GERDA: Study of Neutrinoless Double Beta Decay of Ge-76

Vasily Kornoukhov
for the GERDA Collaboration
ITEP, INR RAS Moscow

OUTLINE
Double Beta Decay
Motivation of GERDA
Principles of GERDA detector
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Summary
The GERmanium Detector Array Collaboration


a) INFN Laboratori Nazionali del Gran Sasso, LNGS, Assergi, Italy
b) Institute of Physics, Jagellonian University, Cracow, Poland
c) Institute für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
d) Joint Institute for Nuclear Research, Dubna, Russia
e) Institute for Reference Materials and Measurements, Geel, Belgium
f) Max Planck Institut für Kernphysik, Heidelberg, Germany
g) Dipartimento di Fisica, Università Milano Bicocca, Milano, Italy
h) INFN Milano Bicocca, Milano, Italy
i) Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, Milano, Italy
j) Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
k) Institute for Theoretical and Experimental Physics, Moscow, Russia
l) Russian Research Center Kurchatov Institute, Moscow, Russia
m) Max-Planck-Institut für Physik, München, Germany
n) Dipartimento di Fisica dell’Università di Padova, Padova, Italy
o) INFN Padova, Padova, Italy
p) Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
q) Physik Institut der Universität Zürich, Zürich, Switzerland
Neutrino oscillation experiments: neutrinos have a non-vanishing rest mass!

• Questions:
  - Nature of neutrino mass (Dirac or Majorana)?
  - Mass hierarchy (normal, inverse, quasi-degenerate)?
  - Mass scale: a value or an upper limit on $m_1$?

This information can be obtained from $0\nu2\beta$-decay experiments (through measurement of the effective Majorana neutrino mass $m_{ee}$)

$$
\frac{1}{\sqrt{T_{1/2}^{0\nu}}} \approx <m_{ee}> = \left| \sum_j U_{ej} \right|^2 e^{i\Phi_j} m_j \left| m_j \right|
$$

$j = 1,2,3$

$U_{ej}$ – PMNS unitary neutrino matrix, $\Phi_j$ - CP – phases

(*) if a mass mechanism of the $0\nu2\beta$-process is dominating
Sensitivity of DBD experiment

\[ T_{1/2}^{0\nu} \geq 4.17 \times 10^{26} \cdot \epsilon \cdot \left( \frac{a}{A} \right) \cdot \sqrt{\frac{M}{t/B \cdot R}} \]

\[ m_\nu \sim \frac{1}{\sqrt{T_{1/2}^{0\nu}}} \]

- B - background index in cts/(keV kg y)
- R - FWHM energy resolution at \( Q_{\beta\beta} \) in keV
- A - mass number
- \( \epsilon \) - detection efficiency at \( Q_{\beta\beta} \) ! "Detector = source"
- \( a \) - \( \beta\beta \) isotope fraction ! Enrichment \( \rightarrow \) 100%
- M - mass of detector in kg
- T - measurement time in years
Ge diodes as a tool for 76Ge DBD search

- Detector = Source
  \[\downarrow\]
  \(\varepsilon \sim 95\% \text{ efficiency}\)

- Energy resolution \(R \sim \) a few keV (3 – 5 keV)
  \[\downarrow\]
  No \(2\nu\beta\beta\) background from 76Ge

- Technology of the production \(\rightarrow\) High purity
  \[\downarrow\]
  No \(^{238}\text{U-},^{232}\text{Th-}\) intrinsic background

- Big scale production of 76Ge isotope: centrifuges
• Fiorini E. et al., 1967: 
  first \text{nat}Ge experiment \( (T_{2ov} > 3,1 \cdot 10^{20} \text{ yr}) \).
  \text{nat}Ge(Li): m = 0.09 \text{ kg}, R = 4.7 \text{ keV} \text{ at } 1,32 \text{ MeV}, 
  1973, \ (T_{2ov} > 5 \cdot 10^{21} \text{ yr}).
  \text{nat}Ge(Li): m = 0.36 \text{ kg}, R = 6 \text{ keV}, BI = 38 \text{ keV}^{-1}\text{kg}^{-1}\text{yr}^{-1}

