GERMANYUM DETECTOR ARRAY
A search for neutrinoless double beta decay

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Neutrinoless Double Beta Decay

**Effective Majorana Neutrino Mass**

\[ 2\nu\beta\beta \ (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e \]
SM allowed and observed in many isotopes.

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

**Half-life**

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

- \( G^{0\nu} \): Phase space integral
- \( M^{0\nu} \): Nuclear matrix elements
- \( \langle m_{\beta\beta} \rangle^2 = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|^2 \)
Searching in $^{76}\text{Ge}$

Experimental Design Considerations
- Large target mass & long exposures
- Extreme low background levels
- High signal efficiency

Advantages of Germanium
- Source ↔ Detector
  High signal efficiency $\sim 85$–95%
- Ultrapure material, High Purity Ge
- High resolution (FWHM $\sim 0.1$-0.2%)
  Helps to reduce background from $2\nu\beta\beta$ and avoid $\gamma$’s from the Compton continuum.
- Vast experience base

Disadvantages
- $Q_{\beta\beta}=2039$ keV, still plenty of $\gamma$’s
- Enrichment is possible, but expensive!
- Limited sources of crystal & detector manufacturers
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### Previous $^{76}$Ge Experiments

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<thead>
<tr>
<th>Location</th>
<th>HDMo</th>
<th>IGEX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>LNGS</td>
<td>Homestead</td>
</tr>
<tr>
<td>Overburden [m.w.e.]</td>
<td>3800</td>
<td>4000</td>
</tr>
<tr>
<td>Exposure [kg · yr]</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Bg [counts/kg·keV·yr]</td>
<td>0.11</td>
<td>8.9</td>
</tr>
<tr>
<td>$T_{1/2}$ limit (90% CL)[yr]</td>
<td>$1.9 \times 10^{25}$</td>
<td>$1.57 \times 10^{25}$</td>
</tr>
</tbody>
</table>

“Evidence for $0\nu\beta\beta$”  
$0.69 - 4.18 \times 10^{25}$ [yr] 3σ  

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![Graph showing energy vs. counts for $^{76}$Ge](image1.png)

$T_{1/2}(0\nu) > 1.57 \times 10^{25}$ yr (90% CL) 
$m_\nu < (0.3-1.1)$ eV 
$2038.5$ keV
Two New $^{76}$Ge Projects

- **GERDA**
  - ‘Bare’ $^{enr}$Ge array in liquid argon
  - Shield: high-purity liquid argon/H$_2$O
  - Phase I: 18 kg (HdMo/IGEX)/15 kg nat.
  - Phase II: add $\sim$ 20 kg new enr. detectors total $\sim$ 40 kg

- **Majorana**
  - Array(s) of $^{enr}$Ge housed in high-purity electroformed copper cryostat
  - Shield: electroformed copper/lead
  - Initial phase: R&D demonstrator module
    Total $\sim$ 60 kg (30 kg enr.)

**Physics goals:** degenerate mass range
**Technology:** study of bgds. and exp. techniques

**LoI:**
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana
GERDA Collaboration

INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
Institute of Physics, Jagellonian University, Cracow, Poland
Institut für Kern- und Teilchenphysik, 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
Dipartimento di Fisica, Università Milano Bicocca, Milano, Italy
INFN Milano Bicocca, Milano, Italy
Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, Milano, Italy
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
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Physik Department E15, Technische Universität München, Germany
Dipartimento di Fisica dell’Università di Padova, Italy
INFN Padova, Padova, Italy
Shanghai Jiaotong University, Shanghai, China
Physikalisches Institut, Eberhard Karls Universität Tübingen, Germany
Physik Institut der Universität Zurich, Switzerland

