Search of Neutrinoless Double Beta Decay with the GERDA Experiment

SWAPS 2014

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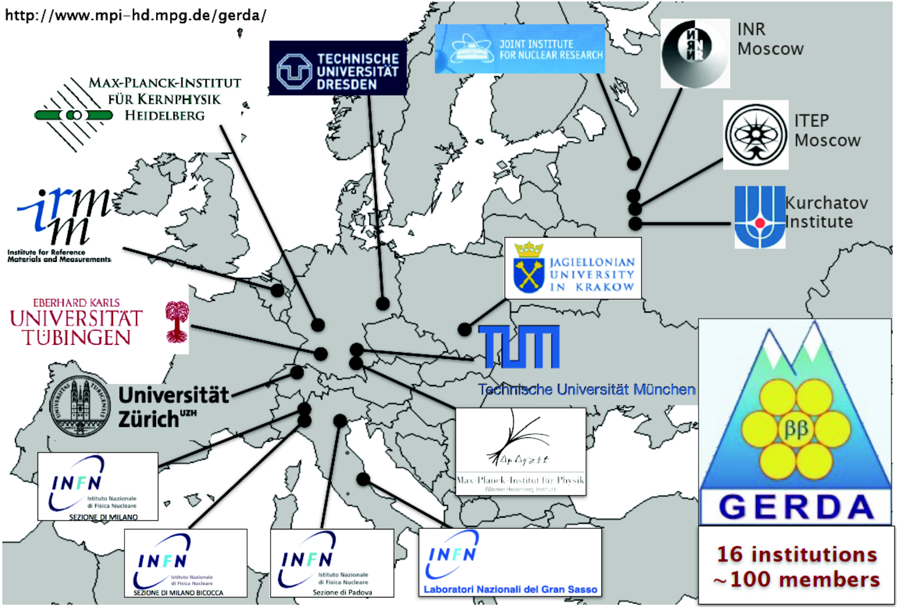
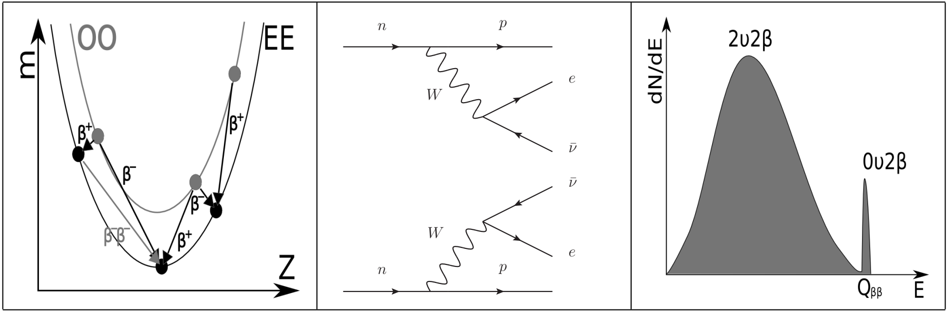
University of Zurich

Cartigny, 11-13 June 2014

The GERDA Collaboration

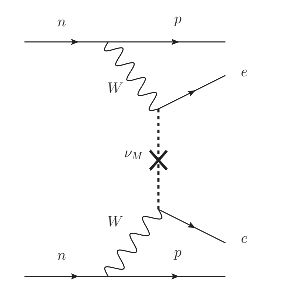


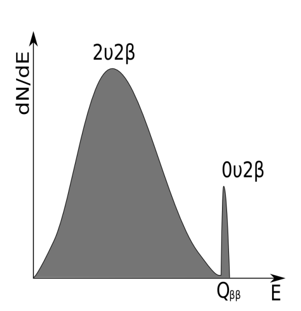
The Double Beta Decay



- If β-decay energetically forbidden $\rightarrow 2\nu2\beta$ decay might be possible
- $2\nu2\beta$ decay introduced by Maria Goeppert-Mayer in 1935
- The experimental spectrum is a continuum ending at the Q-value
- $T^{2\nu}_{1/2}$ usually of order of 10^{19-21} years
- For ^{76}Ge: $T^{2\nu}_{1/2} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21}$ yr*

