GERDA Phase II detectors: behind the production and characterisation at low background conditions

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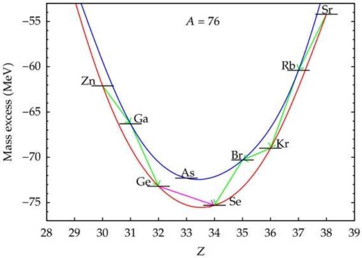
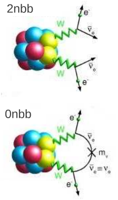
Low Radioactivity Techniques Workshop - LRT2013
April 10-12, 2013, LNGS, Italy

Searching for the rare neutrinoless double beta decay



Towards the valley of stability:

- Second-order nuclear transition that can occur between two odd-odd isobars:
  → single β decay energetically forbidden
  → Among partly ompeting alternatives ($\beta^-\beta^-$, $\beta^+\beta^+$, ECβ^+, ECEC) $\beta^-\beta^-$ has highest rates
- 35 candidates in Nature; Examples:
  ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe



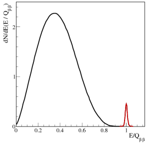
Role of neutrinos in $\beta\beta$ decay:

1. $2\nu\beta\beta$ decay
   → Allowed by Standard Model
   → Signature: β -like spectrum
   → Observed in 12 candidates: O($T_{1/2}$)=10^{18}-10^{24} yr
   (Longest-lived decay processes observed in Nature)
2. $0\nu\beta\beta$ (or $0\nu\chi^0(\chi^0)\beta\beta$) decay
   → Signiture: Full energy peak at $Q_{\beta\beta}$
   → Lepton-number violation (ΔL=2), thus not allowed by Standard Model
   - Note: One claim (in ^{76}Ge) by subgroup of Heidelberg-Moskow Collaboration

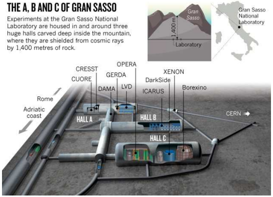
Expected experimental

signature from $2\nu\beta\beta$

and $0\nu\beta\beta$ decays



The low background experiment GERDA



Setup and background shielding (1):

- Overburden of 3500 m w.e. at Hall A of LNGS
  → Reduction of cosmic-muon flux by six orders of magn. down to $\sim 1\,\mu/(m^2 \cdot h)$ (PB)
- Water tank and plastic scintillator
  - R=5 m, h=9.0 m, 590 m^3 ultra-pure water
  → water acts as neutron moderator/absorber (PB)
  → both components act as muon Cherenkov veto (AB)
- Large volume cryostat:
  - R=2 m, h=5.9 m, 64 m^3 LAr
  → LAr acts as cooling medium for diodes
  → LAr attenuates external radiation (PB)
  → LAr scintillation light planned to be used as a background rejection (AB)
- GERmanium Detector Array:
  - 1-string and 3-string arms, each string with 3 detectors (Phase I)
  - Up to ~12 strings (depending on final design for Phase II)
  - Handling of diodes within a glovebox flushed mit N2 gas (PB)
  - Operating bare diodes in LAr using low-mass holders (PB)
  → $0\nu\beta\beta$ source = Detector, enriched in ^{76}Ge
  - coincidence mode and pulse shape tracing (AB)

PB = passive background rejection
AB = active background rejection
All construction materials close to detectors screened for radiopurity

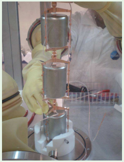
GERDA Phase I and II

GERDA Phase I (November 2011 - summer 2013) (1):

