GERDA and the search for neutrinoless double-$\beta$ decay: first results and perspectives

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Outline

- Neutrinoless double-$\beta$ decay
- The GERDA experiment
- GERDA Phase I – prior to data unblinding
- GERDA Phase I – $0\nu\beta\beta$ analysis
- Conclusions and outlook on GERDA Phase II
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Neutrinoless double-$\beta$ decay
Double-$\beta$ decays

Second order nuclear transitions $\rightarrow$ decay of two neutrons into two protons

2-neutrino double-$\beta$ decay ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr
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[Diagram showing 2-neutrino double-$\beta$ decay]

Neutrinoless double-$\beta$ decay (0$\nu\beta\beta$):
- $$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$
- lepton number violation ($\Delta L = 2$)
- physics beyond the Standard Model (e.g. light Majorana $\nu$, R-handed weak currents, SUSY particles)
- $\nu$ Majorana mass component (Schechter-Valle theorem)
- $T_{1/2}^{0\nu}$ limits in the range $10^{21} - 10^{26}$ yr ($10^{25}$ yr for $^{76}$Ge)
- claim for a signal (subgroup of HdM experiment)

[Diagram showing neutrinoless double-$\beta$ decay]
Neutrinoless double-$\beta$ decay

Neutrinoless double-$\beta$ decay & neutrino physics

Assuming light-Majorana neutrino exchange as dominant $0\nu\beta\beta$ channel:

- $(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A, Z)|^2 \langle m_{\beta\beta} \rangle^2$

- effective Majorana mass:
  $$\langle m_{\beta\beta} \rangle \equiv |\sum_i U_{ei}^2 m_i| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta}|$$

- $\nu$ mass spectrum (inverted/normal hierarchy, absolute mass scale)

[arXiv:1305.0056]
[more details in PV IV]

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Neutrinoless double-β decay

State of the art of $0\nu\beta\beta$ search with $^{76}$Ge and $^{136}$Xe

- 71.7 kg·yr
- 28.75±6.86 signal events
- $T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

KK claim 2006 [Mod Phys Lett A21]
Claim strengthened with pulse shape analysis but many inconsistencies in the analysis summarized in:
In particular:
- missing efficiency corrections
- uncertainty on signal cts smaller than Poisson error

$T_{1/2}^{0\nu}$ central value and errors incorrect
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The GERDA experiment

Institutions

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

other talks at DPG: HK 15.1, HK 15.3, HK 15.4, HK 15.5, PV IV

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The GERDA experiment  
Sensitivity and background goals

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 $T^{0\nu}_{1/2}$ in the $10^{26}$ yr range
The GERDA experiment

Detectors

- HPGe detectors from material enriched in $^{76}\text{Ge}$ ($\sim 87\%$)
- Detectors well-established technology
- Optimal spectroscopy performance:
  - Long-term stability
  - $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$
  - Radio purity

- Energy (keV)
  - $2\nu\beta\beta$: $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e + 2\nu$
  - $0\nu\beta\beta$: $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e$
The GERDA experiment

Shielding strategy and 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.)
The GERDA experiment
Backgrounds and mitigation techniques

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:

• detector anti-coincidence

• time-coincidence (Bi-Po or $^{68}$Ge)

• pulse shape analysis (bulk localized energy deposition)

• LAr-scintillation (in Phase II)

  dedicated tasks: HK 15.1, HK 15.3 and HK 15.4
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GERDA Phase I – prior to data unblinding

Detector array assembly

- 3 + 1 strings
- 8 $^{\text{enr}}$Ge coaxial detectors (2 not considered in the analysis)
- 5 $^{\text{enr}}$Ge BEGe detectors (1 not considered in the analysis)
- 1 $^{\text{nat}}$Ge coaxial detectors

$^{\text{enr}}$Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)
GERDA Phase I – prior to data unblinding

Overview of the data taking

- data taking Nov11 - May13 (492 d)
- average duty cycle 88%
- total exposure 21.6 kg·yr
- (bi)weekly calibration with Th-228 (blue spikes)

- BEGe detectors from Jul12
- 3 data sets:

<table>
<thead>
<tr>
<th>dataset</th>
<th>exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>coaxial (golden)</td>
<td>17.9 kg·yr</td>
</tr>
<tr>
<td>coaxial (silver)</td>
<td>1.3 kg·yr</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4 kg·yr</td>
</tr>
</tbody>
</table>
GERDA Phase I – prior to data unblinding

Calibration of the energy scale ($^{228}$Th)

Energy resolution at 2.6 MeV (FWHM):

- $4 - 5$ keV for coaxial data sets
- $\sim 3$ keV for BEGe data set
GERDA Phase I – prior to data unblinding

Stability of the energy scale and resolution

Calibration runs:
- calibration every one/two weeks
- off-line energy reconstruction (semi-Gaussian filter)
- energy resolution stable
- energy shift between successive calibrations \( \lesssim 1 \text{ keV} \) @ \( Q_{\beta\beta} \)

\[ \begin{align*}
0\nu\beta\beta \text{ data set:} & \\
& \bullet \text{ peak position within 0.3 keV at correct position} \\
& \bullet \text{ resolution 4\% larger than in calibration runs} \\
& \bullet \text{ mean FWHM at } Q_{\beta\beta} \text{ (mass/exposure weighted):} \\
& \hspace{1cm} \text{coax} \rightarrow 4.8 \pm 0.2 \text{ keV} \\
& \hspace{1cm} \text{BEGe} \rightarrow 3.2 \pm 0.2 \text{ keV}
\end{align*} \]
GERDA Phase I – prior to data unblinding