• Caldwell D.O. et al., 1986: 
  \text{nat}Ge diodes \( (T_{2ov} > 2,5 \cdot 10^{23} \text{ yr}) \)
  m = 3.5 \text{ kg}, R = 3.7 \text{ keV}, BI = 0.35 \text{ keV}^{-1}\text{kg}^{-1}\text{yr}^{-1} \text{(with NaI)}

• ITEP group (Kirpichnikov et al.) 1987-89:
  first \text{76}Ge experiment \( (T_{2ov} > 2 \cdot 10^{24} \text{ yr}) \)
  two \text{76}Ge(Li) crystals (m = 1.14 \text{ kg}), R = 3.7 \text{ keV},
  BI = 2.6 \text{ keV}^{-1}\text{kg}^{-1}\text{yr}^{-1} \text{(with NaI)}

*) For references see at the end of the presentation
IGEX experiment:
C. Aalseth et al., Phys. Rev. D 65, 092007
\[ T_{1/2} > 1.6 \times 10^{25} \text{ y (90\% C.L.)} \]
8.5 kg\*yr, BI \sim 0.1 cts/(keV\cdot kg\cdot yr) with PSA

Heidelberg-Moscow experiment:
\[ T_{1/2} > 1.9 \times 10^{25} \text{ y (90\% C.L.)} \]
71.7 kg\*yr
BI = 0.11 cts/(keV\cdot kg\cdot yr) before PSA
Claim: \[ T_{1/2} = (0.7 - 4.2) \times 10^{25} \text{ y (3\sigma)} \]
\( m_\nu \sim 0.24 - 0.58 \text{ eV} \)

Confirmation needed with same & different isotopes!
Sources of background in $^{76}$Ge-DBD exp

**External background (main source now):**

* $\gamma$-rays from the rock, shielding material and detector supporting material;
* neutrons from fission, ($\alpha$,n)-reactions in rock and $\mu$-induced reactions in rock and shielding material;
* muons from cosmic rays showers

**Intrinsic background:**

* cosmogenic isotopes (Ge-68, Co-60) due to spallation reactions on Ge isotopes at sea level ($T_{1/2} \rightarrow$ year)
GERDA goal: how to proceed?

Reduction of bkg-index by two orders of magnitude to $10^{-3}$ cts/kg/keV/yr + increase of $^{76}$Ge mass:

- Removal of materials around crystal – naked HPGe detectors
  

- Use of highly enriched Ge (87%)

- Use of (water + liquid argon) for passive shielding

- Use of muons veto (Cherenkov + plastic scintillator)

- Use of liquid argon for active shielding (option*)

- Use for Phase II *highly segmented* or *point-like p-type* detectors

- Improvement of Pulse Shape Analysis
Basic design of GERDA: cryostat made of ss-steel inside water tank

Most dangerous TI-208 of Th-232 chain
\[ E_\gamma = 2,615 \text{ MeV} \]

Activity of TI-208, mBq/kg:
- Rock, concrete ~ 3000
- Stainless steel < 5
- Cu(OFHC) < 0.02
- Water purified < 0.001
- LAr ~ 0

Principle of “Russian MATRESHKA” except that last girl (Ge crystals) is naked

Cu shielding
Vacuum-insulated double wall stainless steel cryostat

\[ \text{U/Th} \leq 5 \text{ mBq/kg} \]

Clean surface

Liquid argon

\[ ^{222}\text{Rn} = \leq 1 \text{ \(\mu\)Bq/m}^3 \]

Additional inner copper shield

detectors holders

\[ \text{U/Th} \leq 16 \text{ \(\mu\)Bq/kg} \]

