **2005:** Ge enr. at 88% in $^{76}\text{Ge}$ at ECP, Zelenogorsk, RUS
- **2010:** Purification via zone-refinement at PPM GmbH, Langelsheim, GER
- **2011/12:** Crystal pulling at Canberra Industries Inc., Oak Ridge, USA
- **2012:** BEGe Diode production at Canberra Semiconductors NV, Olen, BEL;

- Production of 30 new BEGe detectors: high mass yield (20.2 kg), all operational
- BEGe detector properties: fully characterized
- Exposure to cosmic radiation: minimized and tracked
Half-life correlation with effective Majorana neutrino mass

\[
(\frac{T_{1/2}}{2})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{ee} \rangle^2
\]

with \(G^{0\nu}\): phase space factor, \(M^{0\nu}\): nuclear matrix element, \(\langle m_{\beta\beta} \rangle = |\sum_j m_j U_{ej}^2|\)

- \(M^{0\nu}\) calculations:
  - Improvements for NSM and QRPA:
    - Most QRPA discrepancies solved
    - Progress in understanding source of spread of NSM values
  - New methods IBM, EDF, pHFB

- \(Q_{\beta\beta}\) values:
  - Penning-traps (e.g. \(^{130}\)Te: 5% shift)

- Cross sections for neutron reactions:
  (e.g. \(^{207}\)Pb\((n,n'\gamma)\): DEP of 3062 keV \(\simeq Q_{\beta\beta}\) of \(^{76}\)Ge)

Theory's demand for a larger number of measurements with different isotopes

- Avoid (not well) known rare background events at \(Q_{\beta\beta}\)
- NME uncertainties \(\leq 30\%\) for neutrino mass spectrum & CP violating phases
- Mechanisms: Light vs. heavy Majorana neutrino exchange, RHC,...
Experimental sensitivity and constraints

Determination of the half-life

\[ T_{1/2} \propto \begin{cases} a \cdot \epsilon \cdot M \cdot T, & \text{background-free} \\ a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, & \text{if background is present} \end{cases} \]

with \( a \): Abun./Enrich.; \( M \): Mass; \( \epsilon \): act.volume; \( \Delta E \): e-res.; \( T \): life-time; \( B \): bkgd ([counts/kg/keV/yr] around region-of-interest)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( Q_{\beta\beta} ) [keV]</th>
<th>nat. abundance [%]</th>
<th>annual production [ton]</th>
<th>Experiment (oper./funded)</th>
<th>FWHM/E @ ( Q_{\beta\beta} ) [%]</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{48} \text{Ca} )</td>
<td>4273.7</td>
<td>0.19</td>
<td>( 5 \times 10^5 )</td>
<td>Candles</td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td>( ^{76} \text{Ge} )</td>
<td>2039.1</td>
<td>7.8</td>
<td>10</td>
<td>GERDA</td>
<td>0.1-0.2</td>
<td>15 → 35</td>
</tr>
<tr>
<td>( ^{82} \text{Se} )</td>
<td>2995.5</td>
<td>9.2</td>
<td>250</td>
<td>Majorana Dem.</td>
<td>0.1-0.2</td>
<td>30</td>
</tr>
<tr>
<td>( ^{100} \text{Mo} )</td>
<td>3035.0</td>
<td>9.6</td>
<td>( 2.5 \times 10^4 )</td>
<td>SuperNEMO</td>
<td></td>
<td>7 → 100</td>
</tr>
<tr>
<td>( ^{116} \text{Cd} )</td>
<td>2809.1</td>
<td>7.6</td>
<td>( 1.5 \times 10^3 )</td>
<td>Lucifer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^{130} \text{Te} )</td>
<td>2530.3</td>
<td>34.5</td>
<td>50</td>
<td>MOON</td>
<td></td>
<td>480</td>
</tr>
<tr>
<td>( ^{136} \text{Xe} )</td>
<td>2457.8</td>
<td>8.9</td>
<td>6</td>
<td>AMoRe</td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Motivations for a larger number of experiments and isotopes:

→ **Reduction of background**: detector segmentation, particle tracking, pulse shape, \( Q_{\beta\beta} \) above lines of \( ^{228}\text{Th} \)

→ **Advantages of single isotopes**: better \( \Delta E \), enrichment of isotope, scalability (detector size, world annual production, prize)

→ **Avoid/reduce systematics**: independent techniques, measurements with \( \leq 30\% \) precision
Isotopes and applied technologies for $0\nu\beta\beta$ decay search

Selected best isotope candidates: 8 out of 35 (← nat. abundance, $Q_{\beta\beta}$, $G^{0\nu} \propto (Z, Q_{\beta\beta}^5)$, chem. properties)

Techniques:

- **Source=Detector**: large isotopic masses possible and scalable (10-100 kg now, 1 ton near future)
- **Source≠Detector**: Tracking particle momenta → Topology of events and mechanisms
- **Liquid scintillator detectors**: multi-functional, largest target masses, purification strategies
- **Solid state detectors** achieve the best energy resolution: FWHW/E at $Q_{\beta\beta} = 0.15\%$

Last update: Neutrino Conf., July 2016
Remarks about sensitivity limits and discovery potential

Some $\beta\beta$ decay experiments are more suitable to push the sensitivity limits, others are more suitable for the discovery of $0\nu\beta\beta$ signals

Road map towards a discovery of $0\nu\beta\beta$ decay

1. Step: Find $\gamma$-line at $Q_{\beta\beta}$
   - Very good energy resolution $\rightarrow$ solid state $^{76}$Ge / $^{130}$Te det’s
   - No interfering continuous and $\gamma$-line background $\rightarrow$ solid state $^{76}$Ge det’s
   - Enough isotopic $\beta\beta$ mass $\rightarrow$ $^{136}$Xe and $^{130}$Te, but also $^{76}$Ge det’s

2. Step: Identify origin of events in $\gamma$-line found at $Q_{\beta\beta}$
   - Identify $\beta\beta$ events as single-site energy deposition:
     $\rightarrow$ Ge-based det’s can distinguish them from multi-site energy depositions
     $\rightarrow$ Xe-based det’s: liquid scintillator cannot due to low pos. reco. resolution;
     2-phase TPC can partly distinguish
   - Extract $\beta\beta$ daughter nuclides:
     $\rightarrow$ $^{76}$Se from $^{76}$Ge not possible (solid state detector)
     $\rightarrow$ $^{136}$Ba from $^{136}$Xe for TPC under testing, but very challenging (‘Ba tagging’)

3. Step: Identify exchange mechanism responsible for observed $0\nu\beta\beta$ decay
   - Track outgoing particles and reconstruct kinematics:
     $\rightarrow$ tracking calorimeter (e.g. SuperNEMO concept)