The broad physics program of the Gerda experiment

Neutrinoless double beta decay & beyond

Yannick Müller

On behalf of the GERmanium Detector Array (Gerda) collaboration

May 24, 2023

Physik-Institut, University of Zurich

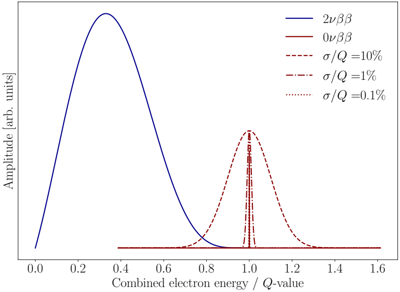
Signature:

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

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

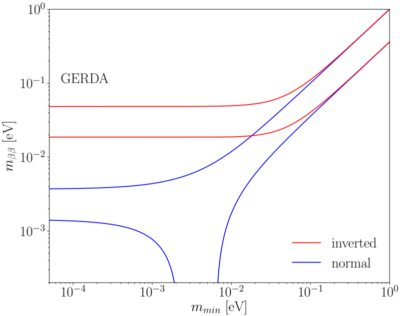
BSM $0\nu\beta\beta$ decay in ^{76}Ge:

- $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2\text{e}^-$
- 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 $\left|m_{\beta\beta}\right| = \left|\sum_i U_{ei}^2 m_i\right|$, U_{ei} from PMNS matrix
- nuclear matrix element $\mathcal{M}$
- phase space factor $\mathcal{G}$
- half-life of $0\nu\beta\beta$ $T_{1/2}$

Half-life sensitivity,
w. background vs background-free:

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

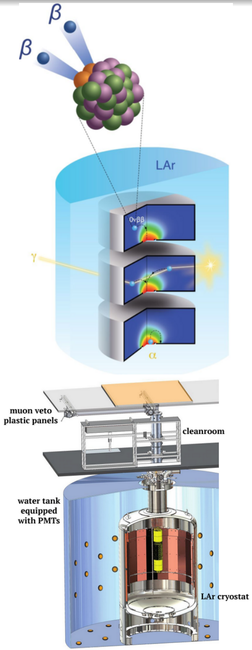
- enrichment fraction f
- efficiency ϵ
- mass M
- measurement time t
- background index B
- energy resolution σ_E at $Q_{\beta\beta}$

→ low background level & good energy resolution crucial

Science 365, 1445 (2019)

Main principles:

- $0\nu\beta\beta$ source = detector,
  high detection efficiency
- operate high-purity Ge (HPGe) detectors,
  semiconductors, bandgap $\mathcal{O}$(1eV),
  excellent energy resolution,
  no measurable internal
  background contamination,
  allow for event pulse shape
  discrimination (PSD)
- liquid argon (LAr) serves as coolant,
  shield & active veto
- LAr cryostat immersed into water tank
  equipped with PMTs
- operated at LNGS,
  1400m rock overburden (3500 mwe),
  cosmic muon reduction $\mathcal{O}\left(10^6\right)$

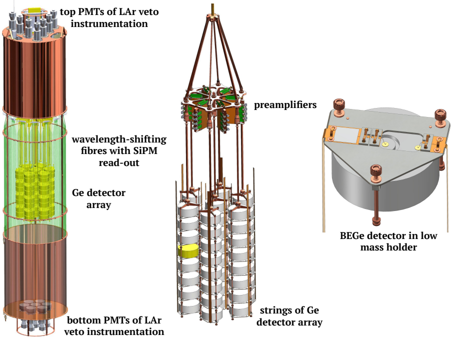


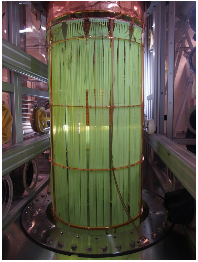
Experimental design

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

Instrumentation:

- up to 41 detectors enriched in ^{76}Ge (up to 87% enrichment & 43.6 kg total mass)
- 6 to 7 detector strings, covered by nylon cylinders
- LAr instrumentation consisting of wavelength-shifting fibres coupled to SiPMs, plus PMTs



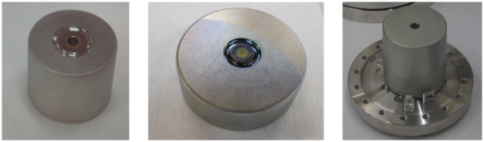


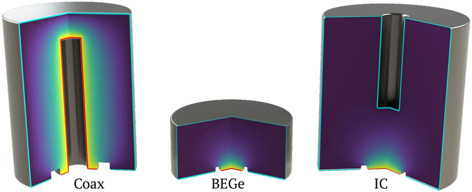
Detector operation

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

Detector types:

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





Operation phases:

- 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
- both phases: regular calibrations with ^{228}Th sources to calibrate energy scale and to measure energy resolution (FWHM of ∼0.15% at $Q_{\beta\beta}$)

Background reduction

More details in backup slides

Analysis cuts for $0\nu\beta\beta$ search:

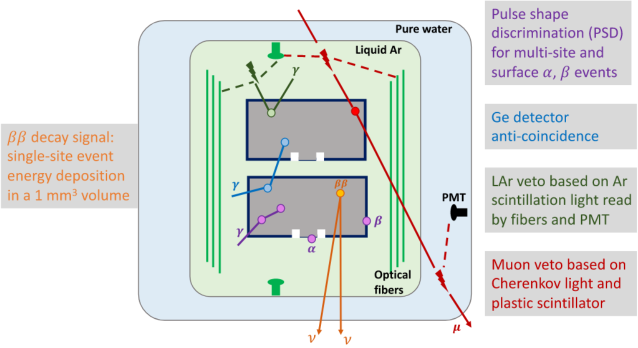
w. signal survival probability

- PSD
  ~69–90%
- multiplicity / coincidence
  ~99.9%
- LAr veto
  ~98%
- muon veto
  ~99.9%

$0\nu\beta\beta$ signal efficiencies:

after all cuts & enrichment

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

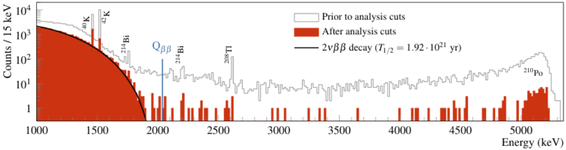


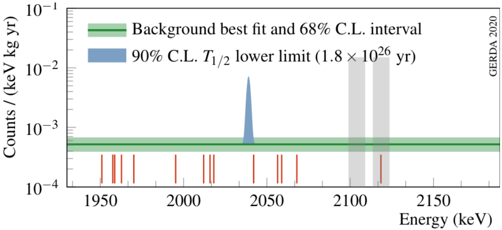
→ ~60% signal detection efficiency after all background cuts

PRL 125, 252502 (2020)

Analysis & results:

- spectrum well understood:
  $\sim$ 0.5 - 2 MeV: $2\nu\beta\beta$,
  $\gtrsim$ 4 MeV: α particles
- flat background in $0\nu\beta\beta$ signal region
- $\pm$25 keV around $Q_{\beta\beta}$ blinded
- unbinned maximum likelihood fit
- best $T_{1/2}$ sensitivity in the field
- lowest background level in the field:
  $B = 5.2 \times 10^{-4}$ cts / (keV kg yr)