*J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110





If $0\nu 2\beta$ decay is discovered:

- Lepton number is violated ($\Delta L = 2$)
- Neutrinos have a Majorana mass component
- Physics beyond the Standard Model

Theoretical aspects of $0\nu 2\beta$ decay

- Expected decay rate:
  $$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$
  $G^{0\nu}(Q,Z) =$ Phase Space integral
  $\left|M^{0\nu}\right|^2 =$ nuclear matrix element
  $\langle m_{ee}\rangle^2 = \sum_i U^2_{ei} m_i =$ effective ν mass
  $U_{ei} =$ elements of the PMNS mixing matrix
- Experimental signature: peak at
  $Q_{\beta\beta} = m(A,Z) - m(A,Z-2) - 2m_e$
  (2039 keV for ^{76}Ge)

Number of signal events:

$$N_{sig}^{0\nu} = \frac{f_{76} \cdot N_A}{m_A} \frac{\ln 2}{T_{1/2}^{0\nu}} \varepsilon \cdot M \cdot t$$

Number of background events:

$$N_{bkg} = M \cdot t \cdot BI \cdot \Delta E$$

Experimental sensitivity:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2 \cdot N_A}{n_\sigma \sqrt{2}} \frac{f_{76} \cdot \varepsilon}{A} \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

f_{76} = enrichment fraction

N_A = Avogadro number

m_A = atomic mass

ε = efficiency

M = detector mass

t = livetime

$M \cdot t$ = exposure

BI = Background Index

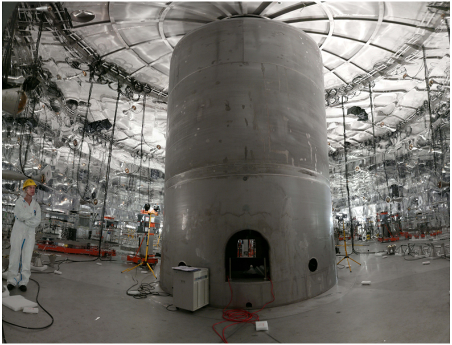
ΔE = energy resolution

n_σ = Confidence Level

Advantages of Ge

Disadvantages of Ge

- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden
- Array of bare enriched Ge detectors in liquid argon (LAr)
- Minimal amount of material in proximity of the diodes



Experiment structure

- 590 m^3 Water Tank to absorb neutrons and veto cosmic muons
- 64 m^3 Liquid Argon (LAr) for cooling and shielding (and vetoing)
- Plastic scintillators above the cryostat to veto cosmic muons

The two phases of GERDA (from the Proposal to LNGS):

	Mass [kg]	BI [counts/(keV·kg·yr)]	Livetime [yr]	Expected $T^{0\nu}_{1/2}$ Sensitivity [yr]
Phase I	15	10^{-2}	1	$2.2 \cdot 10^{25}$
Phase II	35	10^{-3}	3	$2 \cdot 10^{26}$

The time-line of GERDA:

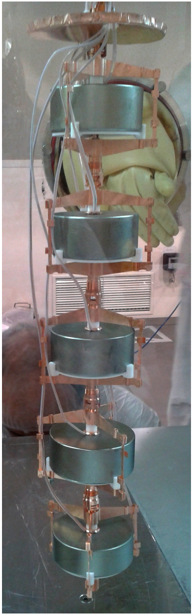
- 2008 - 2010: Construction of GERDA
- 2010 - 2011: Commissioning of GERDA Phase I
- Nov. 2011 - May 2013: Phase I data taking
- Oct. 2013 - now: Phase II preparation
- Autumn 2014: Start of Phase II