Clean surface

D_{int} = 4 \text{ m}

H_{LAr} = 5.5 \text{ m}

V = 70 \text{ m}^3

GERDA s/steel cryostat

\[ \text{BI (TI208)} = 10^{-4} \text{ cts/(keV⋅kg⋅y)} \]
Water tank and muon veto

- Water serves as passive shield (reduces amount of LAr)
- Filled with pure water of 590 m$^3$
- Layer of reflector film VM2000
- 66 PMTs ETL 9350 KB: Cherenkov detector
- 20 panels of plastic scintillator on top ($S = 20$ m$^3$, $\Delta = 3$ cm)

$BI$ (muons) = $10^{-4}$ evts/keV/kg/y
**PHASE I: 17.9 kg of enriched \(^{76}\text{Ge}\) (from HM and IGEX)**

1 year data if \(B=10^{-2} \text{ cts/(keV·kg·yr)}\)  \((\text{check of Klapdor’s claim})\)

Start in 2009 at Gran Sasso, results 2010

\[T_{1/2} > 3 \times 10^{25} \text{ yr} \quad \langle m_{\nu} \rangle < 270 \text{ meV}\]

**PHASE II: 40 kg of enriched \(^{76}\text{Ge}\) (20 kg segmented or point like HPGe detectors)**

if \(B=10^{-3} \text{ cts/(keV·kg·yr)}\)  \(T_{1/2} > 1.5 \times 10^{26} \text{ yr for 3 yr} \times 35 \text{ kg of data taking}\)

\[\langle m_{\nu} \rangle < 110 \text{ meV}\]

**PHASE III: if PHASE I and II succeed**

then world-wide \(\sim 1\) ton experiment with MAJORANA

\[\langle m_{\nu} \rangle < 10 - 20 \text{ meV} \]
GERDA sensitivity: dependence on Bkg

Assumed energy resolution:
\[ \Delta E = 4 \text{ keV} \]

Background reduction!
GERDA at underground laboratory
Gran-Sasso (Italy)
GERDA at underground laboratory Gran-Sasso (August 2007)

Bottom part of the GERDA
Erection of the cryostat
GERDA at underground laboratory
Gran-Sasso (6 March, 2008)
Construction of water tank
GERDA at underground laboratory
Gran-Sasso (18 July, 2008)

GERDA
building
construction
GERDA at underground laboratory
Gran-Sasso (18 July, 2008)

GERDA building construction
• 17.9 kg enriched (IGEX and HdM) and 15 kg non-enriched crystals (GENIUS-TF)
• All diodes were refurbished by Canberra
• Low-mass holder for each diode
• Storage underground during reprocessing (HADES), less than 1 week exposure above ground
• Storage at LNGS under vacuum in special transport container
GERDA Detector Lab (GDL) at Gran Sasso

- Glove box
- Lock
- Cryostat
Testing of naked detectors at LAr (Gran Sasso)

1) Definition of naked detector handling protocol

2) Long-term stability tests (3 HPGe detectors in LN2/LAr during 2 years):
   - Depletion voltage
   - I/V curve
   - Energy resolution

3) Problems reported from GENIUS-Test Facility* have been overcome by GERDA.
   No deterioration after > 1 year of operation at LAr!

GERDA phase II

- Sept 2005: 37.5 kg $^{76}\text{Ge}$ produced in Russia
  - ~87% $^{76}\text{Ge}$ enrichment, 0.015% of $^{70}\text{Ge}$ depletion
  - Chemical purity: 99.95 % or 4N
- 50 kg of $^{\text{dep}}\text{GeO}_2$ the same quality for testing
- Investigation of different options for the material purification and crystals pulling at PPM Pure Metals and the IKZ (Germany)
- Underground storage (HADES, Belgium and Langelsheim, Germany) until and during further processing steps (crystal pulling and detector fabrication)
- Development of true-axial segmented n-type or p-type point-like contact detector (BEGe detector)
Svetlana

