First results on neutrinoless double beta decay from the GERDA experiment

Carla Macolino per la collaborazione GERDA

INFN, Laboratori Nazionali del Gran Sasso

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Outline

- Probing the nature of neutrino with neutrinoless double-beta decay
- The GERDA experiment: design and detection principle
- The GERDA calibrations and energy spectra
- The background models for GERDA Phase I
- The Pulse Shape Discrimination of GERDA events
- Result on $0\nu\beta\beta$ half-life
The GERDA Collaboration

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

16 institutions
~100 members

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First results on $0\nu\beta\beta$ decay from GERDA

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Investigate existence of $0\nu\beta\beta$

- $0\nu\beta\beta \rightarrow$ Majorana nature of neutrino
- Lepton number violation
- physics beyond Standard Model
- Shed lights on effective neutrino mass
- Shed lights on neutrino mass hierarchy
Search for $0\nu\beta\beta$ decay

\[ 2\nu\beta\beta \]
\[ (Z, A) \rightarrow (Z + 2, A) + 2e^- + 2\bar{\nu}_e \]

\[ \Delta L = 0 \Rightarrow \text{Predicted by s.m.} \]

\[ 0\nu\beta\beta \]
\[ (Z, A) \rightarrow (Z + 2, A) + 2e^- \]

\[ \Delta L = 2 \Rightarrow \text{Prohibited by s.m.} \]

Light Majorana neutrino exchange
\[ Q = M_i - M_f - 2m_e \]

The GERmanium Detector Array experiment is an ultra-low background experiment designed to search for $^{76}\text{Ge}$ $0\nu\beta\beta$ decay.

The exp. signature observed searched for

\[ Q_{\beta\beta} = 2039 \text{ keV} \]
Search for $0\nu\beta\beta$ decay

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

with $\langle m_{\beta\beta} \rangle$ = effective electron neutrino mass

$\langle m_{\beta\beta} \rangle \equiv |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}$

$m_i$=masses of the neutrino mass eigenstates

$U_{ei}$=elements of the neutrino mixing matrix

$e^{i\phi_2}$ and $e^{i\phi_3}$=Majorana CP phases

→ information on the absolute mass scale!

- **Phase I result**: $B\ell \sim 10^{-2}$ cts/(keV kg yr) and $\sim 20$ kg yr exposure
  → limit on $\langle m_{ee} \rangle$ between 0.2 and 0.4 eV

- **Phase II goal**: $B\ell \sim 10^{-3}$ cts/(keV kg yr) and 100 kg yr exposure
  → sensitivity on $\langle m_{ee} \rangle \sim 100$ meV
Ge detectors

\[
T_{1/2} \propto \epsilon \cdot \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}
\]

| \(\epsilon\) | detection efficiency | \(\gtrsim 85\%\) |
| \(\varepsilon\) | enrichment fraction | high natural or enrichment |
| \(M\) | active target mass | increase mass |
| \(T\) | measuring time |
| \(b\) | background rate (cts/(keV kg yr)) | minimize & select radio-pure material |
| \(\Delta E\) | energy resolution | use high resolution spectroscopy |

**Very low background High-Purity Germanium Detectors (HPGe)**

**Advantages:**

- well established enrichment technique
  \(\epsilon = 86\%\) for \(^{76}\text{Ge}\)

- \(M\) and \(T\) expandable

- very good energy resolution
  \(\Delta E \sim 0.1\% - 0.2\%\)

- very good detection efficiency \(\epsilon \sim 1\)
  (Ge as source and detector)

- high-purity detectors \(\rightarrow\) low background \(b\)

- higher \(M^{0\nu}\) w.r.t. other isotopes

**Disadvantages:**

- Low \(Q_{\beta\beta}\) value
  (lower than \(^{208}\text{Tl} 2614\) keV)
  \(\rightarrow\) background

- Need enrichment from 7\% to 86\%
  \(\rightarrow\) it is expensive

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GERDA @ LNGS

- Hall A of Gran Sasso Laboratory (INFN)
- 3800 m.w.e.

Background from:

External:
- $\gamma$'s from Th and Ra chain
- neutrons
- cosmic-ray muons

Internal:
- cosmogenic $^{60}$Co ($T_{1/2}=5.3$ yr)
- cosmogenic $^{68}$Ge ($T_{1/2}=271$ d)
- Radioactive surface contaminations

Background reduction and events identification

- Gran Sasso suppression of $\mu$ flux ($10^6$)
- Material selection
- Passive shield ($H_2O$) - LAr - Cu
- Muon veto
- Detector anticoincidence
- Pulse-shape analysis

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The GERDA detectors

- 3 + 1 strings
- 8 enriched Coaxial detectors: working mass 14.6 kg (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: working mass 3.0 kg (testing Phase II concept in the real environment)
Energy calibrations and data processing

- Weekly calibrated spectra with \(^{228}\text{Th}\) sources and pulser with 0.05 Hz frequency
- Data useful for resolution and stability over time monitoring
- FWHM at \(Q_{\beta\beta}\) is about 4.8 keV for Coaxials and 3.2 keV for BEGes

**Data processing:** diode → amplifier → FADC → digital filter → energy, pulse shape,…

**Data selection:** anti coincidence (20% rej.), quality cuts (9% rej.), pulse-shape discrimination (50% rej.)
Energy spectra

- Silver coax: data from coaxial detectors during BEGe deployment (higher BI)
- Golden coax: data from coaxial detectors except Silver coax
- BEGe: data from BEGe detectors

Events in $Q_{\beta\beta} \pm 20$ keV kept BLINDED to not bias analysis and cuts

Phase I data divided in three subsets:
- Golden coax: 17.9 kg yr exposure
- Silver coax: 1.3 kg yr
- BEGe: 2.4 kg yr

Background level:
- @ 2614 keV: $1.1\pm0.3$ cts/(keV kg yr)
- @ 1764 keV: $3.3\pm0.5$ cts/(keV kg yr)
- @ $Q_{\beta\beta}$: $0.018\pm0.002$ cts/(keV kg yr)

Background 10x lower than previous Ge experiments!!

