The GERDA experiment,  
a search for neutrinoless double beta decay

Daniel Lenz  
Max-Planck-Institute for Physics, Munich  
on behalf of the  
GERDA Collaboration

Outline:  
• Motivation  
• Experimental considerations  
• GERDA concept  
• Current status  
• R&D  
• Summary
The GERDA experiment, a search for neutrinoless double beta decay

GERmanium Detector Array

Daniel Lenz
Max-Planck-Institute for Physics, Munich
on behalf of the
GERDA Collaboration

Outline:
• Motivation
• Experimental considerations
• GERDA concept
• Current status
• R&D
• Summary
Motivation

- Neutrinoless double beta decay ($0^{\nu}\beta\beta$) is the only way to unveil the nature of neutrinos

![Dirac](image_url) or ![Majorana](image_url)

- If $0^{\nu}\beta\beta$ observed:
  - neutrino is Majorana type
  - lepton number violation $\Delta L = 2$
  - seesaw mechanism $m_\nu = \frac{m_D^2}{M_R} < m_D$
  - possible to determine absolute neutrino mass scale
  - possible to determine neutrino hierarchy
What is $\beta\beta$ Decay

2$\nu\beta$-decay:
- allowed process
- observed for several isotopes

$\nu\nu$-decay:
- forbidden process in SM, needs Majorana neutrino
- half-life limits available

Effective Majorana neutrino mass:

$$|m_{ee}| = |\sum_j m_j U_{ej}^2|$$

$$|m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i(a_2-a_1)} + m_3|U_{e3}|^2 e^{i(a_3-2\delta)}$$

$$T_{1/2} \propto |m_{ee}|^{-2}$$

F. Feruglio, A. Strumia, F. Vissani, NPB 637
Experimental Signature

2νβ-decay

\[
\begin{align*}
\text{n} & \rightarrow \text{p} + \text{e}^- + \nu + \bar{\nu} \\
\text{p} & \rightarrow \text{n} + \text{e}^- + \bar{\nu}
\end{align*}
\]

- allowed process
- observed for several isotopes

0νβ-decay

\[
\begin{align*}
\nu = \bar{\nu} & \rightarrow \text{p} + \text{e}^- \rightarrow \text{n} + \text{p} + 2\nu \beta \beta
\end{align*}
\]

- forbidden process in SM, needs Majorana neutrino
- halflife limits available

\[
Q_{\beta\beta} (^{76}\text{Ge}) = 2039 \text{keV}
\]
Heidelberg-Moscow experiment:

- 5 enriched Ge p-type crystals
- background index $\sim 0.1$ cts/(keV kg y)
- $T_{1/2} \geq 1.9 \times 10^{25}$ y (90% C.L.) 35.5 kg y


- part of collaboration claims a signal


IGEX:

- 3 enriched Ge p-type crystals
- $T_{1/2} \geq 1.57 \times 10^{25}$ y (90% C.L.) 8.87 kg y


- 62 TeO$_2$ bolometers 40.7kg
- $T_{1/2} \geq 3.0 \times 10^{24}$ y (90% C.L.) 11.83 kg y
### Experimental Considerations - Germanium Detectors

\[ T_{1/2} \propto \text{const} \cdot \epsilon \cdot (M \cdot T / b \cdot \Delta E)^{1/2} \quad \text{if background} \]

#### General Considerations

- **High Q-value:**
  - Phase space scales with \( Q^5 \)
  - Natural radioactivity contribution reduced

- **Large target mass \( M \); large natural abundance, or enrichment**

- **High signal efficiency \( \epsilon \)**

- **Low background rate \( b \)**
  - In ROI crucial!
  - Rate := counts/(keV \cdot kg \cdot y)

- **Good energy resolution \( \Delta E \)**
  - To separate \( 0\nu \beta \beta \) from \((2\nu \beta \beta + \text{other bkg})\)

#### Ge Detectors

- **\( Q_{\beta \beta}^{(76\text{Ge})} = 2039 \text{ keV} \)**

- **Enrichment in \(^{76}\text{Ge} \) of 86%**

- **Source = detector**

- **Germanium is one of the purest materials to produce**

- **Excellent energy resolution**
  - \( \text{FWHM(} Q_{\beta \beta} ) < 5 \text{ keV}; \quad \Delta E/E = 0.2\% \)
Phase I:  
- operate existing $^{76}$Ge detectors from HdM and IGEX + natGe Diodes  
- reach background of $10^{-2}$ cts/(keV kg y)  
- exposure of $\sim 15$ kg y, check claim

