The GERDA Neutrinoless double beta decay experiment

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Paul Scherrer Institut, Villingen, Switzerland
Outline

• Introduction:
  • 0-νββ and physics implications
  • Effective Majorana neutrino mass $<m>$
  • Predictions on $<m>$ from oscillation experiments
  • Sensitivity with and w/o backgrounds

• GERDA design
  • Concept
  • Sensitivities: Phase I, II, III
  • Locations at LNGS
  • Phase I detectors
  • Phase II detectors
  • Front-end electronics
  • Infrastructures: cryogenic tank, WT, clean room,..
  • Screening

• Examples of backgrounds and reduction techniques:
  • Detector segmentation
  • Liquid argon scintillation read out

• Conclusion/Outlook
$2\nu - \beta\beta$ Decay

Observed in more than 10 isotopes
Life times $10^{18} - 10^{21}$ years
Mass parabolas

Ground states of even-even nuclei: $0^+$
$0\nu-\beta\beta$ Decay

Not observed yet;
Life time limits $> 10^{24} – 10^{25}$ y;
Claim for evidence in Ge-76 by part of Heidelberg-Moscow Collab.

$0\nu\beta\beta$ can be generated by:
• exchange of light Majorana neutrinos
• SUSY
• ......

Schechter & Valle:
if $0\nu\beta\beta$ observed $\Rightarrow$ $\nu$ is Majorana particle!
Physics motivations

1) Dirac vs. Majorana particle: (i.e. its own anti-particle)?

\[ 0\nu\beta\beta \Rightarrow \text{Majorana nature} \]

\[ \text{Majorana} \Rightarrow \text{See-Saw mechanism} \]

\[ m_\nu = \frac{m_D^2}{M_R} << m_D \]

For \( m_3 \sim (\Delta m_{\text{atm}}^2)^{1/2} \), \( m_D \sim m_t \) \( \Rightarrow \)
\[ M_R \sim 10^{15}\text{GeV} \]

\[ \text{Majorana} \Rightarrow \text{CP violation in } M_R \rightarrow \text{higgs} + \text{lepton} \Rightarrow \text{Leptogenesis} \Rightarrow \text{B asymmetry} \]

2) Absolute mass scale:

Hierarchy: degenerate, inverted or normal

(effective) neutrino mass

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0ν-ββ Decay

\[(A, Z) \rightarrow (A, Z + 2) + e_1^- + e_2^-\]

Assume leading term is exchange of light Majorana neutrinos

\[T_{1/2} (0\nu)^{-1} = G \, M^2 \, m_{ee}^2\]

Phase space

Nuclear matrix element

Effective neutrino mass

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Effective Majorana mass

\[ m_{ee} = |\sum_i U_{ei}^2 m_i | \]

\( U_{ei} \) complex:
\( \Rightarrow \) sensitive to CP phases (optimist ☺)
\( \Rightarrow \) cancellation possible (pessimist)

NB: Beta-endpoint (Katrin)

\[ m_{\nu_e} = (\sum_i |U_{ei}|^2 m_i^2)^{1/2} \]

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If CP is conserved:

\[
\begin{align*}
    m_{\beta\beta} &= |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\lambda_{21}} m_2 + |U_{e3}|^2 e^{2i(\lambda_{31} - \delta)} m_3 \\
    &= |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3
\end{align*}
\]
$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\lambda_{21}} m_2 + |U_{e3}|^2 e^{2i(\lambda_{31}-\delta)} m_3$

$= |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3$

$\not\Rightarrow$: Destructive interference possible
\[ m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\lambda_{21}} m_2 + |U_{e3}|^2 e^{2i(\lambda_{31}-\delta)} m_3 \]

\[ = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 \]

Standard parametrization:

\[
\begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13} \\
    \ldots & \ldots & s_{23}c_{13}e^{i\delta} \\
    \ldots & \ldots & c_{23}c_{13}e^{i\delta}
\end{pmatrix}
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & e^{i\alpha_{21}/2} & 0 \\
    0 & 0 & e^{i\alpha_{31}/2}
\end{pmatrix}
\]
Experimental evidences for neutrino oscillations

- $\nu_e - \nu_{\mu,\tau}$; $\bar{\nu}_e - \bar{\nu}_x$
- Solar- and reactor-$\nu$'s:
  - $\Delta m^2_{\text{sol}} \approx 8 \cdot 10^{-5} \text{ eV}^2$
  - $\sin^2 2\theta_{12} \approx 0.8$
- Reactor-$\nu$'s:
  - $\nu_e - \nu_x$
  - $\sin^2 2\theta_{13} < 0.2$
- $\nu_{\mu} - \nu_{\tau}$
  - Atmospheric- and accelerator-$\nu$'s:
  - $\Delta m^2_{\text{atm}} \approx (2-4) \cdot 10^{-3} \text{ eV}^2$
  - $\sin^2 2\theta_{23} \approx 1$