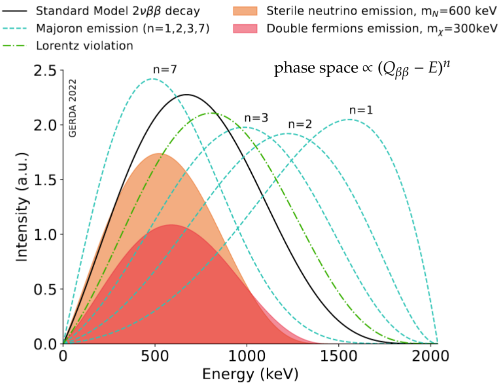


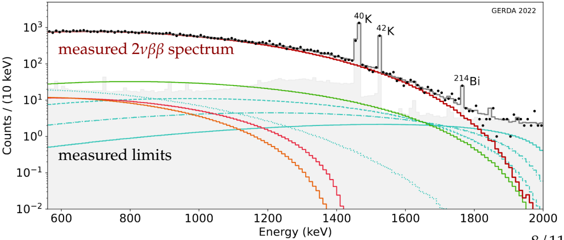
Limit & sensitivity:
$T_{1/2} > 1.8\ (1.4) \times 10^{26}$ yr 90% CL (CI) $\rightarrow |m_{\beta\beta}| \lesssim 79 - 180$ meV

JCAP 12 (2022) 012

Exotic signatures in $2\nu\beta\beta$ spectrum:
(selected constraints, 90% CL)

- sterile neutrino emission,
  $2n \rightarrow 2p + 2e^- + \bar{\nu}_e + N$
  $m_N = 600$ keV:
  $\sin\theta < 0.03$
- Z_2-odd fermion emission,
  $2n \rightarrow 2p + 2e^- + 2\chi$
  $m_\chi = 300$ keV:
  $T_{1/2} > 1.3 \times 10^{23}$ yr
- Majoron emissions,
  $2n \rightarrow 2p + 2e^- + J(JJ)$
  $J, n = (1,2,3)$:
  $T_{1/2} > (6.4, 2.9, 1.2) \times 10^{23}$ yr,
  $JJ, n = (3,7)$:
  $T_{1/2} > (1.2, 1.0) \times 10^{23}$ yr
- Lorentz violation in neutrino sector, $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_{LV}$, perturbation $\propto a_{of}^{(3)}$
  $(-2.7 < a_{of}^{(3)} < 6.2) \times 10^{-6}$ GeV

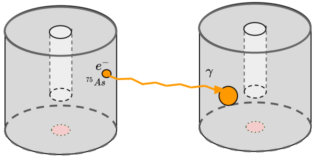




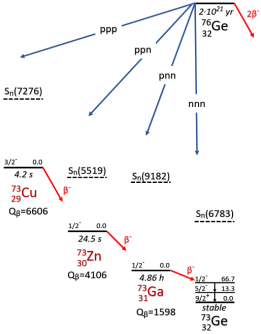
paper on tri-nucleon decays submitted to Eur. Phys. J. C,
2 papers in preparation (single-nucleon & electron decays, 0νECEC in ^{36}Ar)

Probes of baryon number, charge, & lepton number conservation:

- inclusive neutron & proton decays (^{76}Ge $\rightarrow$ ^{75}Ge, ^{76}Ge $\rightarrow$ ^{75}Ga $\rightarrow$ ^{75}Ge), $e^-\gamma$-pair signal from ^{75}Ge β decay to ^{75}As & de-excitation,
  $\tau_n > 1.6\ (1.5) \times 10^{24}$ yr 90% CL (CI),
  $\tau_p > 1.4\ (1.3) \times 10^{24}$ yr 90% CL (CI)
- inclusive tri-nucleon decays (ppp, ppn, pnn) of ^{76}Ge, γ events at 66.7 keV from de-excitation in ^{73}Ge after β decay of ^{73}Ga,
  $\tau_{ppp,ppn,pnn} > 1.6 \times 10^{26}$ yr 90% CI
- semi-visible electron decay $e^- \rightarrow \nu\gamma$, Doppler-broadened line signal at ~256 keV,
  $\tau_e > 1.2\ (0.7) \times 10^{26}$ yr 90% CL (CI)
- radiative neutrinoless double electron capture in ^{36}Ar, γ-line signal at ~430 keV,
  $T_{1/2} > 1.6 \times 10^{22}$ yr 90% CL

