

Searching for ⁷⁶Ge neutrinoless double-beta decay with GERDA and beyond

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The GERmanium Detector Array (GERDA) experiment at the Laboratori Nazionali del Gran Sasso (LNGS, Italy) searched for the lepton-number-violating neutrinoless double-beta ($0\nu 2\beta$) decay of ⁷⁶Ge. The potential discovery of such phenomenon would have significant implications in cosmology and particle physics, helping unrevealing the Majorana nature of neutrinos. In 2019, a lower bound on the half-life of $0\nu 2\beta$ decay in ⁷⁶Ge was set at $T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L.), which coincides with the median expectation under the no signal hypothesis. The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay (LEGEND) project is optimized for discovering $0\nu 2\beta$ and it will explore new energy frontiers beyond the inverted ordering scenario.



CTORS AND ENERGY SPECTRUM AFTER HIGH-LEVEL CUTS

Why Germanium?

- Enrichment procedure is established and allowed in ample quantities for ⁷⁶Ge isotope
- Source = detector \rightarrow high detection efficiency
- Best energy resolution among any $\beta\beta$ detector $\rightarrow 0.1\%$ FWHM @ $Q_{\beta\beta}$
- Pure Ge detectors \rightarrow low intrinsic background
- GERDA operated in a regime where the half-life $T_{1/2}$ scales almost linearly with the exposure

 $\varepsilon \cdot f \cdot M \cdot t_{run}$ without background

E: efficiency *f*: abundance of isotope

GERDA was an experiment dedicated to the search for the ⁷⁶*Ge* neutrinoless double beta decay ($0\nu 2\beta$) expected at $Q_{\beta\beta} = 2039.06 \ keV.$ [1]

- GERDA was located at LNGS-Hall A at a depth of **3500** *m.w.e*.
- Ge detectors enriched in ⁷⁶Ge (~87%) deployed in LAr \rightarrow 3 detector types: coaxial (large), Broad Energy Germanium (performant, but small), inverted coaxial (performant and large)
- LAr instrumented with PMTs + wavelength-shifting fibers + SiPMs for vetoing photons $\rightarrow \epsilon_{LAr} \sim 97.5\%$
- Ultra-pure water tank + 66 PMTs + top-plastic scintillators for Cherenkov vetoing external μ (flux~1.25/ $(m^2 \cdot h)$, neutrons and photons \rightarrow veto efficiency $\varepsilon_{\mu} \sim 99.9\%$



NEUTRINOLESS DOUBLE-BETA DECAY

 $(A, Z) \rightarrow (A, Z + 2) + 2e^{-2}$

• $2\nu 2\beta$ is a 2nd order weak process allowed in SM and already measured, e.g. $T_{1/2}^{2\nu}({}^{76}Ge) = (1.926 \pm 0.094) \times 10^{21} \text{ yr}$ • $0\nu 2\beta$ is a lepton number violating process $(\Delta L = 2)$ forbidden in SM. The phenomenon requires neutrinos to be Majorana particles, i.e. $v = \overline{v}$. This could be an explanation for the smallness of ν mass (see-saw mechanism) [2] • Experiments measure the total energy of the two emitted e^- expected at $Q_{\beta\beta}$ (peak-like signature)



• Analysis cuts to remove events with slow/incomplete charge collection + LAr/muon vetoes + active **background suppression based on event topology** to further reduce the background [6] • $0\nu 2\beta$ events deposit energy within a small value, ~1 mm³ (single-site event, SSE); background events deposit energy at several locations separated by a few cm in the detector (multi-site event, MSE). Energy depositions from α/β decays near or at the detector surface lead to peculiar pulse shapes as well

> • For BEGe and IC detectors, pulse shape discrimination (PSD) of detector signals is performed by looking at the shape of current pulses. Coaxials require an **artificial neural network** + **risetime cut** to discriminate MSEs from SSEs • The granularity of the array allows for identifying and discarding events with energy depositions in multiple detectors (e.g. $\gamma\gamma$, $\alpha\gamma$ or $\beta\gamma$)