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Input for $m_{ee}$ from $\nu$-oscillations

Solar/Reactor-$\nu$: $\theta_{12}$, $\Delta m^2_{sol}$  
Atmosph.-$\nu$: $\Delta m^2_{atm}$  
Reaktor-$\nu$: $\theta_{13}$

\[ m_{ee} = \left| \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right| \]

\[ \Rightarrow m_{ee} = f(m_1, \Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha, \beta) \]

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Predictions from oscillation experiments

F. Feruglio, A. Strumia, F. Vissani, NPB 659

Negligible errors from oscillations; width due to CP phases

90% CL
Claim for evidence for $\beta\beta(0\nu)$

(subgroup of Heidelberg-Moscow Collaboration)

Heidelberg-Moscow data:
• Nov 1990 - May 2003
• 71.7 kg year
• Bgd 0.11 / (kg y keV)

• 28.75 ± 6.87 events (bgd:~60)
• 4.2 sigma evidence for $0\nu\beta\beta$

• 0.69-4.18 $\times 10^{25}$ y (3 sigma)
• Best fit 1.19 $\times 10^{25}$ y

• $m_{ee} = 0.24$-0.58 eV
• best fit 0.44 eV

NB. Statistical significance depends on background model!

Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in $^{76}$Ge), for the period November 1990 – May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).
Experimental sensitivity: w/o background

\[ \tau = \frac{N_N}{N_S} \times T \]

 Experimental life time

- number of nuclides under control \( \propto M \)
- live time
- number of detected decays

Background free limit:
0 cnts in the analysis energy window \( \Rightarrow \) Poisson upper limit: \( N_P \)

Remember:
\[ \left[ T_{2}^{0v}(0^+ \rightarrow 0^+) \right]^{-1} = G^{0v}(E_0, Z) \left| M_{GT}^{0v} - \frac{g^2_{A}}{g^2_{V}} M_{F}^{0v} \right|^2 <m_v>^2 \]

\[ \tau \geq \frac{N_N}{N_P} \times T \propto M \times T \Rightarrow <m> \leq \frac{\text{const}}{(M \times T)^{1/2}} \]
Sensitivity: with background

If no decay is observed in presence of \( N_B \) background events in an energy window \( \Delta E \):

\[
N_S < \left( N_B \right)^{1/2} \quad \Rightarrow \quad \tau > \frac{N_N T}{\left( N_B \right)^{1/2}}
\]

\[
N_B = b M T \Delta E \quad \text{b: background index} \ [1/(\text{kg} \cdot \text{year} \cdot \text{keV})]
\]

\[
\Rightarrow \quad \tau > \frac{N_N T}{\left( b M T \Delta E \right)^{1/2}} \propto \left( \frac{M T}{b \Delta E} \right)^{1/2}
\]

\[
\Rightarrow \quad <m> \leq \text{const.} \cdot \left( \frac{b \Delta E}{M T} \right)^{1/4}
\]
### Comparison of DBD Isotopes

\[
T^{0\nu}_{1/2} = \frac{1}{\Gamma(Q_{\beta\beta}^5) \, M^2 \, \langle m_{ee}\rangle^2}
\]

\[
N_{\text{sig}} = N_{\text{Avg}} \cdot \frac{\text{mass} \cdot t}{A} \cdot \ln 2 \cdot \Gamma \cdot M^2 \cdot \langle m_{ee}\rangle^2
\]

<table>
<thead>
<tr>
<th>isotope</th>
<th>Q_{\beta\beta}</th>
<th>nat. abund.</th>
<th>rel. A</th>
<th>rel. \Gamma</th>
<th>rel. M^2</th>
<th>N_{\text{sig}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>2039 keV</td>
<td>7.4%</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2.4</td>
</tr>
<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>2995 keV</td>
<td>9.2%</td>
<td>0.93</td>
<td>4.4</td>
<td>0.71</td>
<td>7.0</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
<td>3034 keV</td>
<td>9.6%</td>
<td>0.76</td>
<td>7.2</td>
<td>0.23</td>
<td>3.0</td>
</tr>
<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>2529 keV</td>
<td>34%</td>
<td>0.58</td>
<td>6.9</td>
<td>0.33</td>
<td>3.2</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>2479 keV</td>
<td>8.9%</td>
<td>0.56</td>
<td>7.4</td>
<td>0.15</td>
<td>1.5</td>
</tr>
</tbody>
</table>