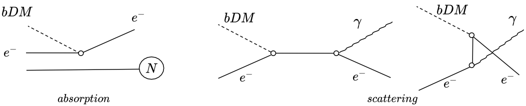


^{75}Ge decay tagging as a neutron & proton decay signature



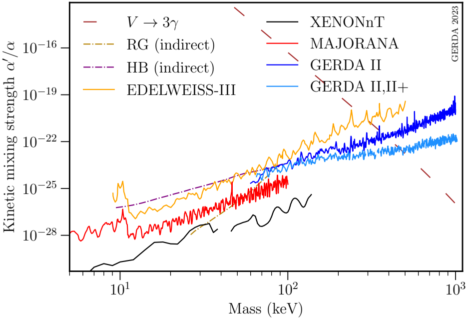
Tri-nucleon decay scheme of ^{76}Ge

Phys. Rev. Lett. 125 (2020) 011801, Erratum: Phys. Rev. Lett. 129 (2022) 089901, new paper in preparation



Bosonic dark matter interactions:

- vector (dark photons) & pseudoscalar (axion-like particles) candidates
- photoelectric-like absorption & dark Compton scattering channels
- mass range 60(65)-1000(1021) keV/c^2
- search for full energy deposition of e^- or $e^-\gamma$-pair



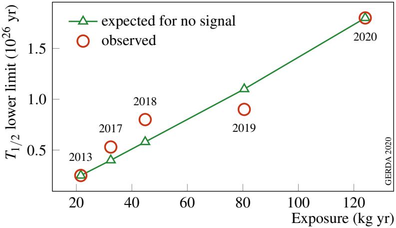
SUMMARY & OUTLOOK

GERDA employed an array of up to 43.6 kg of HPGe detectors enriched in ^{76}Ge to search for $0\nu\beta\beta$.

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

With excellent energy resolution & background performances, GERDA provides an ideal environment to probe new physics beyond $0\nu\beta\beta$, such as exotic particle-emissions or -decays, & dark matter interactions.

Benefitting from the experience of GERDA, LEGEND will operate ~200 kg & ~1000 kg of HPGe detectors in two stages, probing $0\nu\beta\beta$ $T_{1/2}$ sensitivities beyond 10^{28}yr, & further broadening the physics program beyond $0\nu\beta\beta$.



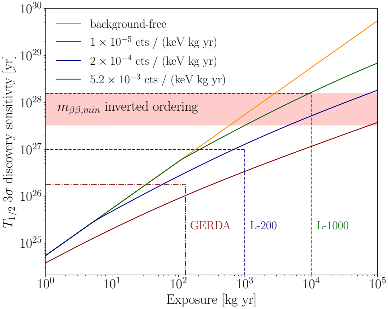
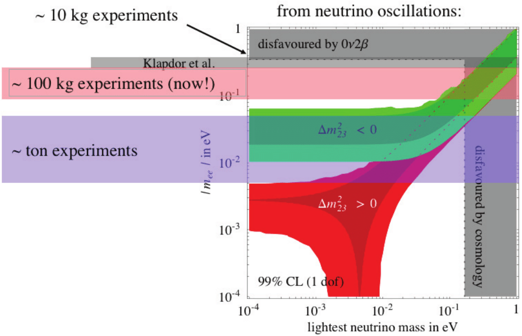


Figure assumes the numerical parameters from LEGEND, arxiv:2107.11462

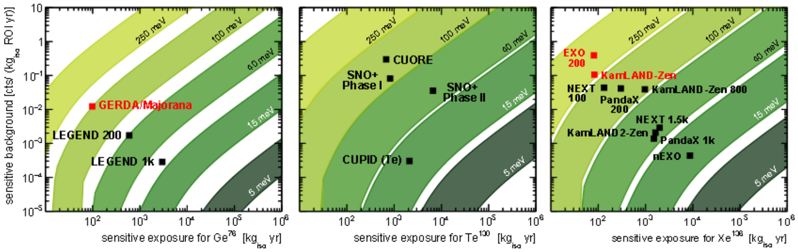
see talk on LEGEND by Sofia Calgaro on Thursday, parallel session 20