Centrifuge hall

Collection of GeCl$_4$

Storage of samples
Rally Siberia – Munich is over: 
\(^{76}\text{GeO}_2\) is in MPI fuer Physik
Refurbishing of CZ crystall puller at IKZ

- Inductive heating with silver coils
- Molybdenum susceptor
- 4” and 6” ultra high purity crucible made of quartz
- System of pure forming gas (Ar + H₂)
Phase II 18-fold segmented n-type detector

Copper hold for Phase II:
31 g Cu 7 g Teflon

Low mass contacts (Cu on Kapton):
2.5 g Kapton cable (+ Cu)

First successful operation of segmented n-type HPGe detector in LN (during 5 months)
Phase II Broad-energy Ge-detector

- covers energy range 3 keV - 3 MeV
- enhanced efficiency for low-energy gammas
- low capacitance (⇒ low noise)

Specifications:
- depletion voltage 4000 V
- FWHM @ 122 keV 0.63 keV
- FWHM @ 1.33 MeV 1.8 keV
- mass 870 g
**BEGe vs. 18-fold segmented HPGe**

**Comparison of discrimination power for \(^{228}\text{Th}\) spectrum**

**BEGe point-contact**

Fractions remaining after PSA cut:
- DEP: 91.01% ± 0.62%
- 1.62 MeV: 13.20% ± 0.45%
- 2.61 MeV: 13.19% ± 0.06%
- ROI \(Q_{\beta\beta}\): 49.06% ± 0.40%

**18-fold segmented coax**

Fractions remaining after combined single-segment and PSA cut:
- DEP: 81.93% ± 2.22%
- 1.62 MeV: 18.98% ± 0.39%
- 2.61 MeV: 14.57% ± 0.31%
- ROI \(Q_{\beta\beta}\): 48.10% ± 1.12%

(PSA data without Compton background subtraction)

SSE/MSE discrimination with BEGe comparable to 18-fold segmented detector
Summary

- $0\nu 2\beta$ - decay is identified as one of the top priority topics in particle physics for the next 10–20 years.

- The experiments based on $^{76}$Ge diodes are the most promising ones for investigation of $0\nu 2\beta$ - process.

- The GERDA experiment is designed as the next-generation $0\nu 2\beta$ -decay $^{76}$Ge experiment with sensitivity:
  - $3 \times 10^{25}$ yr for Phase I
  - $1.5 \times 10^{26}$ yr for Phase II
  - the future world-wide ~ 1 t experiment $<m_{ee}> \sim 10$ meV.

- Commissioning of GERDA and start of the experiment in 2009.
Backup slides
June 2007: GERDA setup officially approved by LNGS
All Phase I detectors (8 pieces) refurbished & ready to use
Meanwhile: Detector prototype testing in LN2 ongoing
Cryostat has been mounted in March 2008 and successfully tested
Water tank construction has been completed in June 2008
Hydrostatic and fast draining tests will be done soon
Construction of lab building has been completed
Next: cleanroom and lock (~ till Spring 2009)
Muon Veto (Cherenkov and Plast Scintillators) – after WT testing
Filling with LAr and Commissioning of GERDA - Spring 2009
Commissioning of GERDA and start of the experiment in 2009
## Best results on $0\nu\beta\beta$ search