Coaxial detectors

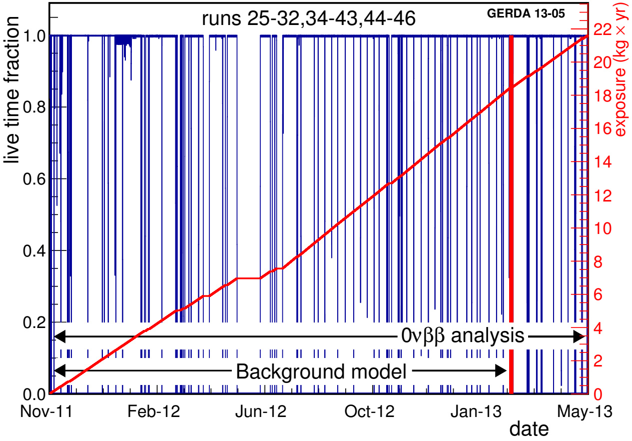
- $\sim$ 86% isotopically enriched in ^{76}Ge
- 5 enr-Ge ("ANG") detectors from Heidelberg-Moscow (HdM), 3 enr-Ge ("RG") from IGEX, 3 nat-Ge from Genius Test Facility (GTF)
- detectors reprocessed at Canberra before being used
- $\sim 2‰$ FWHM at 2.6 MeV
- Total enriched mass: 17.7 kg
- Two detectors turned off because of high leakage current $\rightarrow$ total enriched mass 14.6 kg

BEGe detectors (design for Phase II)

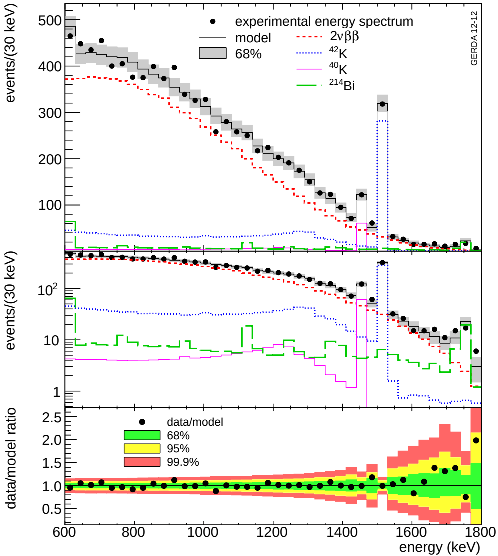
- BEGe = Broad Energy Germanium
- $\sim 1‰$ FWHM at 2.6 MeV
- Enhanced Pulse Shape Discrimination (PSD)
- $\sim$ 20 kg of BEGe's successfully produced and tested in 2012
- 5 BEGe's inserted in GERDA in July 2012



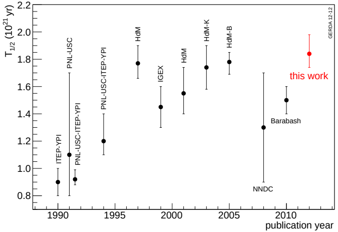
- Total Phase I exposure: 21.6 kg·yr between 9th Nov 2011 and 21st May 2013
- Total livetime of 492.3 days with 88% duty factor
- 5% of data not used due to temperature-related instability of the electronics
- Used for analysis: 6 enr-Ge coaxial detectors (14.6 kg) and 4 BEGe (3.0 kg)
- Blinding of events in the [2019; 2059] keV range!