100 Members
19 Institutes
7 Countries
# GERDA Physics Goal

<table>
<thead>
<tr>
<th>Phase</th>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure $[\text{kg} \cdot \text{yr}]$</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>Bg $[\text{counts/} \text{kg} \cdot \text{keV} \cdot \text{yr}]$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Upper limit $m_{\beta \beta} [\text{eV}]$</td>
<td>0.23-0.39</td>
<td>0.09-0.15</td>
</tr>
</tbody>
</table>

A. Smolnikov, P. Grabmayr

PRC 81 028502(2010)
Background Reduction

Deep underground site for suppression of cosmic ray muons
Graded shielding against ambient radiation
Rigorous material selection
Signal Analysis

GERDA Experiment at LNGS, Italy
3400 m.w.e

Steel cryostat
with internal Cu shield
Water tank: γ, n shield, Cherenkov medium for µ veto
Array of bare Ge-diodes
Clean room lock system

High-purity liquid argon (LAr); shield & coolant Option: active veto

Suppression of µ-flux > 10⁶
Unloading of vacuum cryostat
(6 March 08)
Produced from selected low-background austenitic steel
Construction of water tank

∅ 10 m
H = 9.5 m
V = 650 m³

Designed for external γ, n, μ background
~10⁻⁴ cts/(keV kg y)

19 May 08
clean room, active cooling device getting prepared for installation
Water tank and cryostat prior muon veto installations

WT and cryostat with muon veto installed

“Pill box”
Glove-box for Ge-detector handling and mounting into commissioning lock under N₂ atmosphere installed in clean room
Nov/Dec. ’09: Liquid argon fill
Jan ’10: Commissioning of cryogenic system
Apr/Mai ’10: Emergency drainage tests of water tank
Apr/Mai ’10: Installation of c-lock
May ’10: 1st deployment of FE&detector mock-up (27 pF) - pulser resolution 1.4 keV (FWHM); first deployment of non-enriched detector
June ‘10: Start of commissioning run with natGe detector string
Soon: start of Phase I physics data taking
Commissioning runs with non-enriched low-background detectors to study performance and backgrounds.
Energy Calibration with $^{228}$Th $\gamma$-Source

Energy Resolution in GERDA during commissioning
Dependant on chosen detector configuration
In range 3.6 keV-6keV FWHM @ 2.6 MeV
Muon induced events

Run12. Exposure: 0.525 kg × year

Events with muon veto

Muon induced rate \( \sim 1 \times 10^{-2} \) counts/(kg \cdot keV \cdot yr)
(as estimated by MC in GERDA proposal)

Cosmic ray veto efficiency 94% (preliminary)

Water Čerenkov only; mounting of scintillator panels not completed yet
The Unexpected $^{42}\text{Ar}(^{42}\text{K})$ Signal

GERDA Proposal: $^{42}\text{Ar}/^{\text{nat}}\text{Ar} < 3 \times 10^{-21}$
[Barabash et al. 2002]

GERDA Measurement:

- True Value could be $x10$ higher than limit
- Additional enhancement of count rate due to collection of $^{42}\text{K}$ ions by E-field of diodes
- if $^{42}\text{K}$ decay on detector surface $\Rightarrow$ bgd to $0\nu\beta\beta$
E-Field Enhancement of $^{42}\text{K}$ Peak Rate

Run 1-3 (0.59 kg·years)

Run 10-11 (1.0 kg·years)
E-Field Enhancement of $^{42}\text{K}$

High Energy Rate

Without mini-shroud: 0.169 counts/(keV × kg × year)

With mini-shroud: 0.074 counts/(keV × kg × year)
### Summary of Commissioning Runs
(Non-Enriched Detectors)

<table>
<thead>
<tr>
<th>Date</th>
<th>Counting Rate (counts/kg × day)</th>
</tr>
</thead>
</table>
| 02-Jul-2010   | w/o mini-shroud: 1.5  
                 | w/ mini-shroud: 2.0      |
| 01-Sep-2010   | w/o mini-shroud: 2.0  
                 | w/ mini-shroud: 2.5      |
| 01-Nov-2010   | w/o mini-shroud: 2.5  
                 | w/ mini-shroud: 3.0      |
| 31-Dec-2010   | w/o mini-shroud: 3.0  
                 | w/ mini-shroud: 3.5      |
| 02-Mar-2011   | w/o mini-shroud: 3.5  
                 | w/ mini-shroud: 4.0      |