Constraints on the two neutrino mass ordering regimes:



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

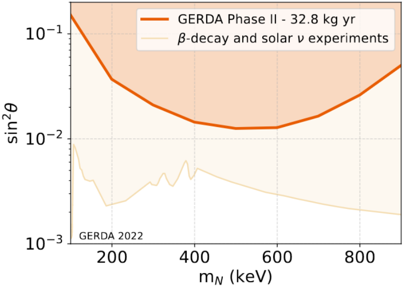
Comparison of rough sensitivity between ongoing & planned experiments (marked: 5 yr runtime):



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

JCAP 12 (2022) 012

Comparison of the results of Gerda & other experiments on exotic spectral distortions in $2\nu\beta\beta$ spectrum
(left: sterile neutrinos, right: Lorentz violation):



Isotope	Limits on $\mathring{a}_{\text{of}}^{(3)}$ (GeV) at 90% C.L.	Ref.
^{76}Ge	$(-2.7 < \mathring{a}_{\text{of}}^{(3)} < 6.2) \cdot 10^{-6}$	this work
^{136}Xe	$-2.65 \cdot 10^{-5} < \mathring{a}_{\text{of}}^{(3)} < 7.6 \cdot 10^{-6}$	EXO-200 [68]
^{116}Cd	$\mathring{a}_{\text{of}}^{(3)} < 4.0 \cdot 10^{-6}$	AURORA [56]
^{100}Mo	$(-4.2 < \mathring{a}_{\text{of}}^{(3)} < 3.5) \cdot 10^{-7}$	NEMO-3 [28]
^{82}Se	$\mathring{a}_{\text{of}}^{(3)} < 4.1 \cdot 10^{-6}$	CUPID-0 [69]
^{3}H (single-β decay)	$\lvert\mathring{a}_{\text{of}}^{(3)}\rvert < 2 \cdot 10^{-8}$	Díaz et al. [65]
	$\lvert\mathring{a}_{\text{of}}^{(3)}\rvert < 3 \cdot 10^{-8}$	KATRIN [70]

paper on tri-nucleon decays submitted to Eur. Phys. J. C.
paper on nucleon & electron decays in preparation

Comparison of the results of GERDA & other experiments on BSM decays
(left: neutron & proton decays, right: top: tri-nucleon decays, bottom: electron decays):

Experiment	Decay	n_{eff}	τ_{low} (yr)
GERDA	$^{76}Ge \xrightarrow{n} {}^{75}Ge + X$	16	$1.6(1.5) \times 10^{24}$
	$^{76}Ge \xrightarrow{p} {}^{75}Ga + X$	14	$1.4(1.3) \times 10^{24}$
SNO [14] (a)	$^{16}O \xrightarrow{n} {}^{15}O + inv.$	8	1.9×10^{29}
	$^{16}O \xrightarrow{p} {}^{15}N + inv.$	8	2.1×10^{29}
SNO+ [15] (a)	$^{16}O \xrightarrow{n} {}^{15}O + inv.$	8	2.5×10^{29}
	$^{16}O \xrightarrow{p} {}^{15}N + inv.$	8	3.6×10^{29}
Borexino [16] (b)	$^{12}C \xrightarrow{n} {}^{11}C + inv.$	4	1.8×10^{25}
	$^{13}C \xrightarrow{p} {}^{12}B + inv.$	4	1.1×10^{26}
DAMA/LXe [17]	$^{136}Xe \xrightarrow{n} {}^{135}Xe + X$	32	3.3×10^{23}
	$^{136}Xe \xrightarrow{p} {}^{135}I + X$	26	4.5×10^{23}
DAMA [18]	$^{129}Xe \xrightarrow{p} {}^{128}I + X$	24	1.9×10^{24}
NaI(Tl) [19]	$^{127}I \xrightarrow{n} {}^{126}I + X$	34	1.5×10^{24}
	$^{127}I \xrightarrow{p} {}^{126}Te + X$	20	3.0×10^{24}
Geochemical [20, 21]	$^{130}Te \xrightarrow{n} {}^{129}Te + X$	28	8.6×10^{24}
	$^{130}Te \xrightarrow{p} {}^{129}Sb + X$	24	7.4×10^{24}

