New constrains on neutrinoless double-$\beta$ decay from the GERDA experiment

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Les Rencontres de Physique de la Vallée d’Aoste
23 Feb - 01 Mar 2014
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

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
- $T^{2\nu}_{1/2}$ in the range $10^{19} - 10^{24}$ yr

0-neutrino double-$\beta$ decay ($0\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$
- 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)
- $T^{0\nu}_{1/2}$ limits in the range $10^{21} - 10^{26}$ yr ($10^{25}$ yr for $^{76}$Ge)
- claim for a signal (subgroup of HdM experiment)
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

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)
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:
  \[
  \langle m_{\beta\beta}\rangle \equiv |\sum_i U_{ei}^2 m_i| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta}\right|
  \]

- $\nu$ mass spectrum (inverted/normal hierarchy, absolute mass scale)
Neutrinoless double-\(\beta\) decay

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

- **HdM Collaboration**
  - \(T_{1/2} > 1.9 \times 10^{25} \text{ yr (90\% CL)}\)

- **IGEX Collaboration**
  - [Phys.Rev.D65,092007 (2002)]
  - \(T_{1/2} > 1.6 \times 10^{25} \text{ yr (90\% CL)}\)

- **Klapdor-Kleinrothaus et al.**
  - \(T_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25} \text{ yr}\)

- **EXO Collaboration**
  - [PRL 109 (2012)]
  - \(T_{1/2} > 1.6 \times 10^{25} \text{ yr (90\% CL)}\)

- **KamLAND-Zen Collaboration**
  - [PRL 110, 062502 (2013)]
  - \(T_{1/2} > 1.9 \times 10^{25} \text{ yr (90\% CL)}\)

- **EXO + KamLAND-Zen**
  - [PRL 110, 062502 (2013)]

- 71.7 kg\cdot yr
- 28.75\(\pm\)6.86 signal events
- \(T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \times 10^{25} \text{ yr}\)

**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/

16 institutions
~100 members
Phase I (Nov 2011 - May 2013):
- 15 – 20 kg of target mass (87% $^{76}$Ge)
- $\text{bkg} \sim 10^{-2} \text{cts/(keV} \cdot \text{kg} \cdot \text{yr)}$ at $Q_{\beta\beta}$
- exposure 21.6 kg\cdot yr
- sensitivity to scrutinize KK claim

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

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

Calorimeter detectors:
- Source = detector
- High detection efficiency
- Peak at Q-value ($Q_{\beta\beta}$)

\[ 2\nu\beta: ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e + 2\nu \]
\[ 0\nu\beta: ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e \]
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)
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• 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>

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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 $\lesssim 1$ keV @ $Q_{\beta\beta}$

$0\nu\beta\beta$ 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 $\rightarrow 4.8\pm0.2$ keV
  - BEGe $\rightarrow 3.2\pm0.2$ keV
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

**enriched coaxials, 19.20 kg $\times$ yr**

- $^{39}$Ar
- $^{226}$Ra
- $^{222}$Rn
- $^{210}$Po
- $^{218}$Po

**enriched BEGes, 2.40 kg $\times$ yr**

Blinded analysis

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GERDA Phase I – prior to data unblinding
Background modeling

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

- $\gamma$-rays (close sources): Bi-214, Tl-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±2)%
  - 2.6 MeV $\gamma$-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%

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

- background acc at $Q_{\beta\beta} = \sim 45\%$

BEGe detectors:
- A/E method (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) (92±2)%
- $2\nu\beta\beta$ acc (91±5)%
- background acc at $Q_{\beta\beta} \leq 20\%$


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

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

![Energy spectrum graph]

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

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2+3</th>
<th>4</th>
<th>5</th>
</tr>
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<tbody>
<tr>
<td>w/o PSD</td>
<td>~99%</td>
<td>~60%</td>
<td>~100%</td>
<td>~50%</td>
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**Data set**

<table>
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<tr>
<th>data set</th>
<th>exposure [kg·yr]</th>
<th>background $10^{-2}$ cts/(keV·kg·yr)</th>
<th>expected cts ($Q_{\beta\beta} \pm 5$ 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>
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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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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 $H_1 \left( T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25} \text{ yr} + \text{ bkg} \right)$

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

• GERDA Phase I collected 21.6 kg·yr of exposure

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

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

• 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)
• new custom made BEGe detectors providing enhanced pulse shape discrimination performance