**Shroud:** +500V  
**Mini-shroud:** -200V
Summary of Commissioning Runs (Non-Enriched Detectors)

Counting rate at the 1525-keV $\gamma$ line

- w/o mini-shroud
- with mini-shroud

Shroud: +500V
Mini-shroud: -200V

Encapsulation

Date
02-Jul-2010 01-Sep-2010 01-Nov-2010 31-Dec-2010 02-Mar-2011

counts/(kg x day)
Summary of Commissioning Runs (Non-Enriched Detectors)

Counting rate at the 1525-keV $\gamma$ line

- w/o mini-shroud
- with mini-shroud

E-field Free
-HV core contact
Shroud: +500V
Mini-shroud: -200V

Date
02-Jul-2010 01-Sep-2010 01-Nov-2010 31-Dec-2010 02-Mar-2011

Counts/(kg x day)
Summary of Commissioning Runs (Non-Enriched Detectors)

Date
02-Jul-2010 01-Sep-2010 01-Nov-2010 31-Dec-2010 02-Mar-2011

Run History
w/o mini-shroud
with mini-shroud
w/o mini-shroud
encapsulation
E-field Free
The Low Energy Spectrum: \(^{39}\text{Ar}\)

\[ ^{39}\text{Ar}_{\text{fit}} = 1.076 \pm 0.011(\text{stat}) \text{ Bq/kg} \]

Data
Monte Carlo
Fit boundaries

Preliminary
Event Time Distribution

Run12. Exposure: 0.587 kg × year

- All events
- Muon veto
- Multiple-detector

ROI

Date
17-Feb 24-Feb 02-Mar 09-Mar 16-Mar
Energy (keV)
0
1000
2000
3000
4000
5000
6000
7000

0.587 kg × year
Count Rate in Region of Interest

Run 12. Exposure: 0.587 kg \times y. Energy: Q_{\beta\beta} \pm 200 keV.

- Bgd rate significantly lower than previous experiments (HdMo, IGEX), but still higher than Phase I bgd goal (0.01 cnts/(kg \cdot keV \cdot yr))
- Possible cosmogenic bgd contribution due to exposure history of diodes
- Run 13: "Field-free" (n+ outer contact @0V) & removal of mini-shroud
- Deployment of 3 enriched detectors with known low activation history
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<th>Phase I</th>
<th>Phase II</th>
</tr>
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<tr>
<td>3 IGEX &amp; 5 HdMo Detectors 17.9 kg</td>
<td>35 kg 6N enriched Ge Metal</td>
</tr>
<tr>
<td>(6 non-enriched Genius-TF for reference)</td>
<td>18 kg Detector slices expected for BEGe diode production</td>
</tr>
<tr>
<td></td>
<td>IKZ Crystal pulling R&amp;D for segmented detectors</td>
</tr>
</tbody>
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Background Identification

- Time structure of the charge signal: Pulse Shape Analysis

- Granulation/Segmentation: 18 fold-segmented n-type detectors

- Liquid Argon Veto Instrumentation
Background Identification

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PSA discrimination results

- Fractions remaining after cut:
  - DEP: 91.01% ± 0.62%
  - 1.62 MeV: 13.20% ± 0.45%
  - SEP: 9.10% ± 0.29%
  - 2.61 MeV: 13.19% ± 0.06%
  - ROI Qββ: 49.06% ± 0.40%

D. Budjáš et al., J INST 4 P10007(2009)

Granulation/Segmentation: 18 fold-segmented n-type detectors

Liquid Argon Veto Instrumentation
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I. Abt et al. EPJ C 52(2007)
I. Abt et al. NIM A 583(2007)