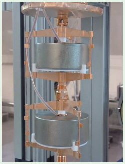
- Technology: Refurbished coaxial HPGe detectors, 6 ^{76}Ge enriched (HdM, IGEX) for ∼15 kg, 3 natural (GTF)
- Since July 2012: added 5 enriched Phase II BEGe prototype detectors for ∼3.5 kg
- Energy resolution of coaxial diodes: 4.5-5.1 keV (FWHM) at 2614.5 keV
- Background index (BI)*: ∼0.02 cts/(keV·kg·yr) → Talk by N. Becerici-Schmitt (April 11, Session 6)

* BI defined in region: $Q_{\beta\beta}$ of ^{76}Ge (2039 keV) ± 100 keV (minus 40 keV blinded region)

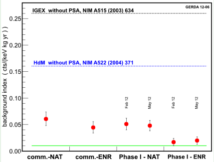
String with coaxial HPGe diodes



String with BEGe diodes



BI of Phase I (1)



GERDA Phase II (planned start within 2013):

- Technology: additional 25 enriched Phase II BEGe detectors for ∼17 kg:
  → Expected better sensitivity due to: larger target mass, better energy resolution, and enhanced pulse shape performance for background rejection
- Envisioned BI in ROI: ≤0.001 cts/(keV·kg·yr)

GERDA Phase II: Towards a higher sensitivity

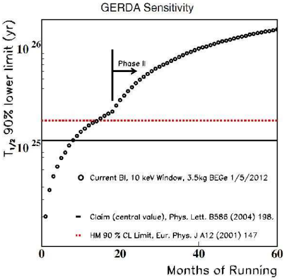
Sensitivity expressed in terms of half-life

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, \quad \text{(if background is present)}$$

where:

- f_{76}: Abundance of $0\nu\beta\beta$ candidate isotope
  → Enrichment
- ϵ: Efficiency
  → precise characterisation via dedicated acceptance tests
- **M**: Mass
  → Increasing target mass
- **T**: DAQ livetime →high duty cycle
- **ΔE**: Energy resolution
  → Novel detector technology with improved resolution
- **B**: Background:
  → Keep exposure to cosmogenic radiation low
  → Apply pulse shape discrimination techniques to reject background events
  → Read-out LAr scintillation light to discriminate background events

Expected sensitivity of GERDA Phase I-II

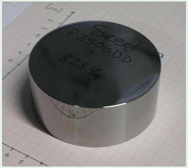


Production of GERDA Phase II detectors: Overview

From enrichment to diode operation

1. Germanium enriched at 87% in ^{76}Ge at Electrochemical Plant, Zelenogorsk, Krasnojarsk, Russia (delivered in form of GeO_2 powder)
2. Purification to 6N grade material via zone-refinement at the high purity metals producer PPM GmbH in Langelsheim, Germany
3. Crystal pulling at Canberra Industries Inc., Oak Ridge, USA
4. BEGe Diode production at Canberra Semiconductors NV, Olen, Belgium;
   Characterisation at HADES underground laboratory, Mol, Belgium;
   Contacting at Canberra, Olen
5. Delivery to GERDA experimental site

Crystal slice before diode conversion



Production of GERDA Phase II detectors: Enrichment and mass yield

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

Enrichment fraction f_{Ge} (1):

Isotope	^{70}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{76}Ge	Mean nuc. mass
Isot. mass (g/mole)	μ^1: 69.92	μ^2: 71.92	μ^3: 72.92	μ^4: 73.92	μ^5: 75.92	
Isot. abundance of: ^{nat}Ge (2003)	a_0^1: 0.204(2)	a_0^2: 0.273(3)	a_0^3: 0.078(1)	a_0^4: 0.367(2)	a_0^5: 0.078(1)	μ_0: 72.70
Isot. abundance of:	a^1:	a^2:	a^3:	a^4:	a^5:	μ:
HDM–ANG1, ^{enr}Ge	0.0031(2)	0.0046(19)	0.0025(8)	0.131(24)	0.859(29)	75.68
IGEX, ^{enr}Ge	0.0044(1)	0.0060(1)	0.0016(1)	0.1329(1)	0.8551(10)	75.60
BEGe, ^{enr}Ge	0.0002(1)	0.0007(3)	0.0016(2)	0.124(4)	0.874(5)	75.77

