The GERDA Experiment: Search for the Neutrinoless Double Beta Decay

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Contents

1. Introduction

- Neutrinoless double beta decay
- Detection signature
- Consequences of discovery

2. The GERDA Experiment

- Set-up and detection method
- Background reduction techniques
- Results

3. Upgrade and Future

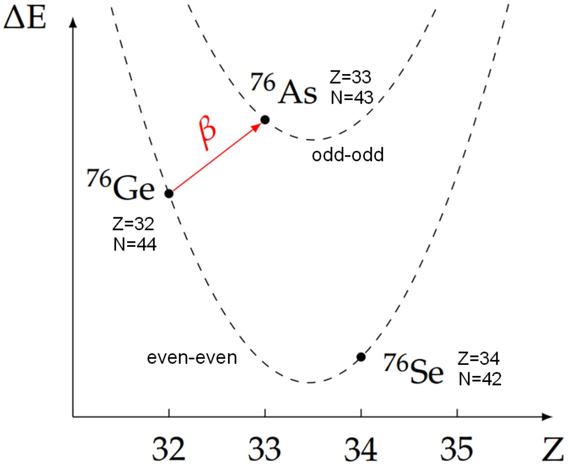
- Upgrade details
- Future of the experiment

4. Conclusion and Outlook

Ettore Majorana

Decay channels of ^{76}Ge:

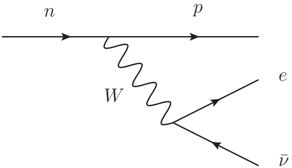
- Beta decay β^- to ^{76}As energetically forbidden.



Beta decay β^-

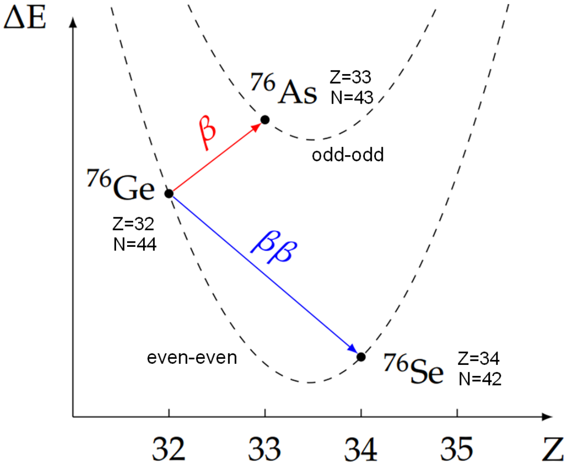
- Neutron decays to

$$\Rightarrow \begin{cases} \text{proton} \\ \text{electron} \\ \text{antineutrino} \end{cases}$$



Decay channels of ^{76}Ge:

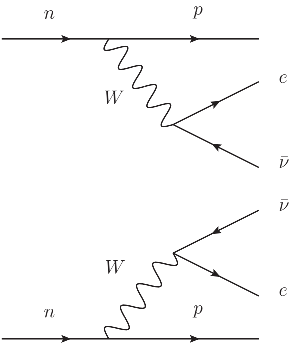
- Double beta decay $\beta\beta$ to ^{76}Se allowed.



Double beta decay $\beta\beta$

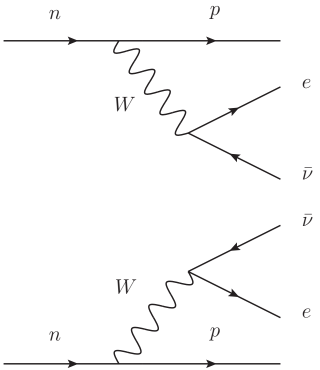
- 2 neutrons decay to

$$\Rightarrow \begin{cases} \text{2 protons} \\ \text{2 electrons} \\ \text{2 antineutrinos} \end{cases}$$



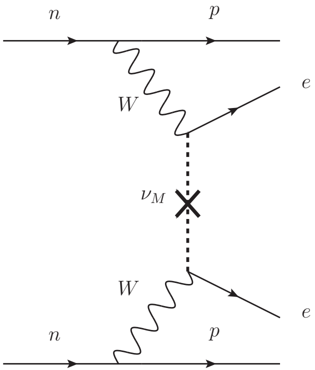
Double beta decay $2\nu\beta\beta$:

- **Rarest** observed decay.
- Possible for Dirac and Majorana neutrinos, SM ΔL=0.
- **2 neutrinos** in the final state.