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J. Janisckó-Csáthy et al., arXiv:1011.2748v1 [physics.ins-det]
Phase II Detector Production

- Purchase Enriched $^{76}\text{GeO}_2$: ECP Zelenogorsk, RU

- Metal Reduction and Zone Refinement: Langelsheim, DE
  08.03.2010 to 30.4.2010

- Crystal Pulling at Canberra: Oakridge, TN, USA

- BEGe Detector Diode Production: Olen, BE

- Crystal Pulling Institut für Kristallzüchtung: Berlin, DE

- Segmented Detector Diode Production: Lingolsheim, Fr
Phase II Detector Production

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35.5 kg Enriched HPGe 6N material

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Production Chain Worldwide

Maritime Shipping Routes and Strategic Locations

Zelenogorsk
Geel/Olen
Munich
Oakridge

http://people.hofstra.edu/geotrans/index.html

\[ ^{68}\text{Ge concentration in } ^{111}\text{Ge} \]

\[ ^{60}\text{Co concentration in } ^{111}\text{Ge} \]

clock starts at enrichment

at crystal pulling
Conclusions

- GERDA experimental installations completed
cryogenic and auxiliary systems operations stable
- Detector commissioning with non-enriched detectors started summer 2010 and is ongoing
- Initial count rate dominated by increased $^{42}\text{K}$ ($^{42}\text{Ar}$ progenitor) concentration due to diode E-field \(\Rightarrow\) "Field-free" configuration identified
- Background with non-enriched detectors currently at $0.05\,\text{cts}/(\text{kg} \cdot \text{keV} \cdot \text{yr})$. Goal for Phase I: $0.01\,\text{cts}/(\text{kg} \cdot \text{keV} \cdot \text{yr})$.
- Deployment of first string(s) with enriched detectors, Phase I, to start soon
- Thick window p-type BEGe detectors for Phase II, production chain has been tested on depleted Ge
- $37.5$ kg of $86\%$ enr Ge (GeO$_2$) reduced and purified to $35.4$ kg 6N HPGe
- Crystal pulling and detector production under preparation
Neutrino Properties

Simplest explanation for observations by 3-neutrino flavor mixing

Quark Mixings

Weakly interacting and mass eigenstates are independent basis

\[
\begin{pmatrix}
|d'\rangle \\
|s'\rangle \\
|b'\rangle \\
\end{pmatrix}
= \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb} \\
\end{pmatrix}
\begin{pmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle \\
\end{pmatrix}
\]

\[
V_{ij} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta_{13}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{12}s_{23}s_{13}e^{i\delta_{13}} \\
s_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{23}s_{13} \\
s_{23}s_{13} & c_{23}s_{13} & c_{23}s_{13} \\
\end{pmatrix}
\]
Neutrino Properties

Simplest explanation for observations by 3-neutrino flavor mixing

Neutrino Mixings

Weakly interacting and mass eigenstates are independent basis

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix} \]

\[ U_{\nu i} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\delta_{13}} & s_{13}e^{i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}s_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}s_{13} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ e^{i\frac{\alpha_{21}}{2}} \end{pmatrix} \]

\[ e^{i\frac{\alpha_{31}}{2}} \]
Neutrino Properties

**Observed Properties**

- Two mass differences
  - $m_2^2 - m_1^2 = \Delta m_\odot^2$
  - $|m_1^2 - m_3^2| = \Delta m_{atm}^2$
- Two mixing angles
  - $\theta_{12} = \theta_\odot$ and $\theta_{23} = \theta_{atm}$
- and an upper limit on $\theta_{13}$

**Still Missing**

- Value of the third mixing angle
- Absolute mass scale
- Mass hierarchy
- CP violating phases
- Nature of the neutrino mass (Majorana or Dirac)
The Hierarchy Problem