Mass yield:

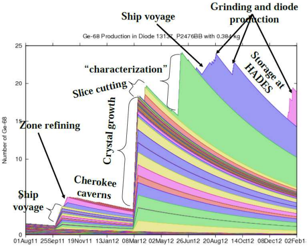
Germanium	Mass [kg]	Fraction relative to 1. and 2. [%]
1. GeO_2 powder after enrichment	37.5	100
2. Purified Ge for crystal pulling	35.5	95; 100
3. Cut crystal slices	25.2	67; 71
4. 30 grinded and lapped crystal slices	20.8	55; 59
5. 30 crystals converted into operational diodes	~20.2	54; 57

Production of GERDA Phase II detectors: Cosmic activation

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

Challenging: Minimisation of exposure to cosmic radiation

- Cosmogenically-induced radioisotopes mimic $0\nu\beta\beta$ events
- Main candidates:
  - ^{68}Ge: τ=270.95 d, Saturation at sea level: ~20000 nuclei/kg
  - ^{60}Co: τ=5.27 y, Saturation at sea level: ~800 nuclei/kg
- Counteractions:
  - Minimize exposure during transportation: bottom of container ship, transport container filled with water on truck
  - Underground storage close to manufacturing sites (Oak Ridge→Cherokee Caverns, Olen→HADES UG lab)
  - Characterisation of germanium in HADES UG lab (see next slide)

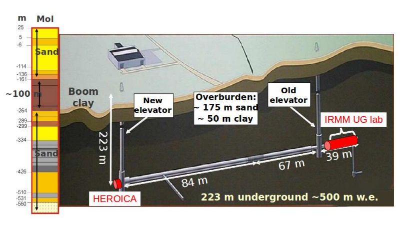


Achievements:

- Database: Precise tracking of Ge storage above ground
- Rough estimate of activation of Phase II detector (Status: February 2, 2013):
  - ^{68}Ge: ~20-50 nuclei/kg → BI≈4e-4 cts/(keV·kg·yr)
  - ^{60}Co: ~20-40 nuclei/kg → BI≈4e-5 cts/(keV·kg·yr)

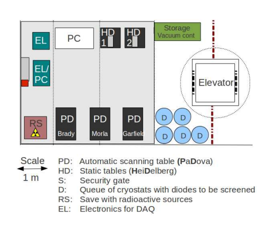
GERDA Phase II detectors: characterisation in HADES

HADES underground laboratory



- HADES (High Activity Disposal Experimental Site):
  → Research infrastructure for disposal of nuclear waste in clay environment located at the Belgian Nuclear Reseach Center SCK·CEN in Mol
- Only 25 km from diode manufacturer Canberra in Olen

Diode characterisation at HEROICA site in HADES



- HEROICA (Hades Experimental Research Of Intrinsic Crystal Appliances): (2)
  → A facility for fast and precise characterisation of Ge detectors in vacuum cryostat
- Fully equipped with DAQ (MCA, FADC), HV supply, network, large radioactive source set
- Fast screening capability: 2 detectors/week
  → `Poster by E. Andreotti (April 11, Poster Session)`