Neutrinoless double beta decay $0\nu\beta\beta$:

- **Postulated** decay channel.
- Involved Majorana neutrinos **annihilate**, non-SM ΔL=2.
- **0 neutrinos** in the final state.



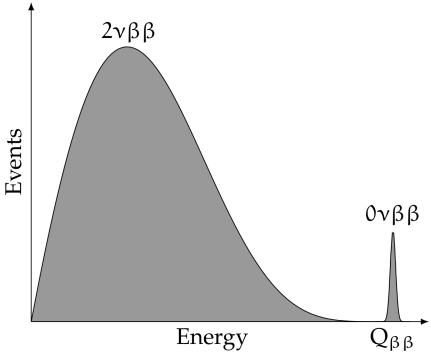
Summed **energy spectrum** of final state electrons:

Double beta decay $2\nu\beta\beta$:

- Continuum

Neutrinoless double beta decay $0\nu\beta\beta$:

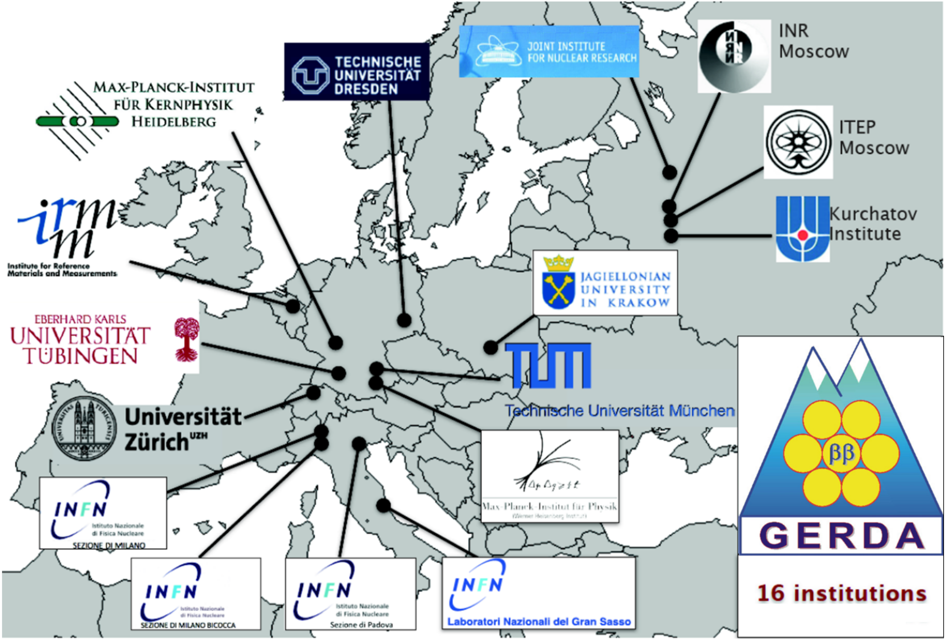
- Peak at $Q_{\beta\beta}$= 2039 keV



(peak not to scale)

Consequences of discovery:

- Neutrinos have Majorana mass component.
- Rate of decay clue on absolute neutrino mass and hierarchy.
- Violation of lepton number conservation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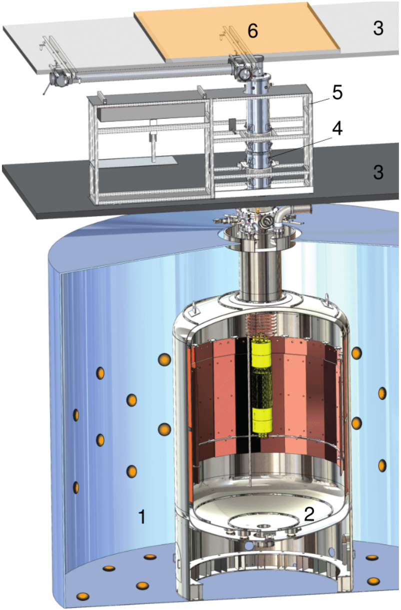
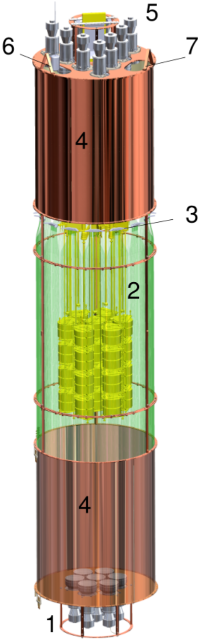
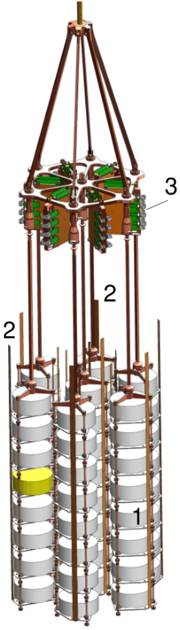
INFN Laboratori Nazionali del Gran Sasso
ββ
GERDA
16 institutions

- **Germanium Detector Array** searches for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{76}Ge.
- Ge detectors enriched to >86% in ^{76}Ge immersed in liquid argon act simultaneously as **detector** and **source** material.
- Located underground Laboratori Nazionali del Gran Sasso (LNGS) with 3400 mwe shielding.
- Surrounded by water tank with photomultipliers (**PMTs**) to detect Cherenkov light induced by muons.

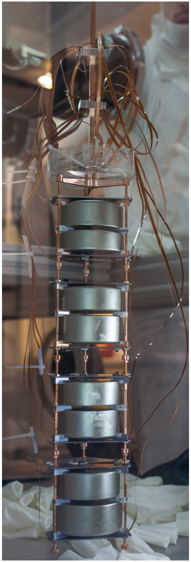


1 Water tank
2 Cryostat
3–5 Clean room & Lock system
6 Plastic scintillator



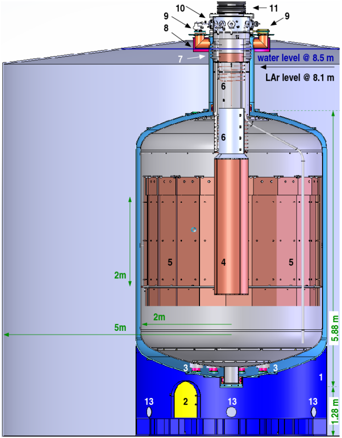


- Cryostat filled with **liquid argon** (LAr) for cooling and shielding.
- PMTs and silicon photomultipliers (connected to optical fibre shroud) detect induced **LAr scintillation light** to veto background events.
- **36 kg** enriched Ge detectors arranged on 7 strings and directly submerged in LAr.



Rare decay measurement requires low background.

- Operation of the experiment **underground**.
- Background suppression with **water** and **LAr shielding**.
- **Active veto** for cosmic muons and external radiation.
- **Minimise** radioactivity of materials close to detectors.
- Detector anti-coincidence.
- **Pulse Shape Discrimination (PSD).**



Background limited scenario:

$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

$M \cdot t$: exposure, ΔE: energy resolution, BI: background index.

Zero background regime:

$$T^{0\nu}_{1/2} \propto M \cdot t$$

- Goal: Achieve **zero background regime** to enable proportional scaling with exposure.

June 2016

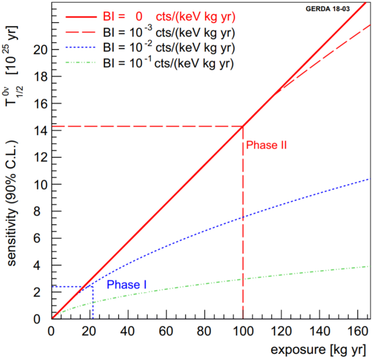
- Exposure: 10.8 kg·yr.
- Published in **Nature 554 (2017)**.