Phase II:  
- operate new segmented or BEGe $^{76}$Ge detectors  
- reach background of $10^{-3}$ cts/(keV kg y)  
- exposure of $\sim 100$ kg y $\Rightarrow T_{1/2} \geq 1.35 \cdot 10^{26}$ y

Key issue: low background rate

Phase II: $O(10^3)$ $\ll$ HdM

Assuming $\langle M^0 \rangle = 3.92$  
**Background**: processes which cause energy deposition inside ROI

- **Decay of cosmogenically produced radioactive isotopes**
  - Cosmic muons
  - Neutrons:
    - Muon induced
    - From radioactive isotopes in the rock
  - Radioactive isotopes in the surrounding:
    - Electrons/positrons
    - Photons
    - Alphas (surface)

**Detector production and storage**

- **Depth and laboratory dependent**
- **Choice of material close to detectors**
- **Purity of the liquid argon**

**Background units:** 

- counts / (keV·kg·y)
- around $Q_{\beta\beta}$
- total mass measuring time
HdM Background Revisit

**setup:**
copper cryostat
lead shield
conventional cooling

Main background from natural decay chains from Cu-cryostat and CuPb-shield
GERDA Concept

LNGS: 3800 m. w. e. rock above

Watertank:
- $r = 5\text{m}$, $h = 9.0\text{m}$
- 590 m$^3$ ultra-pure water
- acts as:
  - $n$ moderator
  - $\mu$ Cherenkov veto

Cryostat: (copper-lining)
- $r = 2.1\text{m}$, $h = 5\text{m}$
- 70 m$^3$ liquid Argon
- acts as:
  - shielding medium
  - cooling medium

Plastic scintillators on top as muon veto
**Clean room**: Class 10.000

**Detector array**:
- 3 detectors per string
- up to 16 strings
- little (high-Z) material close to detectors
Active Background Reduction

Anti-Coincidences:

**Signal:**

- Single Site Event (SSE)

**Background:**

- Multi Site Event (MSE)

  - crystal and segment anti-coincidence possible

Pulse Shape Analysis (PSA)

**Single Site Event (SSE):**

- Knee indicates that one charge carrier reaches electrode and stops drifting

**Multi Site Event (MSE):**

- MSE tends to have more complicated pulse structures.
Expected Background Phase II

- simulation of an array with 21 segmented detectors, 7 strings, each 3 detectors
- simulation carried out with **MaGe** (MajoranaGerda) GEANT4 based framework
- background including segment anti-coincidence

<table>
<thead>
<tr>
<th>Part</th>
<th>Background contribution [10^{-4} counts/(keV·kg·y)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>18</td>
</tr>
<tr>
<td>Holder</td>
<td>3</td>
</tr>
<tr>
<td>Cabling</td>
<td>18</td>
</tr>
<tr>
<td>Electronics</td>
<td>5</td>
</tr>
<tr>
<td>Muons</td>
<td>~ 0.1</td>
</tr>
<tr>
<td>Neutrons</td>
<td>~ 0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~ 44</td>
</tr>
</tbody>
</table>

- More recent, more detailed simulation of realistic array yields comparable values

D. Lenz, NDM09 Madison, 08/31-09/05
Current Status - Cryostat & Watertank finished

Cryostat
March 2008

Watertank and Superstructure
August 2008
Current Status - Cleanroom & Cherenkov Veto finished

Clean room
May 2009

mounting of PMTs in water tank
August 2009
Current Status - Detectors

**Phase I detectors:** p-type coaxial detectors

Total of 17.9kg enriched Ge

- well tested procedures for detector handling
- all detectors reprocessed and tested in LAr
- FWHM (1.33MeV) ~ 2.5 keV
- leakage current stable
Enriched Germanium:

- 37.5 kg of enriched Ge (86% $^{76}$Ge) bought by MPI Munich, currently stored underground