Prominent structures in the energy spectrum

Blinded analysis

events in $Q_{\beta\beta} \pm 20$ keV not available

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GERDA Phase I – prior to data unblinding
Background modeling

**Data/model ratio**

- **Coaxial (golden):** $1.75^{+0.26}_{-0.24}$
- **BEGe:** $3.6^{+1.3}_{-1.0}$

**Contribution at $Q_{\beta\beta}$:**

- **$\gamma$-rays (close sources):** Bi-214, TI-208, K-42
- **$\alpha$- and $\beta$-rays (surface decays):** Ra-226 daughter, Po-210, K-42

**More details in [arXiv:1306.5084]**

- No line expected in the blinded window
- Background flat between 1930-2190 keV (excluding peaks at 2104 and 2119 keV)
- Extrapolated background at $Q_{\beta\beta}$ before pulse shape analysis in units of $10^{-2}$ cts/(keV·kg·yr):
  - Coaxial (golden): $1.75^{+0.26}_{-0.24}$
  - BEGe: $3.6^{+1.3}_{-1.0}$
GERDA Phase I – prior to data unblinding
Pulse shape discrimination

Coaxial detectors:
- artificial neural network TMLpANN
- cut defined using $^{228}$Th calibration data
  cut fixed to 90% acceptance of 2.6 MeV DEP
- cross checks:
  - $2\nu\beta\beta$ acc. = $(85\pm2)\%$
  - 2.6 MeV $\gamma$-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%

  $0\nu\beta\beta$ acceptance = $90^{+5}_{-9}\%$

  background acc at $Q_{\beta\beta}$ = $\sim45\%$

BEGe detectors:
- A/E method (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) $(92\pm2)\%$
- $2\nu\beta\beta$ acc $(91\pm5)\%$
- background acc at $Q_{\beta\beta}$ $\leq 20\%$

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GERDA Phase I – $0\nu\beta\beta$ analysis

Energy spectrum 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 at $Q_{\beta\beta}$:
- 1 $\sim$ 99%
- 2+3 $\sim$ 60%
- 4 $\sim$ 100%
- 5 $\sim$ 50%

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<th>exposure [kg·yr]</th>
<th>background $10^{-2}$ cts/(keV·kg·yr)</th>
<th>expected cts ($Q_{\beta\beta}\pm5$ keV)</th>
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<tr>
<td>golden</td>
<td>17.3</td>
<td>1.8</td>
<td>3.3</td>
<td>5</td>
</tr>
<tr>
<td>silver</td>
<td>1.3</td>
<td>6.3</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>4.2</td>
<td>1.0</td>
<td>1</td>
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GERDA Phase I – $0\nu\beta\beta$ analysis

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

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<td>golden</td>
<td>17.3</td>
<td>1.8, 1.1</td>
<td>3.3, 2.0</td>
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<tr>
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<td>2.4</td>
<td>4.2, 0.5</td>
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GERDA Phase I – $0\nu\beta\beta$ analysis

Statistical analysis

Baseline analysis (profile likelihood):
- maximum likelihood spectral fit (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $T_{1/2}^{0\nu}$)
- $T_{1/2}^{0\nu} \geq 0$ (coverage tested)
- systematic uncertainties in the fit

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.
- $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T_{1/2}^{0\nu} > 2.4 \times 10^{25}$ yr (90% C.L.)

Results (GERDA + IGEX [1] + HdM [2]):
- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr (90% C.L.)

GERDA Phase I – $0\nu\beta\beta$ analysis


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

In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):
- expected $2.0 \pm 0.3$ bkg cts
- expected $5.9 \pm 1.4$ signal cts (assuming $H_1$)
- observed 3 cts

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

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

Long standing claim strongly disfavoured!
GERDA Phase I – $0\nu\beta\beta$ analysis

Comparison between $^{76}$Ge and $^{136}$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)
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Conclusions

• GERDA Phase I collected 21.6 kg·yr of exposure

• background order of magnitude lower than previous Ge experiments:
  \[ \sim 0.01 \text{ cts/(keV·kg·yr)} \text{ at } Q_{\beta\beta} \text{ (after PSD)} \]

• blind analysis —> no positive $0\nu\beta\beta$ signal:
  \[ T^{0\nu}_{1/2} > 2.1 \cdot 10^{25} \text{ yr at 90\% C.L. (GERDA only)} \]
  \[ T^{0\nu}_{1/2} > 3.0 \cdot 10^{25} \text{ yr at 90\% C.L. (GERDA+IGEX+HdM)} \]

• Long standing claim excluded at 99\% C.L. (model-independent result)
Outlook on Phase II

Transition to Phase II ongoing. Major upgrade of many components:

- increase of target mass (+20 kg)
- new hardware to detect the LAr scintillation light (anti-coincidence veto) [see HK 15.1]
- new custom made BEGe detectors providing enhanced pulse shape discrimination performance [see HK 15.3 and HK 15.4]
- detector array assembly [see HK 15.5]

Expectations:

- \( \sim 35 \text{ kg of Ge detectors} \)
- background \( \lesssim 10^{-3} \text{ cts/(keV·kg·yr)} \) at \( Q_{\beta\beta} \)
- start the exploration of \( T_{1/2}^{0\nu} \) values in the \( 10^{26} \text{ yr} \) range