Final results of GERDA on the search for neutrinoless double beta decay

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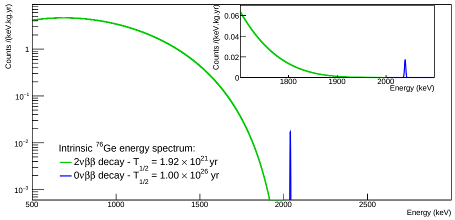
Signature and implications

$2\nu\beta\beta$ decay in ^{76}Ge:

- $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2\text{e}^- + 2\bar{\nu}_e$
- continuous, broad spectrum

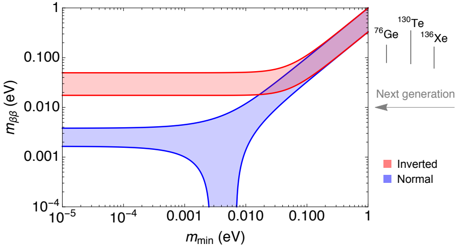
$0\nu\beta\beta$ decay in ^{76}Ge:

- $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2\text{e}^-$
- peak at $Q_{\beta\beta} = 2039$ keV



Physics implications:

- nature of neutrinos (Dirac vs Majorana)
- neutrino mass scale & ordering (normal vs inverted)
- violation of lepton number conservation
- matter-antimatter asymmetry in the Universe



Probing the Majorana mass

Majorana mass sensitivity:

$$|m_{\beta\beta}| \propto \frac{m_e}{\sqrt{\mathcal{M}^2\ \mathcal{G}\ T_{1/2}}}$$

- Majorana mass definition $|m_{\beta\beta}| = \left|\sum_i U_{ei}^2 m_i\right|$
- nuclear matrix element $\mathcal{M}$
- phase space factor $\mathcal{G}$
- half-life of $0\nu\beta\beta$ $T_{1/2}$

Half-life sensitivity
non background-free vs background-free:

$$T_{1/2} \propto f\epsilon\sqrt{\frac{Mt}{B\ \sigma_E}} \quad \text{vs} \quad T_{1/2} \propto f\epsilon Mt$$

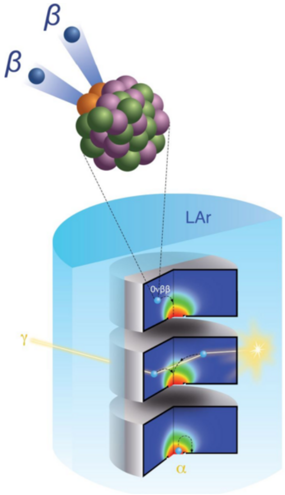
- enrichment fraction f
- efficiency ϵ
- mass M
- measurement time t
- background index B
- energy resolution σ_E at $Q_{\beta\beta}$

→ low background level & good energy resolution crucial

GERDA approach

Science 365, 1445 (2019)

- $0\nu\beta\beta$ source = detector, high detection efficiency
- operate high-purity Ge (HPGe) detectors,
  semiconductors, bandgap $\mathcal{O}$(1eV),
  high energy resolution,
  no measurable internal background contamination,
  allow for event pulse shape discrimination (PSD)
- liquid argon (LAr) serves as coolant, shield & active veto

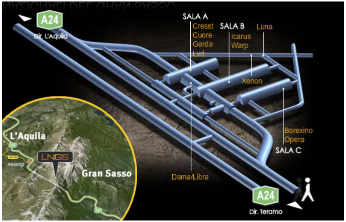


GERDA infrastructure

Eur. Phys. J. C 78 388 (2018)

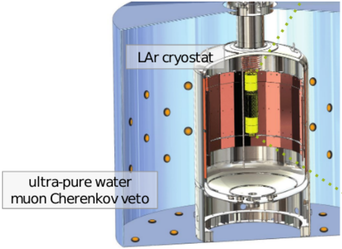
Underground site:

- Laboratori Nazionali del Gran Sasso (LNGS), Italy
- 1400m rock overburden (3500 mwe), cosmic muon reduction $\mathcal{O}(10^6)$



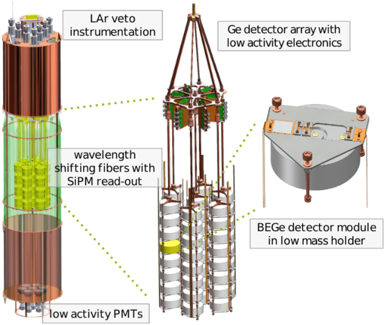
Experimental setup:

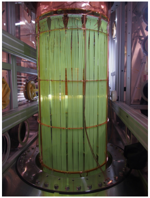
- water tank equipped with PMTs
- cryostat filled with LAr
- detector array surrounded by LAr veto instrumentation



Detector operation

- up to 41 detectors enriched in ^{76}Ge (up to 87% enrichment)
- 6 to 7 strings, covered by nylon cylinders
- surrounded by fibers coated with the wavelength-shifter TPB (tetraphenyl butadiene)

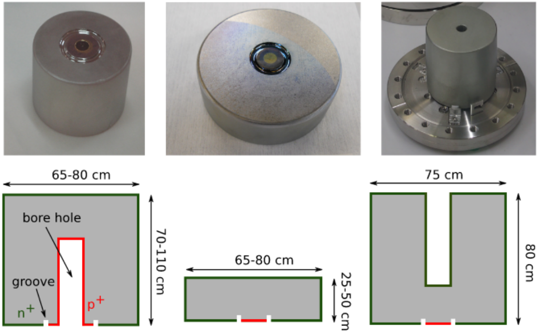




Detector types

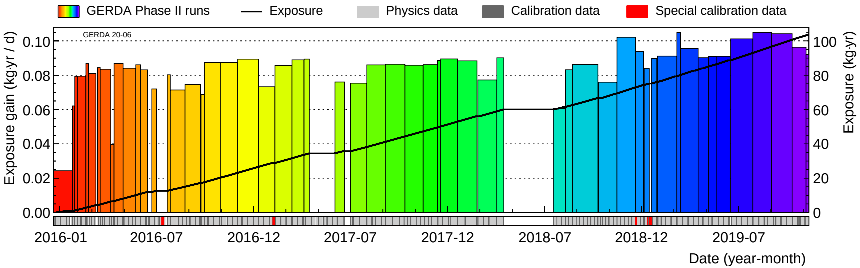
Eur. Phys. J. C. 79 11 978 (2019)
Eur. Phys. J. C, 81 6 505 (2021)

- coaxial shaped (Coax): 1 to 3 kg weight
- broad energy germanium (BEGe): ∼ 0.7 kg weight, superior resolution & PSD
- inverted coaxial (IC): combine ∼ 2 kg weight, superior resolution & PSD



Data taking

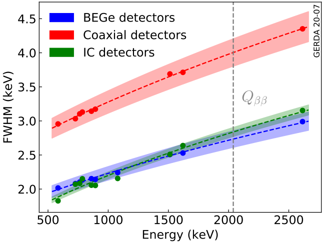
- 2011-2013: Phase I, 23.5 kg yr exposure
- 2015-2019: Phase II, 103.7 kg yr exposure, installation of LAr veto, upgrade with IC detectors in 2018, operation in background-free regime

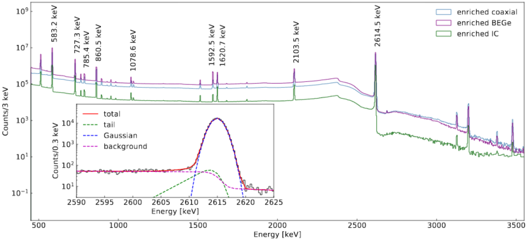


Calibration

arXiv:2103.13777, to be published in Eur. Phys. J. C

- weekly calibrations with 3 ^{228}Th sources
- use γ lines of known energy to convert ADC to keV
- peak fitting algorithm to determine each detector's resolution
- Gaussian mixture models to determine resolutions per detector type





→ GERDA achieved energy resolutions (FWHM) of $\sim 0.15\ \%$ at $Q_{\beta\beta}$

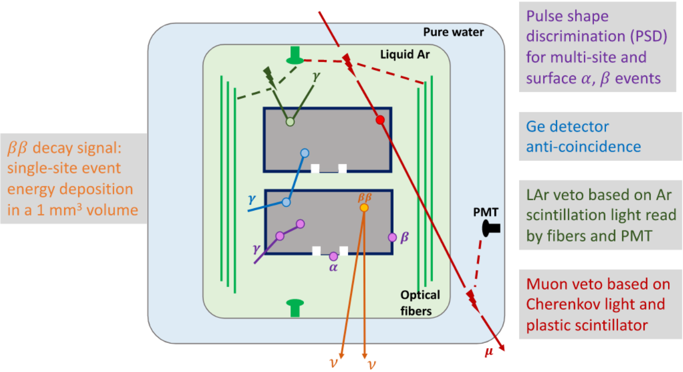
Background reduction

Analysis cuts:

- PSD
- multiplicity/ coincidence
- LAr veto
- muon veto

Signal efficiencies after cuts:

- Coax 46%
- BEGe 61%
- IC 66%

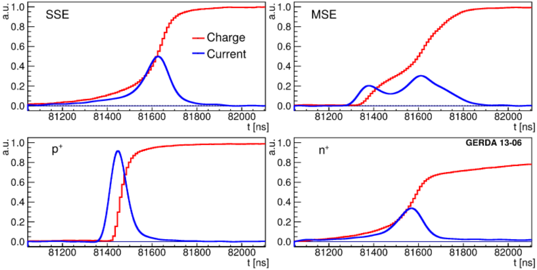


→ ∼ 60 % signal detection efficiency after all background cuts

Pulse shape discrimination

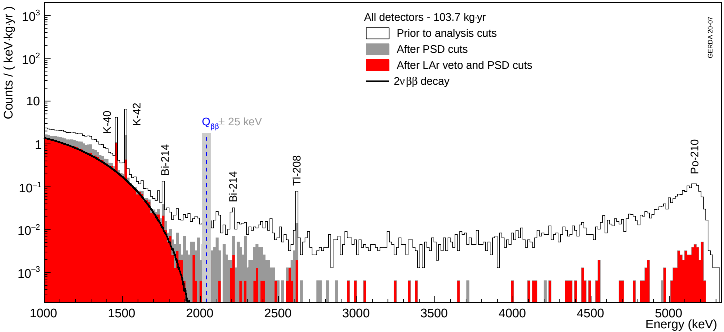
Eur. Phys. J. C 73 2583 (2013)

- single-site events: signal-like
- multi-site events: induce double-peak structure
- surface α events: fast risetime, high current
- surface β events: incomplete charge collection
- rejection based on current amplitude over energy (A/E) for BEGe, IC, & on artificial neural network comparing pulse shape for Coax



Blinded analysis

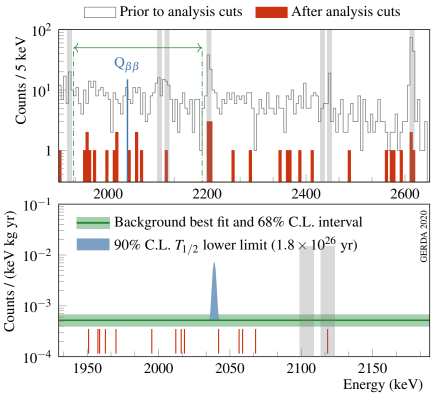
- ± 25 keV around $Q_{\beta\beta}$ blinded
- spectrum well understood: $\lesssim 0.5$ MeV: ^{39}Ar, ~ 0.5 - 2 MeV: $2\nu\beta\beta$, $\gtrsim 4$ MeV: α
- flat background in $0\nu\beta\beta$ signal region



Final results

PRL 125, 252502 (2020)

- unbinned maximum likelihood fit of 13 events in region-of-interest
- combined fit of Gaussian signal & uniform background
- best limit on $T_{1/2}$ in the field
- lowest background level in the field: $B = 5.2 \times 10^{-4}$ cts / keV / kg / yr



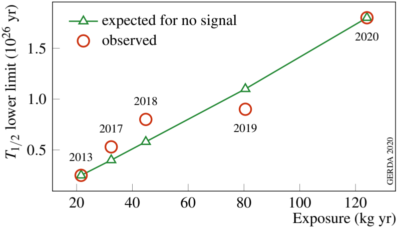
$$T_{1/2} > 1.8 \times 10^{26} \text{ yr (90\% C.L.)} \rightarrow |m_{\beta\beta}| \lesssim 79 - 180 \text{ meV}$$

Summary

GERDA employed an array of HPGe detectors enriched in ^{76}Ge to search for $0\nu\beta\beta$

Due to an excellent energy resolution & the lowest background level in the field, the linear increase of sensitivity with exposure in the background-free regime was measured

A stringent constraint of $T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L.) was set, implying $|m_{\beta\beta}| \lesssim 79 - 180$ meV



Backup: moving forward

LEGEND:

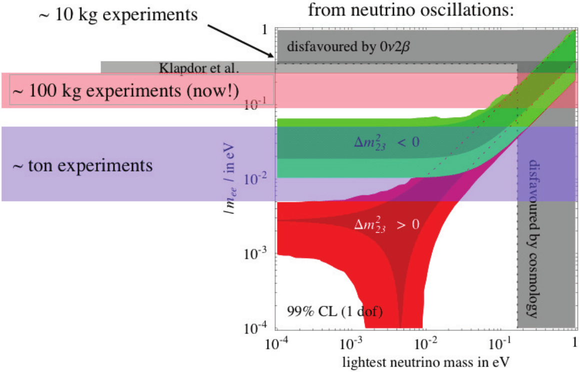
- merger of GERDA & MAJORANA DEMONSTRATOR & new groups
- LEGEND-200 currently under construction, using the existing GERDA infrastructure, discovery sensitivity $T_{1/2} \gtrsim 10^{27}$ yr, start of data taking end of 2021
- LEGEND-1000 will reach discovery sensitivity $T_{1/2} \gtrsim 10^{28}$ yr

Other new physics searches with GERDA:

- bosonic dark matter (Axion-like particles & dark photons)
- majoron emission & light exotic fermions
- nucleon decays
- neutrinoless double electron capture in ^{36}Ar

Backup: sensitivity to neutrino mass hierarchy

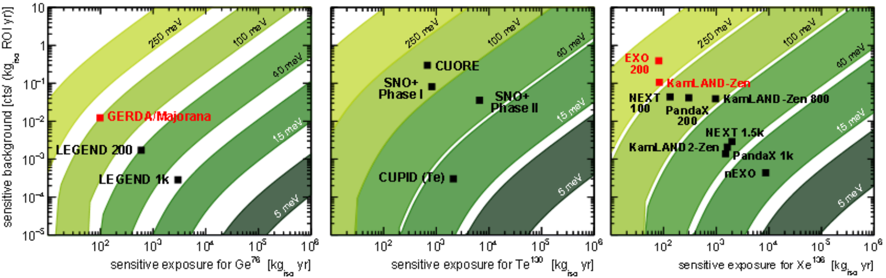
Constraints on the two neutrino mass ordering regimes:



Pocar, Physics Procedia 37:6-15 (2012)

Backup: comparison of experiments

Comparison of rough sensitivity between ongoing & planned experiments (marked: 5 yr runtime):

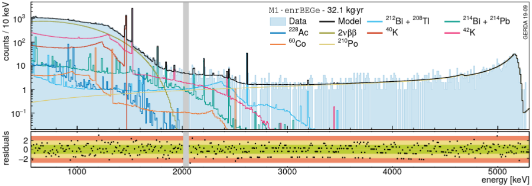


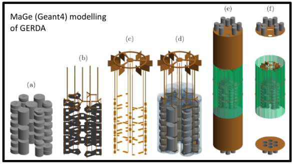
Agostini, Benato, Detwiler, Phys. Rev. D 96 053001 (2017)

Backup: background model

JHEP 03 (2020), 139

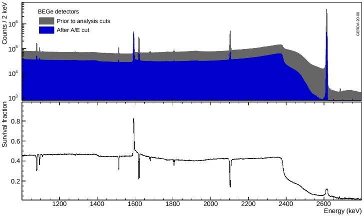
Components of the bkg. model of GERDA &
the implementation of the detector array in the MaGe simulation framework:

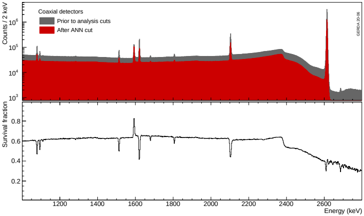




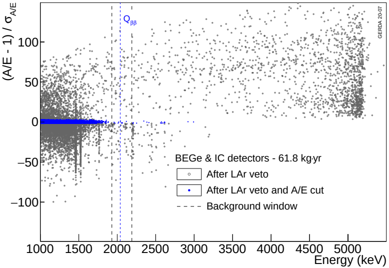
Backup: pulse shape cut

Survival fraction of calibration data events after applying pulse shape discrimination:



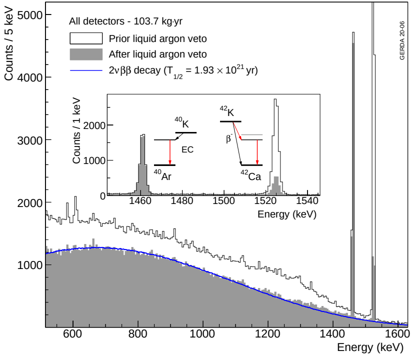


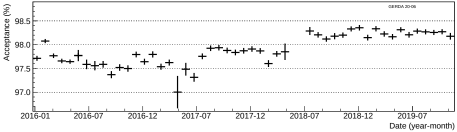
A/E cut applied to physics data:



Backup: LAr veto cut

Background event reduction by applying the LAr veto cut:

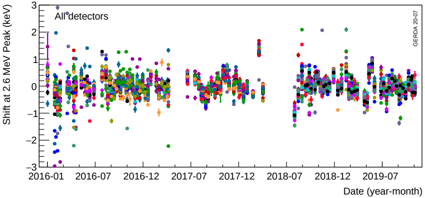


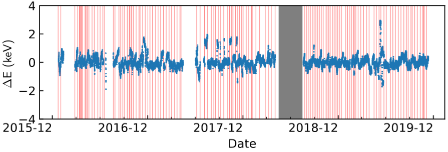


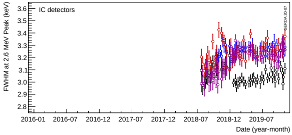
Backup: resolution stability

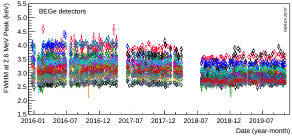
arXiv:2103.13777, to be published in Eur. Phys. J. C

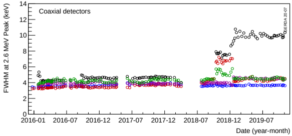
Time behaviour of energy scale & resolution stability of the detectors, determined via calibrations & pulser scans:







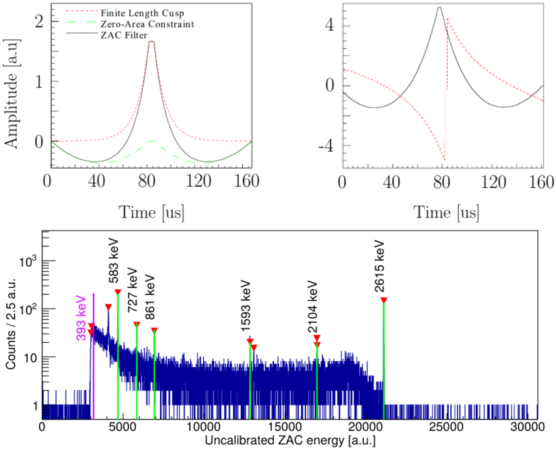




Backup: energy estimator

Eur. J. Phys. C 75 255 (2015)

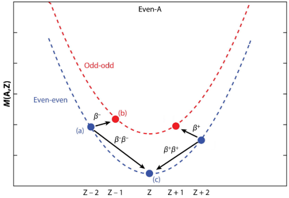
Event energy estimation (in uncalibrated arb. energy units) from integrated signal waveform via Gaussian & zero-area cusp filter, then conversion into physical units via calibration:



Backup: double beta decay

Comparison of the different isotopes undergoing double beta decay:

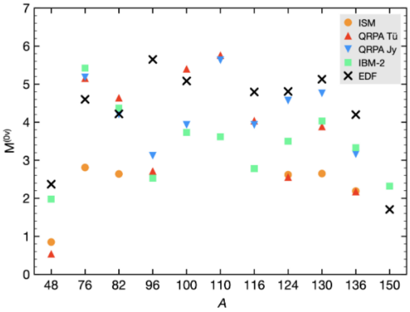
isotope	Q-value [MeV]	nat. abundance [%]
^{110}Pd	2.02	11.7
^{76}Ge	2.04	7.73
^{124}Sn	2.29	5.8
^{136}Xe	2.46	8.86
^{130}Te	2.53	34.1
^{116}Cd	2.81	7.5
^{82}Se	3.00	8.7
^{100}Mo	3.03	9.8
^{96}Zr	3.35	2.8
^{150}Nd	3.37	5.6
^{48}Ca	4.27	0.187



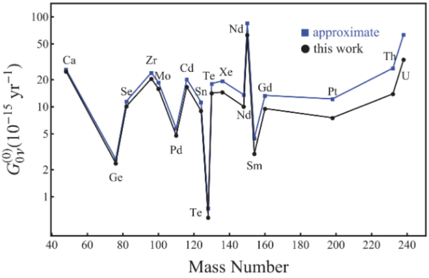
Saakyan, Review of Nuclear and Particle Science 63 503 (2013)

Backup: nuclear matrix element & phase space factors

Comparison of nuclear matrix elements & phase space factors of different isotopes:



Gomez-Cadenas, Martin-Albo, PoS GSSI 14 004 (2015)



Kotila, Iachello, Phys. Rev. C 85 034316 (2012)