Expectations:

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

~100 members, 16 institutions, 6 countries
backup slides
State of the art of $0\nu\beta\beta$ search with $^{76}\text{Ge}$ and $^{136}\text{Xe}$

- **HdM Collaboration**
  - $T_{1/2} > 1.6 \times 10^{25}$ yr (90% CL)

- **IGEX Collaboration**
  - [Phys.Rev.D65,092007 (2002)]
  - $T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)

- **Klapdor-Kleingrothaus et al.**
  - $T_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr
  - $T_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr

- **Klapdor-Kleingrothaus et al.**
  - [Mod Phys Lett A21 (2006)]
  - $T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)

- **GERDA Collaboration**
  - PRL 111, 122503 (2013)
  - $T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)
  - $T_{1/2} > 2.1 \times 10^{25}$ yr (90% CL)
  - $T_{1/2} > 3.0 \times 10^{25}$ yr (90% CL)

- **GERDA + HdM + IGEX**
  - $T_{1/2} > 1.6 \times 10^{25}$ yr (90% CL)
  - $T_{1/2} > 3.0 \times 10^{25}$ yr (90% CL)

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Comparison between $^{76}\text{Ge}$ and $^{136}\text{Xe}$ experiments

- GERDA provides a model-independent test of the signal claim
- comparison with $^{136}\text{Xe}$ 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)
Sterile $\nu$: $3 + 1$

$\langle m_{\beta\beta} \rangle$ (eV)

$m_{\text{light}}$ (eV)

1+3, Normal, SN

1+3, Inverted, SI

[arXiv:1106.1334]
Sterile $\nu$: $3 + 2$

2+3, Normal, SSN

2+3, Inverted, SSI

$\langle m_{\beta\beta} \rangle$ (eV)

$m_{\text{light}}$ (eV)

[arXiv:1106.1334]
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:
  $$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08} \text{ fit } +0.11_{-0.06} \text{ syst}) \cdot 10^{21}$$
  
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Background model – $\alpha$-emitting isotopes

- fit window 3500-7500 keV
- p-value of the fit: 0.7
- 80 bins of width 50 keV:
  - 79% in the green band
  - 98% in the yellow band

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

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

- \( a = 0.180 \pm 0.010 \)
- \( b = 0.0395 \pm 0.004 \)

Diagram showing:
- p-type germanium
- n+ electrode high voltage contact (3000 – 4000 V)
- p+ electrode signal read-out contact (0 V)
- Groove

Graphs showing:
- FWHM vs. energy [keV]
  - FWHM = \( a + bx^{1/2} \)
  - FWHM at 1332 keV [keV]
    - enriched
    - depleted
    - natural

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Charge collection and signal formation

Charge collection:
- electrons $\rightarrow$ n+ electrode
- holes $\rightarrow$ detector center $\rightarrow$ p+ electrode

Signal formation:
- electron contribution usually irrelevant
- narrow current peak induced by hole drift
- peak features independent from interaction site

- single site interactions (0$\nu \beta \beta$-like)
- multiple-site interactions (typically $\gamma$-induced)

A/E method:
- $E$: integral of the current signal (energy)
- $A$: maximum of the current signal

(Budjas et al. JINST 4 P10007, Agostini et al. JINST 6 P03005)

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Signal identification and background reduction

Background expected in Phase II:

- $\gamma$-rays from $^{208}$Tl and $^{214}$Bi $\rightarrow$ measured with many $\gamma$-sources
- Internal decays ($0\nu\beta\beta$ and cosmogenic isotopes) $\rightarrow$ pulse shape simulation
- $\alpha$-rays on the p+ electrode $\rightarrow$ experimental scan with collimated $^{241}$Am source
- $\beta$-rays on the n+ electrode $\rightarrow$ experimental measurements with $^{90}$Sr and $^{106}$Ru
Detection of LAr scintillation

LAr-scintillation (combined design):

- low-background photo-multipliers
- WLS fibers read-out with Si photo-multipliers
Phase II detectors and liquid argon scintillation

**BEGe detectors:**
- excellent energy resolution (1.6 keV @ 1.3 MeV)
- enhanced pulse shape discrimination performance
- 30 new $en^r$Ge detectors ready at LNGS (20 kg)

**LAr-scintillation (combined design):**
- low-background photo-multipliers
- WLS fibers with Si photo-multipliers

---

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

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