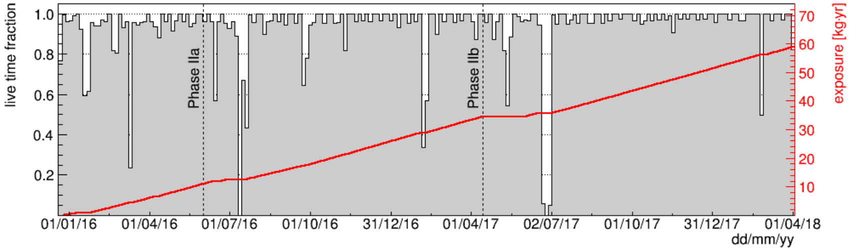
June 2017

- Exposure: 23.2 kg·yr.
- Published in **PRL 120 (2018)**.

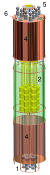
June 2018

- Exposure: **58.9 kg·yr**.
- Going to be published in **Science**.

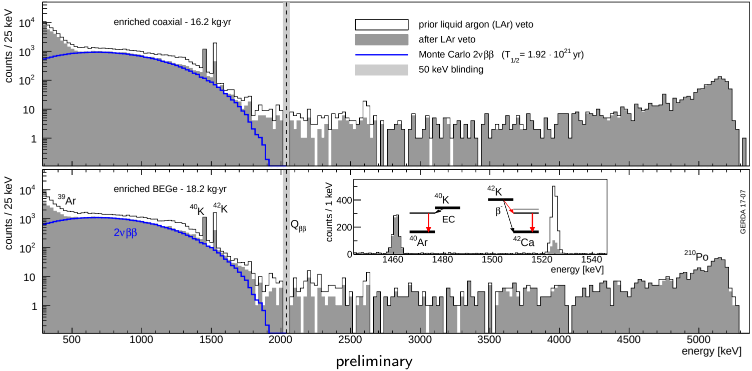




Suppression and Acceptance



- For ^{228}Th calibration source: Suppression factor of (98 ± 4). Depends on event type.
- In calibration and physics data: ^{40}K/^{42}K Compton continuum strongly **suppressed**.
- Acceptance: $(97.7 \pm 0.1)\%$.

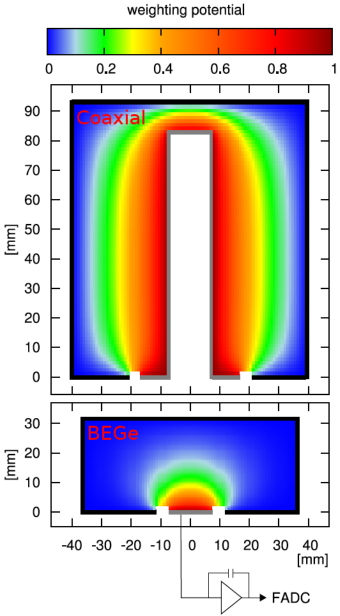


Semi-coaxial Ge detectors (Coax)

- 7 enriched Coax detectors.
- 3 non-enriched natural Coax detectors.
- Total enriched Coax mass: 15.6 kg

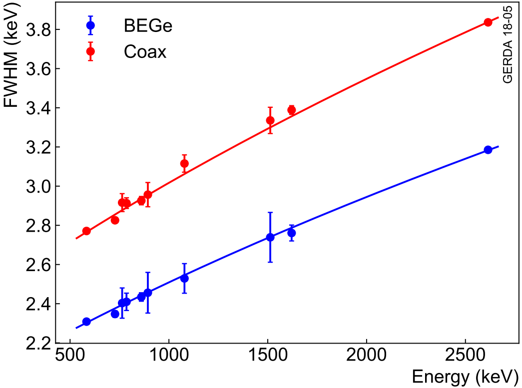
Broad Energy Ge detectors (BEGe)

- 30 enriched BEGes.
- Total enriched BEGe mass: 20.0 kg.
- Superior resolution and Pulse Shape Discrimination (**PSD**) compared to Coax.