• **Introduction:**
  - $0\nu\beta\beta$ and physics implications
  - Effective Majorana neutrino mass $<m>$
  - Predictions on $<m>$ from oscillation experiments
  - Sensitivity with and w/o backgrounds
  - Claim of KK et al. (HdM Data)

• **GERDA design**
  - Concept
  - Sensitivities: Phase I, II, III
  - Locations at LNGS
  - Phase I detectors
  - Phase II detectors
  - Front-end electronics
  - Infrastructures: cryogenic tank, WT, clean room,..
  - Screening

• **Examples of backgrounds and reduction techniques:**
  - Muon veto
  - Detector segmentation
  - Liquid argon scintillation read out

• **Conclusion/Outlook**
Two new $^{76}$Ge Projects:

**GERDA**

- "Bare" enr Ge array in liquid argon (nitrogen)
- Shield: high-purity liquid Argon (N) / H$_2$O
- Phase I: ~18 kg (HdM/IGEX diodes)
- Phase II: add ~20 kg new enr. Detectors; total ~40 kg

- Array(s) of enr Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Staged approach based on 60 kg arrays (60/120/180 kg)

**Majorana**

Physics goals:
- degenerate mass range

Technology:
- study of bgds. and exp. techniques

List of institutions:

- INFN LNGS, Assergi, Italy
- JINR Dubna, Russia
- Institute for Reference Materials, Geel, Belgium
- MPIK, Heidelberg, Germany
- Univ. Köln, Germany
- Jagiellonian University, Krakow, Poland
- Univ. di Milano Bicocca e INFN. Milano, Italy
- INR, Moscow, Russia
- ITEP Physics, Moscow, Russia
- Kurchatov Institute, Moscow, Russia
- MPI Physik, München, Germany
- Univ. di Padova e INFN, Padova, Italy
- Univ. Tübingen, Germany

- ~80 physicists, 13 institutions, 5 countries
- approved Nov 2004 at LNGS
- Status: under construction

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Phases and Physics reach of GERDA

required for ‘background free’ exp. with $\Delta E \sim 3.3$ keV (FWHM): $O(10^{-3})$ $O(10^{-4})$ counts/(kg·y·keV)

**Background requirement for GERDA:**

$\Rightarrow$ Background reduction by factor $10^2 - 10^3$ required w.r. to precursor exps.

$\Rightarrow$ Degenerate mass scale $O(10^2 \text{ kg·y})$ $\Rightarrow$ Inverted mass scale $O(10^3 \text{ kg·y})$
Phases and Physics reach of GERDA

Phase I: 
Phase II: 
Phase III: 

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GERDA at LNGS

GERDA location: hall A of LNGS
GERDA design

- Clean room lock
- Water tank / buffer / muon veto
- Cryogenic vessel
- Liquid argon
- Ge Array
GERDA underground facilities at LNGS
Main Experimental Site

June '06

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Cryostat

- Vacuum insulated stainless steel cryostat with internal Cu liner (stainless steel factor ~100 more radioactive ($^{238}$U, $^{232}$Th) than Cu)

- Ø outer × height 4200 × 8900 [mm × mm]

- Inner vessel volume  70 [m$^3$]

- Empty vessel  25,000 [kg]

- Max. load inner vessel:
  - LAr  98,000 [kg]
  - Cu shield  20,000 [kg]
Infrastructure on Top of Platform

Clean room with lock on platform

Lock with tubes for cables

Rail system to lower position and lower individual strings
Phase I Detectors: Maintenance and Measurements in Underground detector laboratory (LArGe facility)

Since Nov. 2005: 17.9 kg of enriched Ge-detectors underground at LNGS; Characterization completed
Phase I Detectors:
Prototype tests of (natural) low-mass detector assembly in liquid nitrogen

Enriched detectors are currently re-processed and prepared for testing
Phase II Detectors: Procurement of enriched Ge

- Enrichment of 37.5 kg Ge-76 completed in Sep. 05
- Transportation of Material to Europe by truck in spring for further processing
- Specially designed protective steel container reduces activation by cosmic rays by factor 20

Test transportation March 05
Phase II Detectors:
“True-coaxial” natural detectors