GERDA Phase II detector tests: characterisation protocol

Parameters	Source	Collimated	Determination of:	DAQ Used
Mass and dimensions	–	–	Check manufacturer values	—
	Am scan	y	Check: Diode pos. in cryostat	MCA
Operational Param.	Co	n	Energy resolution	MCA/FADC
	Co HV scan	n	Depletion voltage	MCA/FADC
		n	E-res+rate+LC fnc. Of HV	MCA/FADC
		n	Monitoring of LC	USB Logger
	Th+Am+Co	n	Linearity of Ene-scale	FADC
	Co/Th/pulser	n	Stability in time	MCA/FADC
DL/AV	Am	n	Averaged DL+AV	MCA/FADC
	Ba	n	Averaged DL+AV	MCA/FADC
	Am scan	y	Charge collection eff.	MCA
		y	Position-dep. DL	MCA
	Co	n	AV; AV+transition reg.	MCA/FADC
	Co, diff. Trg.rates	n	Deadtime calc.	MCA/FADC
PSA	Th	n	PSD efficiency	FADC
	Am/Th	y	Position-dep. Of A/E; risetime	FADC
	Am scans	y	Surface and crystal effects	FADC
	Th, thermal cycles	n;y	Time-Stability of A/E	FADC
Bkgd	–	–	Background	MCA/FADC

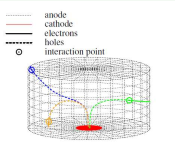
Advanced BEGe test protocol

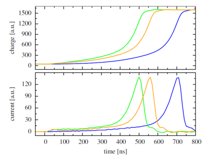
- Mainly adressed parameters: background rejection efficiency via pulse shape analysis (B), dead layer (DL) and active volume (AV) (included in the efficiency ϵ), energy resolution (ΔE), operational voltage, stability in time
- Test protocol based on investigations with BEGe diodes that were obtained from the ^{76}Ge -depleted left-over material from the enrichment process. (3)

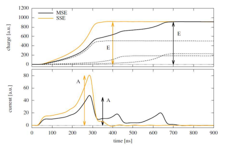
GERDA Phase II detectors: Pulse shape performance

Unsegmented Broad Energy Ge detector design and signal development (4)

- Holes generated at different places move along same trajectory close to the electrode ('funnel-effect'), here the charge signal becomes maximal
  → the charge-signal for depositions of equal energy depositions, but at different locations, is the same (only shifted in time)
- Multi-site energy depositions (MSE) in a single physics event show up a multiple structure in the charge signal
  → Max. Ampl A of MSE < Max. Ampl. A of single-site events (SSE) with same total energy E



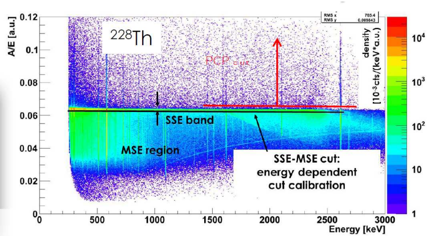




Method: Pulse shape discrimination

- $0\nu\beta\beta$ events are SSE, while most background events are MSE
  → Calibrate diode with ^{228}Th source
  → Calculate A and E, plot A/E vs. E:
  - 1592 keV: 2.6 MeV Double escape peak (DEP) is SSE
  - 2615 keV and Compton cont.: typical MSE

  → Use DEP distribution to define a SSE-MSE cut

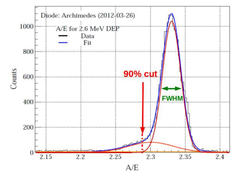


GERDA Phase II detectors: Pulse shape analysis results

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

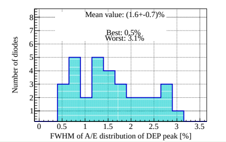
Definition of MSE-SSE pulse shape cut

Example: A/E distributon of SSE from 2.6 MeV DEP



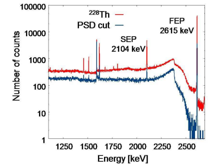
Distribution of A/E resolutions of SSE from 2.6 MeV DEP

(all GERDA Phase II BEGe diodes)



MSE-SSE cut subtraction and efficiencies in vacuum

Apply pulse shape cut and subtract MSE from energy spectrum



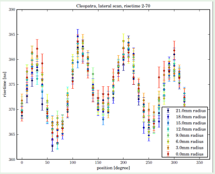
Averaged discrimination eff. (7 Phase II BEGe's)