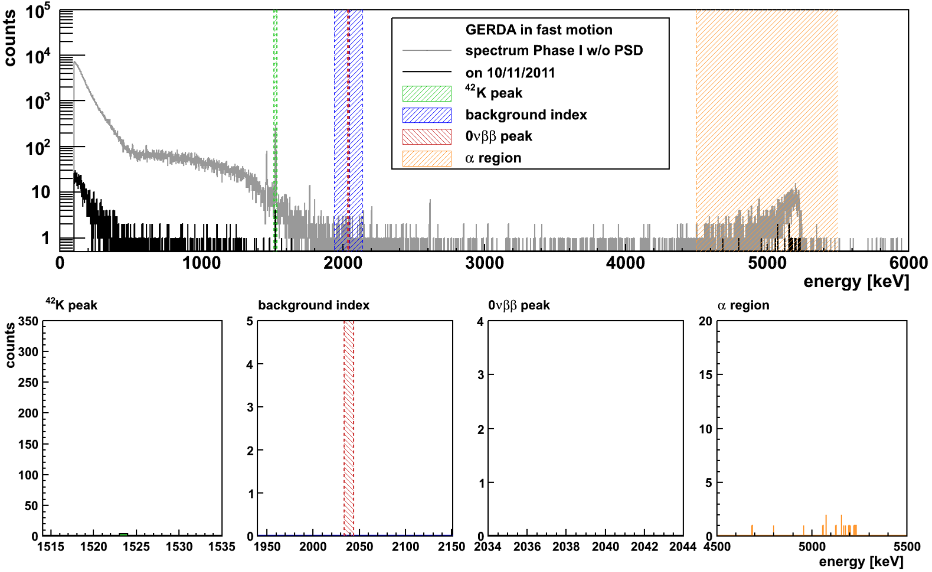
- Spikes: (Bi)-weekly calibration runs
- Flat parts: BEGe's insertion (June 2012), maintenance operations
- Dataset for background model: Nov 2011 - March 2013
- Dataset for $0\nu2\beta$ analysis: Nov 2011 - May 2013

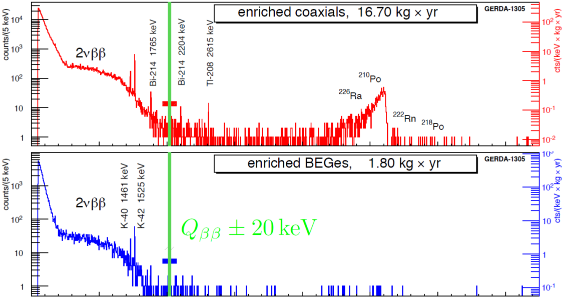


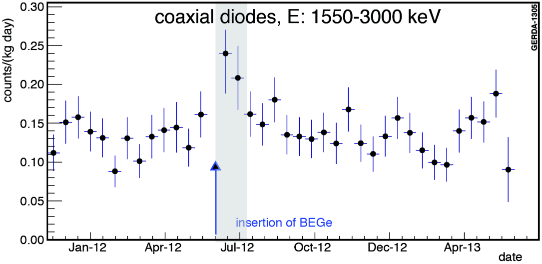
- Measured by GERDA with 5.04 kg·yr exposure
- Very simple background model due to high signal-to-background ratio
- $T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr
- J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110



The Background of GERDA Phase I

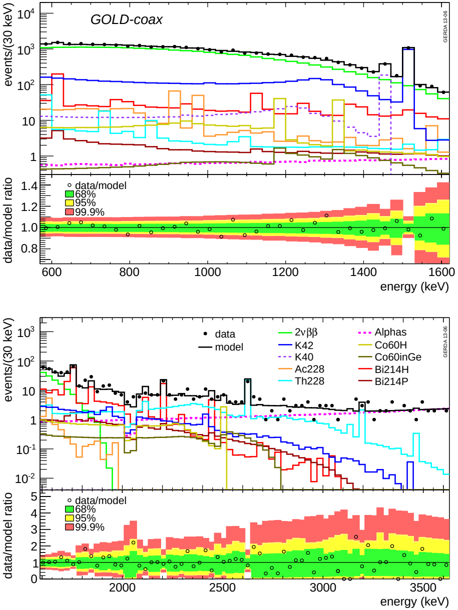






- Split coaxial data in two sets, according to the BI
- Golden: all the coax data, but July 2012
- Silver: coax data taken in June and July 2012 (removal of two nat-coaxial and insertion of BEGe's)
- BEGe data kept separated, due to different resolution and background

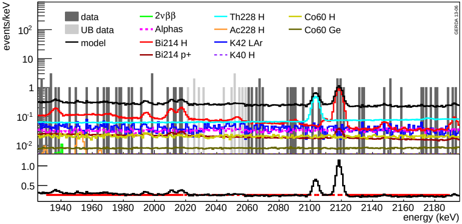
dataset	exposure [kg·yr]
Golden	17.90
Silver	1.30
BEGe	2.40