(a) Searches for γ rays coming from the de-excitation of a residual excited nucleus following the disappearance of a nucleon in ^{16}O.
(b) Searches for decays of unstable nuclei left after nucleon decays of parent ^{12}C, ^{13}C nuclei.

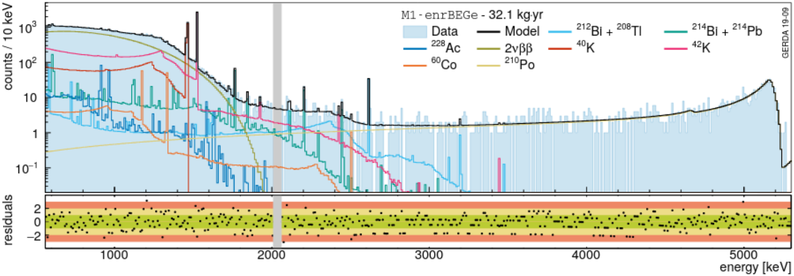
Experiment	decay	$\tau_b[x]$ (yr)
GERDA	$^{76}Ge \xrightarrow{ppp} {}^{73}Cu + X$	1.20×10^{26}
	$^{76}Ge \xrightarrow{ppn} {}^{73}Zn + X$	1.20×10^{26}
	$^{76}Ge \xrightarrow{pnn} {}^{73}Ga + X$	1.20×10^{26}
	$^{76}Ge \xrightarrow{nnn} {}^{73}Ge + X_{invisble}$	$k \times 10^{26}$
MAJORANA [19]	$^{76}Ge \xrightarrow{ppp} {}^{73}Cu + X$	1.08×10^{25}
	$^{76}Ge \xrightarrow{ppp} {}^{73}Cu\, e^+ \pi^+ \pi^+$	6.78×10^{25}
	$^{76}Ge \xrightarrow{ppn} {}^{73}Zn\, e^+ \pi^+$	7.03×10^{25}
EXO-200 [20]	$^{136}Xe \xrightarrow{ppp} {}^{133}Sb + X$	3.3×10^{23}
	$^{136}Xe \xrightarrow{ppn} {}^{133}Te + X$	1.9×10^{23}
Hazama et al. [21]	$^{127}I \xrightarrow{nnn} {}^{124}I + X$	1.8×10^{23}

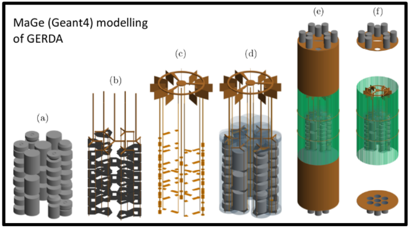
Experiment	Mode	τ_e (yr)
Borexino [51]	semi-visible	6.6×10^{28}
H.V. Klapdor-Kleingrothaus et al. [23]	semi-visible	9.4×10^{25}
MAJORANA DEMONSTRATOR [52]	invisible	1.2×10^{24}
EDELWEISS-III [53]	invisible	1.2×10^{24}
GERDA	semi-visible	1.2×10^{26} (6.6×10^{25})

PRELIMINARY RESULTS

J .High Energ. Phys. 2020, 139 (2020)