∕● ⁷⁶Kr

 $^{76}\mathrm{Br} \bullet$



 $\left(T_{1/2}^{0\nu}\right)^{2}$ $G^{1} = G^{0\nu}(Q_{\beta\beta},Z)|M^{0\nu}$ m_e $m_{ee} = \left|\sum_i U_{\rho i}^2 m_i\right|$

effective neutrino mass



(Majorana-Demonstrator) and GERDA experiments



LEGEND inverted-coaxial point-contact (ICPC) detector [5]

• Same **excellent energy resolution** and **PSD** power of point-contact detectors used in GERDA/MJD • **Higher mass** (> 2 kg) than previous point-contact detectors (~0.7-0.9 kg) • Already **succefully used in GERDA** for 18 months

LEGEND-200

- LEGEND-200 is under commission; it uses the GERDA infrastructure (cryostat, clean room, water plan, ...)
- Reach 200 kg: 35 kg from GERDA + 30 kg from MJD +140 kg (new)
- New elements: part of the enriched Ge detectors, cables, LAr veto, FE electronics, DAQ
- Reduction of the BI of a factor 5 with respect to GERDA Phase II goal

LEGEND-1000

- 1000 kg of Ge in 4 re-entrant tubes containing underground LAr to reduce ⁴²K from ⁴²Ar
- Background reduction of a factor 20 with respect to LEGEND-200
- Location to be defined: SNOLAB (6010 m.w.e.) or LNGS. CD-0 approved by the U.S. DOE



RESULTS OF GERDA ON THE SEARCH FOR $0\nu 2\beta$

- In the analyzed window (1930-2190 keV), the signal $S = 1/T_{1/2}$ is modelled with a Gaussian distribution centred at $\mathbf{Q}_{\boldsymbol{\beta}\boldsymbol{\beta}}$ (σ corresponding to the energy resolution) while the **background** *B* with a **flat distribution**.
- Data of each detector are divided into **partitions** (i.e. periods of time in which all parameters are stable). Background index is assumed equal for all detectors. Each partition k has its own energy resolution (σ_k), efficiency (ϵ_k), exposure (ϵ_k). Phase I datasets are included as individual partitions with independent *B* indices.
- Applied frequentist/Bayesian analysis were based on an unbinned extended likelihood function.
- Likelihood function is given by the product of likelihoods of each partition, weighted with a Poisson term:

$$\mathcal{L} = \prod_{k} \left[\frac{\left(\mu_{s,k} + \mu_{b,k} \right)^{N_{k}} e^{-\left(\mu_{s,k} + \mu_{b,k}\right)}}{N_{k}!} \times \prod_{i=1}^{N_{k}} \frac{1}{\mu_{s,k} + \mu_{b,k}} \times \left(\frac{\mu_{b,k}}{\Delta E} + \frac{\mu_{s,k}}{\sqrt{2\pi}\sigma_{k}} e^{-\frac{\left(E_{i} - Q_{\beta\beta}\right)^{2}}{2\sigma_{k}^{2}}} \right) \right]$$

$$\mu_{s,k} = \frac{\ln(2N_A)}{m_{76}} \epsilon_k \varepsilon_k S \text{ expected signal}$$

$$\mu_{B,k} = B \times \Delta E \times \varepsilon_k \text{ expected background } (\Delta E = 240 \text{ keV})$$

10⁻¹ kg yr) Background best fit and 68% C.L. interval 90% C.L. $T_{1/2}$ lower limit (1.8 × 10²⁶ yr) $> 10^{-2}$

 $0\nu 2\beta$ analysis in 1930-2190 keV excluded two regions containing two known γ peaks: $2104 \pm 5 \text{ keV}$ $2119 \pm 5 \text{ keV}$



- The combination of Phase I and Phase II data led to a total exposure of 127.2 kg yr
- The **background-free regime** results in a nearly linear improvement of sensitivity vs exposure
- The combined analysis of Phase I and II provides the following half-life and effective neutrino mass limits under the null signal hypothesis: [3] $T_{1/2}^{0\nu} > 1.4 \cdot 10^{26} \text{ yr} @ 90\% \text{ C. I.}$
 - $T_{1/2}^{0\nu} > 1.8 \cdot 10^{26} \text{ yr} @ 90\% \text{ C. L.}$ $m_{ee} < 79 - 180 \text{ meV} @ 90\% \text{ C. L.}$

References

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