Germanium Purification @ PPM Pure Metals:

- no isotopic dilution
- total yield (6N) 88%
- total exposure @ sea level < 3 days / purification

Crystal Growing:

- first natural Ge crystals pulled from 6N material with Czochralski method by the Institut für Kristallzüchtung (IKZ) in Berlin
- impurity density $|N_D - N_A| \sim 10^{11} - 10^{13}$ cm$^{-3}$ ($10^{10}$ cm$^{-3}$ needed)
  - main problem is As, needs to be reduced
Detectors:  
- first true coaxial, n-type, 3x6 fold segmented, detector with low mass contacting scheme successfully tested in vacuum (Abt et al, NIM A 577 (2007) 574)

**FWHM** (1.33 MeV) 3 keV, core and segments

Suppression factors due to segment anti-coincidence as estimated from MC

- low mass holder, little high-Z material
  - 19g Cu, 7g PTFE, 2.5g Kapton per 1.62kg detector
Phase II Detector R&D

- second 3x6 fold n-type detector operated in liquid N
- operation stable for 5 month
- cable and component (placement) not optimized for resolution

**FWHM**(1.33MeV)
- Core: 4-5keV
- Segments: 3.5-6keV

- contact scheme functioning
- leakage current 30±5 pA
- test in liquid argon are ongoing
Phase II Detector R&D

- p-type unsegmented Broad Energy (BE)Ge detector

  ![Detector Diagram]

- potential of powerful PSA

  ![Waveforms and Graphs]

- no charge collection inefficency

- BEGe mass production and yield under investigation with Canberra

Budjas et al, submitted to JINST August 2009
R&D Pulse Shape Simulation

- needed to fully understand PSA recognition and rejection efficiencies
- gives inside into crystal properties
- helps reconstructing interaction positions
  - input:
    - impurity density distribution $\rho \Rightarrow$ EField
      - different for each crystal
    - crystal axis orientation
      - different for each crystal
    - drift model for charge carrier
      - same for all crystals

![Core electrode data vs sim](image1.png)

![Segment electrode data vs sim](image2.png)
R&D LArGe (liquid argon scintillation veto)

- veto background by tagging extra energy in LAr
- proof of principal


• veto background by tagging extra energy in LAr
• proof of principal

MC: factor 300 reduction in ROI
• Construction started and is ongoing

• **Phase I:**
  - Phase I detectors refurbished and ready
  - Reach $10^{-2}$ cts/(keV kg y)
  - Test neutrinoless double beta decay claim

• Parallel R&D for **Phase II:**
  - Reach $10^{-3}$ cts/(keV kg y)
  - Test $T_{1/2} \geq 1.35 \cdot 10^{26}$ y
  - Rich R&D program
    - n-type segmented detector working in LN2
    - p-type unsegmented detector strong PSA

• Apparatus commissioning will start this year
Summary and Outlook

- Construction started and is ongoing
- **Phase I:**
  - Phase I detectors refurbished and ready
  - Reach $10^{-2}$ cts/(keV kg y)
  - Test neutrinoless double beta decay claim
- Parallel R&D for Phase II:
  - Reach $10^{-3}$ cts/(keV kg y)
  - Test $T_{1/2} \geq 3.5 \times 10^{26}$ y
- Rich R&D program
  - n-type segmented detector working in LN2
  - p-type unsegmented detector strong PSA
- Apparatus commissioning will start this year

Stay tuned!
GERDA Collaboration

- Jagellonian University, Cracow Poland
- Technische Universität Dresden, Germany
- Joint Institute for Nuclear Research, Dubna Russia
- Institute for Reference Materials and Measurements, Geel Belgium
- Max-Planck-Institut für Kernphysik, Heidelberg Germany
- Institute for Nuclear Research of the Russian Academy of Sciences, Moscow Russia
- Institute for Theoretical and Experimental Physics, Moscow Russia
- Russian Research Center Kurchatov Institute, Moscow Russia
- Gran Sasso National Laboratory, Assergi Italy
- Universita Milano Bicocca and INFN, Italy
- Max-Planck-Institut für Physik, Munich Germany
- Universita di Padova and INFN, Italy
- Eberhard Karls University, Tübingen Germany
- University of Zürich, Switzerland