Calibration Procedure

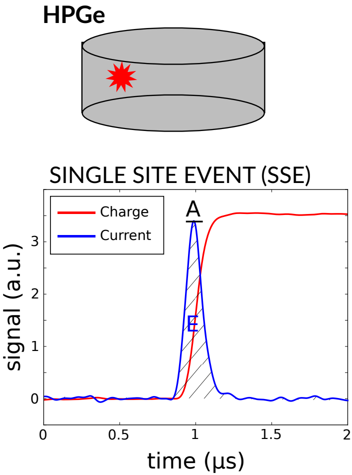
- Weekly ^{228}Th calibrations.
- Comparison of known peaks in data.

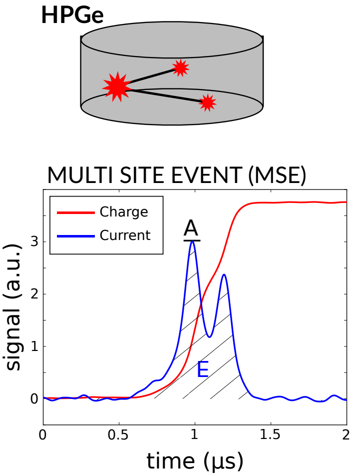


FWHM resolution curves

- BEGe: 3.0 ± 0.1 keV at $Q_{\beta\beta}$.
- Coaxial: 3.6 ± 0.1 keV at $Q_{\beta\beta}$.

- Pulse Shape differences: **Single** location ($0\nu\beta\beta$) and **multiple** location (γ).





- **PSD**: Select target signal (SSE), reject background (MSE) through pulse shape.
- For BEGes based on Current Amplitude (A) to Energy (E) ratio: **A/E**.

PSD rejection at work

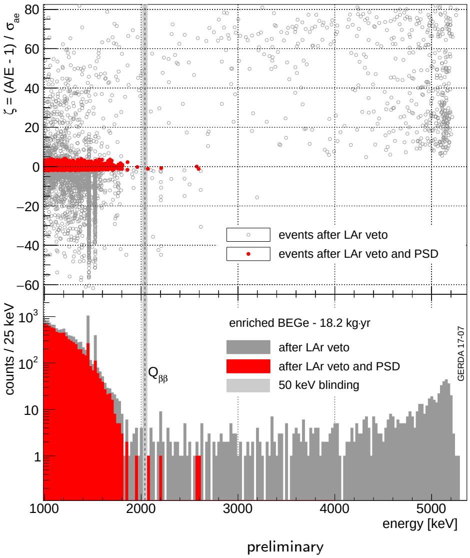
- ^{42}**K** and ^{40}**K** lines and other **MSE** due to low A/E value.
- High energy α **events** with high A/E.

Estimated $0\nu\beta\beta$ signal **efficiency**

- BEGe: $(87.5 \pm 2.6)\%$
- Coax (with artificial neural network): $(84 \pm 5.0)\%$

Background prediction before unblinding

- Events with energy $Q_{\beta\beta} \pm 25$ keV hidden until all analysis cuts frozen.
- Projected flat background around $Q_{\beta\beta}$.