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

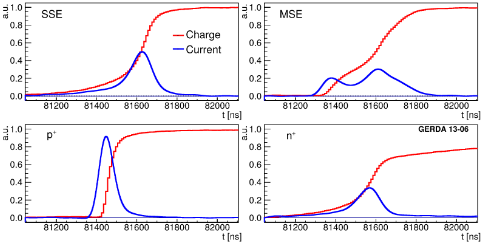




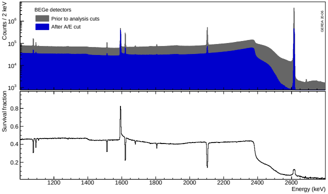
Eur. Phys. J. C 73 2583 (2013), Eur. Phys. J. C 82 284 (2022)

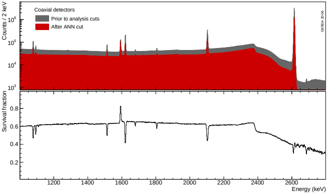
Event classification:

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

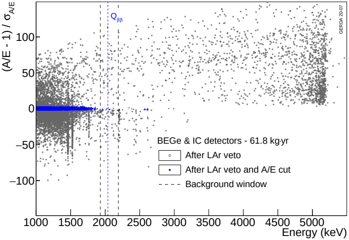


Survival fraction of calibration data events after applying pulse shape discrimination:





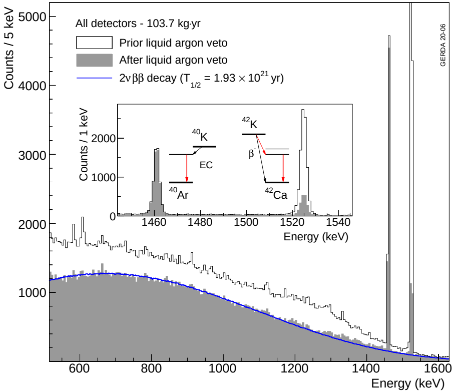
A/E cut applied to physics data:

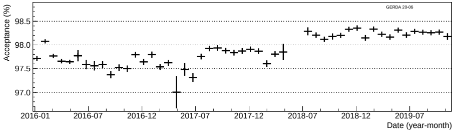


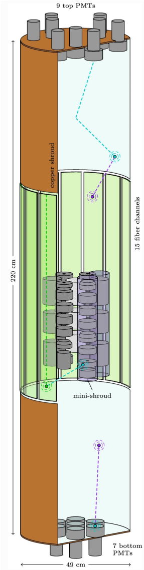
Backup: LAr veto cut

Eur. Phys. J. C 83 (2023) 319

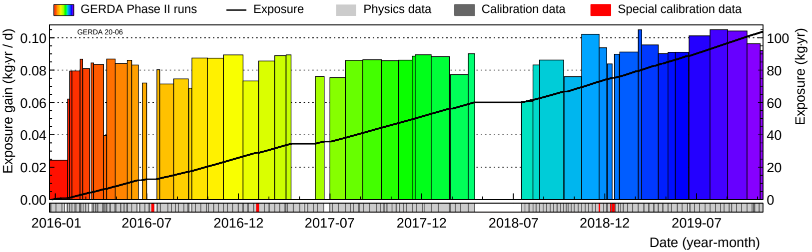
Background event reduction by applying the LAr veto cut:







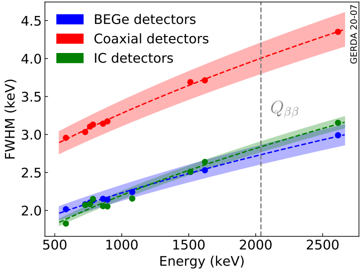
Timeline of the experimental operation:

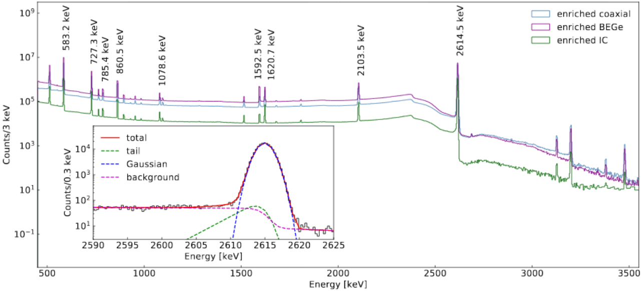


Eur. Phys. J. C 81, 8 682 (2021)

Calibration strategy:

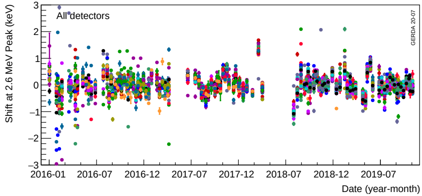
- ~weekly calibrations with 3 ^{228}Th sources
- use γ lines of known energies to convert ADC to physical units (keV)
- peak fitting algorithm to determine each detector's resolution
- Gaussian mixture models to determine resolutions per detector type

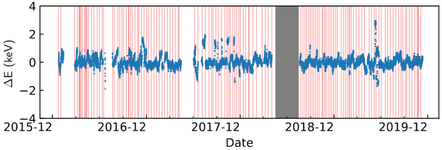


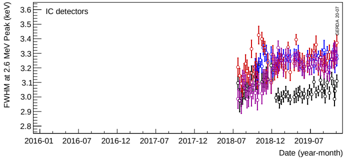


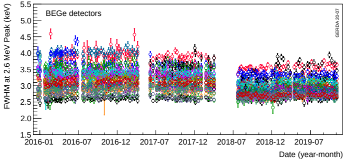
→ GERDA achieved relative energy resolutions (FWHM) of ~ 0.15% at $Q_{\beta\beta}$

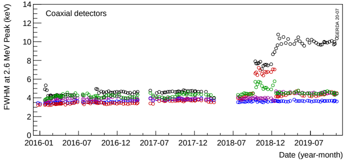
Time behaviour of energy scale & resolution stability of the detectors, determined via calibrations & pulser scans:





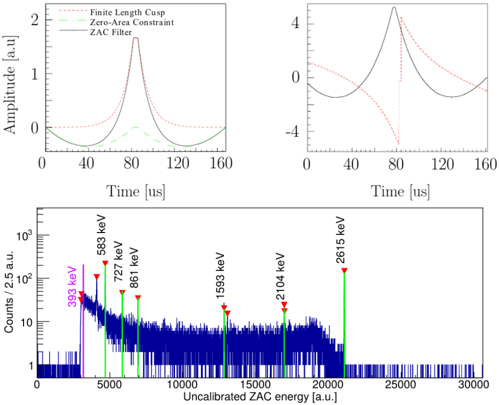






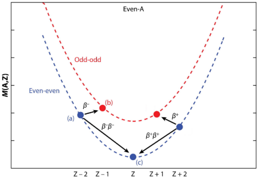
Eur. J. Phys. C 75 (2015) 255

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



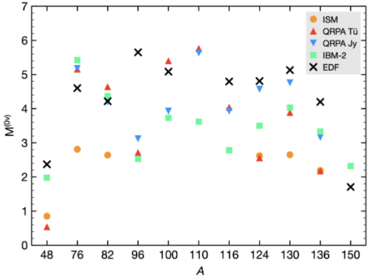
Comparison of the different isotopes undergoing double beta decay:

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

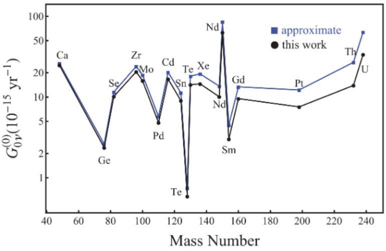


Saakyan, Review of Nuclear and Particle Science 63 503 (2013)

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)