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$, yr</th>
<th>$&lt;m_\nu&gt;$, eV</th>
<th>$&lt;m_\nu&gt;$, eV</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>$&gt; 1.9 \times 10^{25}$</td>
<td>$&lt; 0.22-0.41$</td>
<td>$&lt; 0.69$</td>
<td>HM</td>
</tr>
<tr>
<td></td>
<td>$\approx 1.2 \times 10^{25}$ (?)</td>
<td>$\approx 0.28-0.52$ (?)</td>
<td>$\approx 0.87$ (?)</td>
<td>KK of HM</td>
</tr>
<tr>
<td></td>
<td>$\approx 2.2 \times 10^{25}$ (?)</td>
<td>$\approx 0.21-0.38$ (?)</td>
<td>$\approx 0.64$ (?)</td>
<td>KK of HM’06</td>
</tr>
<tr>
<td></td>
<td>$&gt; 1.6 \times 10^{25}$</td>
<td>$&lt;0.24-0.44$</td>
<td>$&lt; 0.75$</td>
<td>IGEX</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&gt; 3.1 \times 10^{24}$</td>
<td>$&lt; 0.34-0.57$</td>
<td>$&lt; 0.75$</td>
<td>CUORICINO</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$&gt; 5.8 \times 10^{23}$</td>
<td>$&lt; 0.81-1.28$</td>
<td>-</td>
<td>NEMO</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$&gt; 4.5 \times 10^{23}$</td>
<td>$&lt; 1.41-2.67$</td>
<td>$&lt; 2.2$</td>
<td>DAMA</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$&gt; 2.1 \times 10^{23}$</td>
<td>$&lt; 1.40-2.17$</td>
<td>$&lt; 3.4$</td>
<td>NEMO</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$&gt; 1.7 \times 10^{23}$</td>
<td>$&lt; 1.45-2.76$</td>
<td>$&lt; 1.8$</td>
<td>SOLOTVINO</td>
</tr>
</tbody>
</table>
Internal background reduction: segmented detector

Photon – β- particle discrimination

– ββ-signal: local energy deposition – single site event, SSE
– γ -background: several Compton scatterings – multi site event, MSE

Anti-coincidence between segments suppr. factor ~10
Puls shape analysis suppr. factor ~2
Pulse-shape analysis: BEG-detector

Typical SSE candidate

Typical MSE candidate

Raw preamplifier output:

After analog differentiation with TFA:

TFA parameters: 10 ns integration, 10 ns differentiation
Degenerate: can be tested

Inverted: can be tested by next generation of $2\beta$ experiments.

Normal: new approach is needed, with $m_{ee} \sim 10$ meV
Underground storage of depGeO2 in Langelsheim municipal mining museum

a) Reduction procedure
   depGeO2 → depGe
   Technical grade (99.8%)
   No isotope dilution effect was detected
   Yield = 98.5%

b) Three steps zone refinement
   depGe → depGe
   99.8% → 6N (ρ ≥ 50 Ohm*cm)
   $10^{13} \text{ cm}^{-3} → 10^{11} \text{ cm}^{-3}$
   Yield = 91%

Unrecoverable loss is 0.4%.
Total yield of 6N material was 88%
Total exposure of the material at sea level < 2-3 days/purification
Material characterization

- Resistivity measurements at RT, Ohm*cm

- Hall effect measurements at 77 K:
  - $|N_D - N_A| \sim 10^{11} \div 10^{13}$ cm$^{-3}$ (detector grade $\sim 10^{10}$ cm$^{-3}$)
  - Mobility at RT and 77K

- PTIS (Photo Thermal Ionization Spectroscopy) measurements
  - Identification of donors and acceptors

- Optical measurements:
  - Dislocation density ($\sim 10^2 - 10^4$ cm$^{-2}$)

- Photoluminescence measurement (Dresden):
  - Identification of donors and acceptors (As and P, no Al and B)
Liquid Argon scintillation

MC simulation: Background suppression for contaminations located in detector support:

Test facility MiniLArGe at MPIK
Low background test stand LArGe (Heidelberg, Gran Sasso)

**Cryostat:**
Inner diameter: 90 cm  
Volume: 1000 liter  
(under construction)

**PMT:** 9 x 8” ETL9357  
(delivered)

**Shield:**
- Cu: 15 cm  
- Pb: 10 cm  
- Steel: 23 cm  
- PE: 20 cm  
(in place)

**Lock:**
Construction completed

Can house up to 3 Phase 1 strings  
(9 Ge detectors)