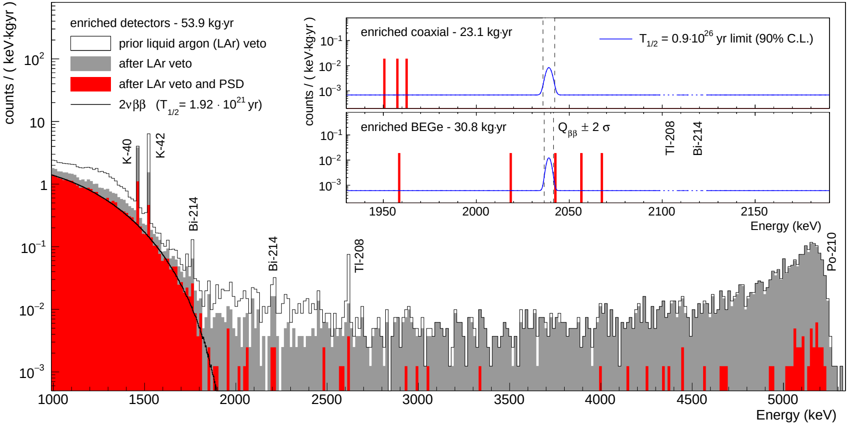


Background

- Prominent: $2\nu\beta\beta$, ^{42}K & ^{40}K lines, α.
- **BEGe BI** at $Q_{\beta\beta}$: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$cts/(keV·kg·yr)
- **Coax BI** at $Q_{\beta\beta}$: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$cts/(keV·kg·yr)

Unblinding

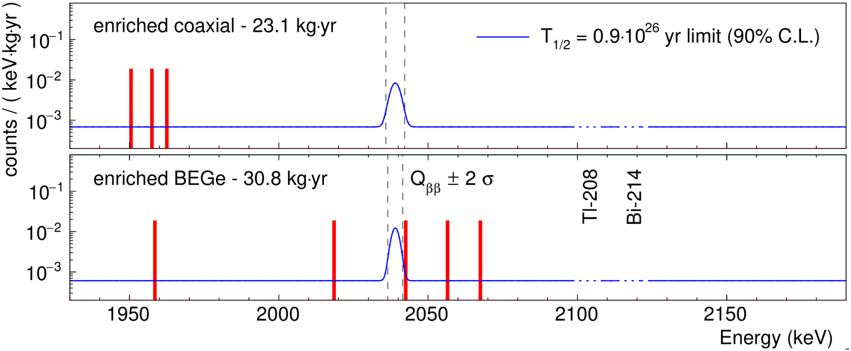
- **One** new event.
- Located in region of interest.
- Energy: **2042 keV**.



preliminary

Signal or background?

- Energy 2042 keV $\iff$ **2.4**σ from $Q_{\beta\beta}$.



Bayesian Analysis

- Sensitivity for limit setting: $0.82 \cdot 10^{26}$ yr (90% C.I.).
- **Background only** as best fit.
- $T^{0\nu}_{1/2} > 0.76 \cdot 10^{26}$ yr (90% C.I.).

Frequentist Analysis

- Sensitivity for limit setting: $1.08 \cdot 10^{26}$ yr (90% C.L.).
- **No signal** as best fit.
- $T^{0\nu}_{1/2} > 0.91 \cdot 10^{26}$ yr (90% C.L.).

Duration

- Started in April and finished in May.

Upgrade Works

- **9.5 kg** of new enriched inverted coaxial detectors.
- New fiber curtain with factor 2 increase in light yield.
- Lower activity HV and signal cables.
- JFET exchange and holder modification.

GERDA Timeline and LEGEND

Experiment	Active Mass [kg]	BI [counts/(keV·kg·yr)]	$T_{1/2}^{0\nu}$ Sensitivity [yr]
GERDA (current)	36	10^{-3}	$1.08 \cdot 10^{26}$
LEGEND-200 (projected)	200	10^{-4}	$\approx 10^{27}$
LEGEND (projected)	1000	10^{-5}	$\approx 10^{28}$

Legend

- New collaboration with Majorana and institutions based all over the world.
- Based on Gerda approach with LAr cryostat.
- First stage with 200 kg at LNGS.
- Ultimate goal to reach **1 t** of Ge detectors.

GERDA results:

- Collection of 58.9 kg·yr exposure with zero background experiment.
- Limit on the ^{76}Ge $0\nu\beta\beta$ decay half life: $T^{0\nu}_{1/2} > 0.91 \cdot 10^{26}$ yr (90% C.L.)
- World's best sensitivity: $T^{0\nu}_{1/2} > 1.08 \cdot 10^{26}$ yr (90% C.L.)

GERDA Outlook

- Faster exposure collection with new detectors.
- Lower background with better LAr veto.

LEGEND Outlook

- Worldwide collaboration to ultimately build 1 t Ge detector experiment.