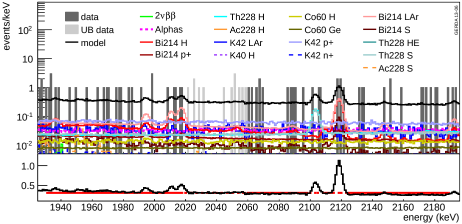


Minimum model for Golden dataset

- Only known and visible contributions considered
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- No hint for any different behavior in the last 3 months of data
- Background Model published: arXiv:1306.5084v1
- Alternative (maximum) model constructed, including all possible backgrounds

- Both min and max model predict a flat bkg at $Q_{\beta\beta}$ $\rightarrow$ unblind side-bands!
- BI predicted form bkg models and fitted from data are in agreement





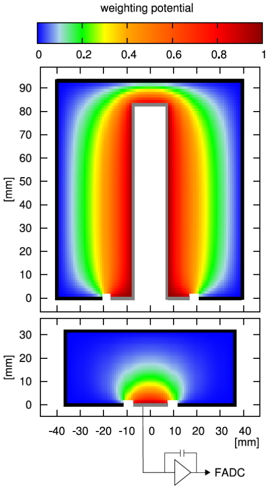
BI before PSD interpolated in the Region of Interest:

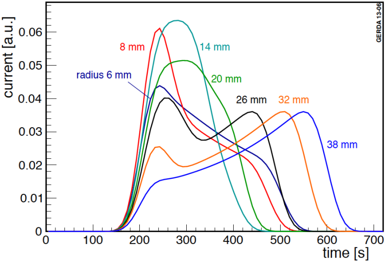
	GOLD-coax	SUM-BEGe
	BI in ROI before PSD (10 keV for coaxial, 8 keV for BEGe) $[10^{-3}$cts/(keV·kg·yr)]	
interpolation	17.5[15.1, 20.1]	36.1[26.4, 49.3]
minimum	18.5[17.6, 19.3]	38.1[37.5, 38.7]
maximum	21.9[20.7, 23.8]	-

Analysis recipe: fit with Gaussian peak and flat background in the 1930-2190 keV region, excluding known gamma peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi).

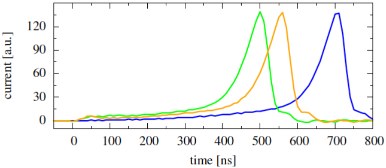
Pulse Shape Discrimination: arXiv:1307.2610

- PSD: distinguish between ($0\nu2\beta$) signal-like events (SSE) and background-like events (MSE, p^+)
- Different PSD needed for coaxial and BEGe detectors





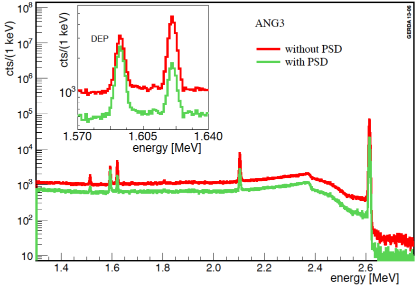
- Simulated current pulse in coaxial detector



- Simulated current pulse in BEGe

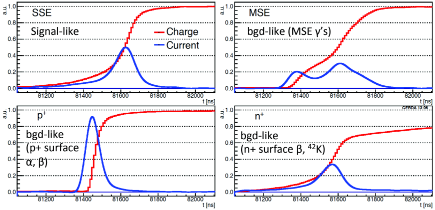
Coaxial: Artificial Neural Network (ANN)

- Applied to 50 rise-times (1,3,. . . ,99%) with TMVA/TMlpANN
- SSE training with signal-like ^{208}Tl DEP at 1592 keV
- MSE training with background-like ^{212}Bi FEP at 1621 keV
- Cut adjusted for each detector to have 90% survival probability on DEP