ROI	Type	Suppression
DEP at 1.592 MeV	SSE	$(90\pm1)\%$
FEP at 1.620 MeV	MSE, peak	$(14\pm3)\%$
FEP at 2.615 MeV	MSE, peak	$(13\pm5)\%$
(2004-2074) keV	MSE, cont.	$(39\pm5)\%$
(1989-2089) keV	MSE, cont.	$(39\pm5)\%$

GERDA Phase II detector: ^{241}Am surface scans

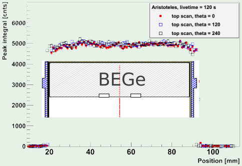
Perform: Fine-grained surface scans (top and lateral) with collimated 5 MBq ^{241}Am sources
Goal: better detector response knowledge → improved sensitivity $T_{1/2}$ by reduction of systematics

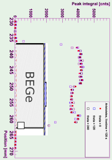
Information from pulse shape analysis



- Lateral circular scans: up to ∼290 points
- Top circular scans: up to ∼230 points
- Observe pulse risetime dependency from fcc-type crystal lattice
  → Study slow pulses from transition layer between inactive surface and active bulk region (see next slide)

Information from count rates





- Top and lateral scans in one direction
- Measure position of diode in vacuum cryostat
  (→ cross-check of manufacturer data; input for MC)
- Measure stability of count rate, → homogeneity of the dead layer (input for MC, see next slide)

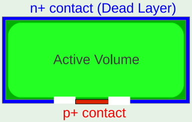
GERDA Phase II detector: Active Volume and Dead Layer

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

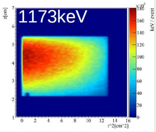
ϵ: includes detection efficiency and the active volume fraction f_{AV}

Sources probing (in)active regions of Ge diodes

- ^{241}Am: surface → Dead Layer
- ^{133}Ba: surface and outer bulk → Dead Layer
- ^{60}Co: bulk → Active volume
- ^{228}Th: surface (238 keV), bulk (2615 keV), corners (DEP, 1592 keV)

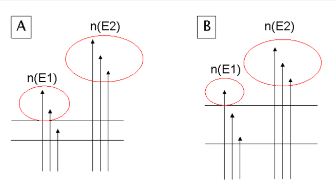


$V_{diode} - V_{DL} \geq V_{AV}$



Methods:

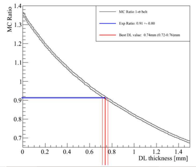
- Peak ratio method:
  - Estimate R_{exp}=n(E1)/n(E2) for two given γ-lines of the same isotope; activity independent measurement !
  - Compare with simulated R_{mc} for variable DL thickness
- Absolute peak count rate method:
  - Estimate $\epsilon_{exp} = n_{emit}(E)/n_{absorb}(E)$ for a given energy; for $n_{emit}(E)$ source activity has to be well known !
  - Compare with simulated ϵ_{mc} for variable DL thickness



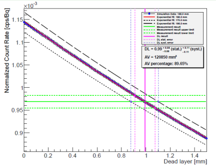
GERDA Phase II detector: active volume and dead layer results

Example: Peak ratio method vs. Absolute peak count rate method

133Ba:
79+81 keV
vs.
356 keV



60Co:
1173 keV
(or
1333 keV)



Investigation of systematics for a precise determination of DL/AV

- Diode: dimensions, off-axis position, distance to endcap of cryostat
- Cryostat: material/thickness of endcap as well of detector cup
- Source: distance, encapsulation material/thickness, size of active element, activity
- MC (Geant4): tracking uncertainty, gamma line probability, angular correlations
- DAQ performance: cross-check with different DAQ systems, dead time calc., stability in time

Preliminary results (7 ^{enr}BEGe):