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The Background Model of GERDA Phase I


- Simulation of known and observed background
- Fit combination of MC spectra to data from 570 keV to 7500 keV
- Different combinations of positions and contributions tested

Main contribution from close background sources: $^{228}$Th and $^{226}$Ra in holders, $^{42}$Ar $\alpha$ on detector surface
The Background Model of GERDA Phase I

Minimum model fit

- No line expected in the blinded window
- Background flat between 1930 and 2190 keV
- $2140 \pm 5$ keV and $2119 \pm 5$ keV excluded
- Partial unblinding after calibration and background model fixed

8.6 (minimum model) or 10.3 (maximum model) events expected while 13 events observed in 30 keV window

Golden coax:
$BI = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}$ cts/(keV kg yr)

BEGe:
$BI = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}$ cts/(keV kg yr)

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Pulse shape discrimination of GERDA Phase I data

**0νββ events:** 1 MeV electrons in Ge ~ 1mm

one drift of electrons and holes SINGLE SITE EVENTS (SSE)

**Background from γ’s:** MeV γ in Ge ~ cm

several electron/holes drifts MULTI SITE EVENTS (MSE)

Current signal = q \cdot v \cdot \Delta \Phi

q=charge, v=velocity

(Schockley-Ramo theorem)

**Surface events:** only electron or hole drift

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Pulse shape discrimination of GERDA Phase I data


PSD for BEGe:

A over E parameter (A/E) between 0.965 and 1.07

Double escape peak of 2615 keV $\gamma$ in $^{228}$Th from calibrations $\rightarrow$ SSE for $0\nu\beta\beta$ 0.92±2% efficiency for $0\nu\beta\beta$ - 7/40 events kept in 400 keV window

PSD for Coaxials:

Artificial Neural Network ANN

Trained on signal SSE: $^{208}$Tl (2614 keV) DEP at 1592 keV

0.90$^{+0.05}_{-0.09}$% efficiency for $0\nu\beta\beta$ - 50% rej.
Results on $0\nu\beta\beta$ decay

- Sum spectrum $21.6 \text{ kg yr}$
- Unblinding after calibration finished, data selection frozen, analysis method fixed and PSD selection fixed
- Consider the 3 data sets separately in the analysis
- 7 events observed in 10(8) keV window - 5.1 expected
- 3 events observed after PSD - 2.5 expected

<table>
<thead>
<tr>
<th>data set</th>
<th>$\mathcal{E} [\text{kg yr}]$</th>
<th>$\langle \epsilon \rangle$</th>
<th>bkg</th>
<th>BI $^1)$</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$^{+16}_{-14}$</td>
<td>1</td>
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<tr>
<td>BEGe</td>
<td>2.4</td>
<td>0.720 ± 0.018</td>
<td>23</td>
<td>42$^{+10}_{-8}$</td>
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<tr>
<td>with PSD</td>
<td></td>
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</tr>
<tr>
<td>golden</td>
<td>17.9</td>
<td>0.619$^{+0.044}_{-0.070}$</td>
<td>45</td>
<td>11±2</td>
<td>2</td>
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<tr>
<td>silver</td>
<td>1.3</td>
<td>0.619$^{+0.044}_{-0.070}$</td>
<td>9</td>
<td>30$^{+11}_{-9}$</td>
<td>1</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>0.663 ± 0.022</td>
<td>3</td>
<td>5$^{+3}_{-3}$</td>
<td>0</td>
</tr>
</tbody>
</table>

$^1)$ in units of $10^{-3}$ cts/(keV·kg·yr).

No peak in spectrum observed, number of events consistent with expectation from background

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Results on $0\nu\beta\beta$ decay

arXiv:1307.4720

- Frequentist analysis
- Maximum likelihood spectral fit (3 subsets, $1/T_{1/2}$ common)
- Bayesian analysis also available

- **Profile likelihood result**: $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr at 90% C.L.
- **Bayesian analysis result**: $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr at 90% C.I.
- Best fit: $N^{0\nu} = 0$

- GERDA+HdM+IGEX:
  $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr at 90% C.I. and
  Best fit: $N^{0\nu} = 0$
Results on $0\nu\beta\beta$ decay


Compare two hypotheses:

- $H_1$: $T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25} \text{ yr}$
- $H_0$: background only

- **GERDA only**:
  Profile likelihood
  $P(N^{0\nu}=0|H_1) = 0.01$
  Bayes factor
  $P(H_1)/P(H_0) = 0.024$

- **GERDA+HdM+IGEX**:
  Bayes factor
  $P(H_1)/P(H_0) = 0.0002$

**Claim strongly disfavoured!**


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Conclusions

- Phase I data taking started on 11.2011 and ended on 05.2013
- Total exposure of GERDA Phase I is 21.6 kg yr
- Very low background 0.01 cts/(keV kg yr) after PSD
- 3 events observed while 2.5±0.3 expected in $Q_{\beta\beta} \pm 5$ keV
- Profile likelihood analysis gives $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for $^{76}$Ge
- Previous claim signal refuted by GERDA at 99%
Grazie per la vostra attenzione e buona conferenza SIF!