- 6-fold-φ segmented p-type
- 18-fold (6-φ; 3-z) segmented n-type

60Co
Core signal: 2 keV FWHM

One segment signal: 3.5 keV FWHM
## Backgrounds in GERDA

<table>
<thead>
<tr>
<th>Source</th>
<th>B [$10^{-3}$ cts/(keV kg y)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ext. $\gamma$ from $^{208}$Tl ($^{232}$Th)</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Ext. neutrons</td>
<td>$&lt;0.05$</td>
</tr>
<tr>
<td>Ext. muons (veto)</td>
<td>$&lt;0.03$</td>
</tr>
<tr>
<td>Int. $^{68}$Ge ($t_{1/2} = 270$ d)</td>
<td>12</td>
</tr>
<tr>
<td>Int. $^{60}$Co ($t_{1/2} = 5.27$ y)</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{222}$Rn in LN/LAr</td>
<td>$&lt;0.2$</td>
</tr>
<tr>
<td>$^{208}$Tl, $^{238}$U in holder</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Surface contam.</td>
<td>$&lt;0.6$</td>
</tr>
</tbody>
</table>

Muon veto

180 days exposure after enrichment + 180 days underground storage

30 days exposure after crystal growing

derived from measurements and MC simulations

### Target for phase II:

$\Sigma B \leq 10^{-3}$ cts/(keV kg y)

$\Rightarrow$ additional bgd. reduction techniques
Background reduction techniques

- Muon veto
- Anti-coincidence between detectors
- Segmentation of readout (Phase II)
- Pulse shape analysis (Phase I+II)
- Coincidence in decay chain
- Scintillation light detection
Background reduction techniques

- Muon veto
- Anti-coincidence between detectors
- Segmentation of readout electrodes (Phase II)
- Pulse shape analysis (Phase I+II)
- Coincidence in decay chain (Ge-68)
- Scintillation light detection (LArGe)
Example: Internal $^{60}$Co

\[ \begin{align*}
\beta: & \quad E_{\text{max}} = 318 \text{ keV} \\
\gamma_1: & \quad 1.173 \text{ MeV} \\
\gamma_2: & \quad 1.332 \text{ MeV}
\end{align*} \]
Example of background topology

Energy deposition in surrounding medium

Multi-site energy deposition inside HP-Ge diode

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$^{60}$Co background spectrum

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$^{60}$Co: suppression by segmentation

MC simulation

counts/keV

energy (MeV)

$Q_{\beta\beta}$
$^{60}$Co: suppression by segmentation

MC simulation

$N_{\text{hit}} = 3$

$N_{\text{seg}} = 1$

$\sim 10$ (7 seg.)

Illustration: Simple 7-fold segmentation
MaGe: $^{60}$Co suppression by segmentation and anti-coincidence

Number of crystals

- Probability per decay to deposit energy within $Q_{\beta\beta}$
- ROI per 1 keV energy bin after combined cuts: (18-fold segm.)
  - $P = 4.7 \times 10^{-6}$/keV
  - (factor ~35 reduction w/r to single unseg. detector)

Number of segments

- $N_{\text{crystals}} = 1$
- $N_{\text{segments}} = 1$

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Phase II detectors
1.6 kg 18-fold segmented true-coaxial n-type

Goal:
• Study of $\gamma$ identification and suppression factors at $Q_{\beta\beta}$: 2 - 100 depending on source location
Th suppression by LAr Ge-anticoinc: (20 cm diameter prototype setup)

1 ton liquid argon detector under construction

Suppression limited by size of Dewar (20 cm Ø)

Compton continuum RoI: 95 % suppr. by LAr veto
$^{60}\text{Co}: \text{segmentation and LAr Ge-anticoinc}$

MC simulation

\[ N_{\text{seg}} = 1 \]

AND

LAr anticoinc

$\sim 1000$
Off-spin of GERDA LAr R&D for DM search
Pulse shape discrimination studies

Data with AmBe n/$\gamma$ source

Liquid Argon for DM Search (WARP, ArDM, CLEAN)

Discrimination of Ar-39 background?

20 kg active LAr target

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Summary & Outlook

• GERDA: probe Majorana nature of neutrino with sensitivity down to inverse mass hierarchy scale

  phase I: background 0.01 cts/\,(kg\cdot\text{keV}\cdot y)
  ▶ scrutinize KKDC result within 1 year

  phase II: background 0.001 cts/\,(kg\cdot\text{keV}\cdot y)
  ▶ $T_{1/2} > 2 \cdot 10^{26} \text{ y}$, $<m_{ee}> < 0.09 – 0.29 \text{ eV}$

  phase III: world wide collaboration
  ▶ $T_{1/2} > 10^{28} \text{ y}$, $<m_{ee}> \sim 10 \text{ meV}$

• 2007: Experimental installations (Cryotank, water tank, building etc.)
• 2008: target for detector readiness
GERDA collaboration