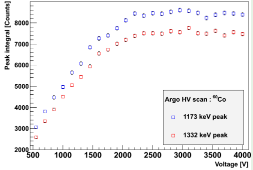
- Dead layer thickness: (0.7-1.2) mm (in agreement with manufacturer)
- Active volume fraction f_{AV}: (86-92)%
  → Final goal: full agreement between different methods AND uncertainty Δf_{AV} at few % level

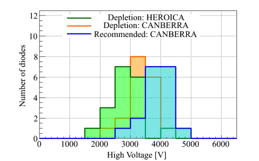
GERDA Phase II detector results: depletion voltage and energy resolution

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

Depletion voltages:

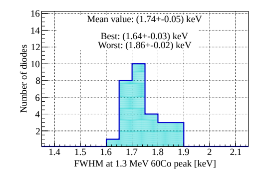
- High voltage scans with ^{60}Co source for monitoring of: peak count rate, peak position, energy resolution, leakage current
- Depletion voltage V_D:
  - Criterion: count rate saturates
  - $V_D \approx$ recommended operational voltage - 500 V





Energy resolution ΔE:

- HEROICA values: in very good agreement with manufacturer's values
- 29/30 diodes have excellent ΔE; $\langle \Delta E \rangle$=1.74 keV at 1.3 MeV ^{60}Co peak (in vacuum)
- BEGe vs. coaxial HPGe diodes: ∼3.2 keV vs. ∼4.7 keV at 2.6 MeV (in Liquid Argon)



GERDA Phase II detectors: Summary

Production and characterisation of 30 new BEGe detectors

- Large effort to suppress cosmic activation during transport and all production steps
- Screening facility HEROICA: fast, precise and detailed characterisation of all diodes

Performance of GERDA Phase II detectors

- Novel detector technology: enhanced pulse shape discrimination of background events
- Active volume fractions f_{AV}: known at a good precision level
- Excellent energy resolution; almost 2$\times$ better than coaxial HPGe diodes
- Study of other parameters for better detector understanding ongoing

$\rightarrow$ *All these ingredients will contribute to an improved sensitivity in the GERDA experiment!*

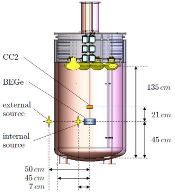
BACK-UP

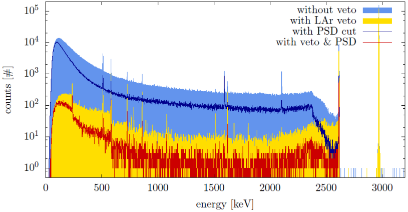
GERDA Phase II: Light instrumentation for background reduction

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

Goal:

- Operate germanium diodes in coincidence with scintillation light instrumentation in liquid argon (λ=128 nm) in order to reject external background
- R&D within LArGe test facility at LNGS





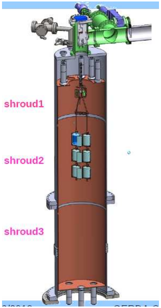
Results for ^{60}Co and ^{228}Th source (6)

source	position	LAr Veto	PSD	total
^{60}Co	int	27±2	76±9	3900±1300
^{228}Th	ext	25±1	2.8±0.1	129±15
	int	1180±250	2.4±0.1	5200±1300

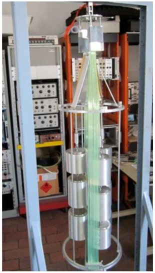
GERDA Phase II: Light instrumentation options

PMT teststand

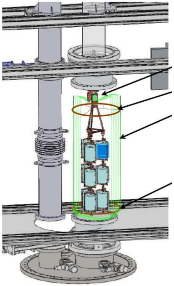
PMT Design



Glass-fibre teststand



Glass-fibre design



Options

1. PMT light instrumentation (based on LArGe experience)
2. Wavelength-shifter glass-fibres
3. Large area avalanche photodiodes or UV sensitive SiPMs on custom-made low-activity substrates

→ Most advanced solution: Combination of 1. and 2. option

Bibliography and further reading

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