BEGe: A/E

- A = amplitude of current pulse
- E = energy
- High capability of distinguishing SSE from MSE, p$^+$ and n$^+$ events
- Well tested and documented method*



- Acceptance for $2\nu2\beta$: 0.91 ± 0.05
- Acceptance for $0\nu2\beta$: 0.92 ± 0.02

[a] JINST 4 (2009) P10007; JINST 3 (2011) P03005; arXiv:1307.2610

From counts to half-life

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot \varepsilon$$

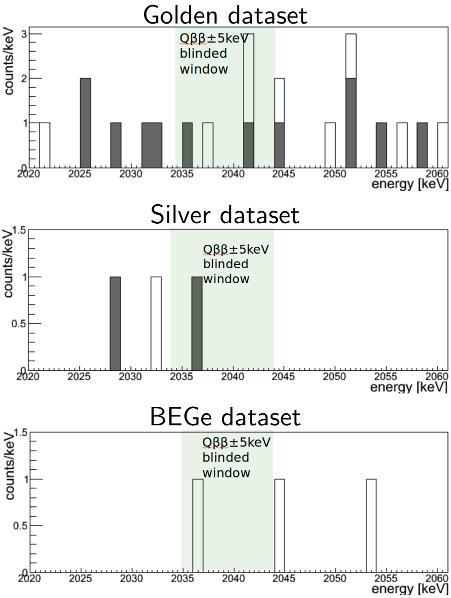
$$\varepsilon = f_{76} \cdot f_{AV} \cdot \varepsilon_{FEP} \cdot \varepsilon_{PSD}$$

Dataset	Exposure M·t [kg·y]	f_{76}	f_{AV}	ε_{FEP}	ε_{PSD}
Golden	17.9	0.86	0.87	0.92	0.90
Silver	1.3	0.86	0.87	0.92	0.90
BEGe	2.4	0.88	0.92	0.90	0.92

N_A = Avogadro number
m_{enr} = molar mass of enr-Ge
$N^{0\nu}$ = signal counts/limit
t = livetime
f_{76} = enrichment fraction
f_{AV} = active volume fraction
ε_{FEP} = FEP efficiency for $0\nu2\beta$
ε_{PSD} = signal acceptance

Fitting method

- Fit 3 datasets with Gaussian over flat background
- 4 parameters: 3 bkg levels and $T^{0\nu}_{1/2}$ with the constraint $1/T^{0\nu}_{1/2} > 0$
- Fixed parameters: $\mu = 2039.07 \pm 0.007$ keV and $\sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1)$ keV for coaxial/BEGe
- Systematic uncertainties on f, ε, μ, σ: MC sampling and averaging



Profile Likelihood Method

- best fit $N^{0\nu} = 0$
- No excess of signal over bkg
- 90% C.L. lower limit:

$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\ \text{yr}$$

Bayesian Approach

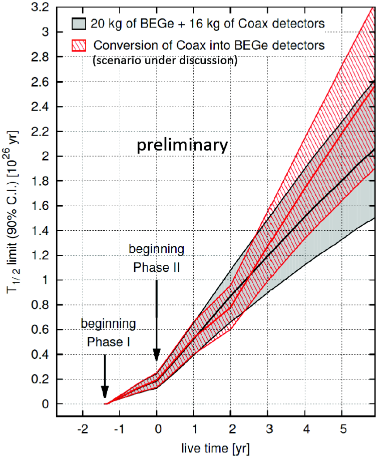
- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]\ \text{yr}^{-1}$
- best fit $N^{0\nu} = 0$
- 90% credibility interval:

$$T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}\ \text{yr}$$

Phys. Rev. Lett. 111 (2013) 122503

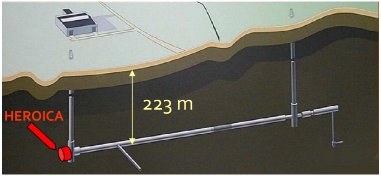
How to reach 10^{26} yr sensitivity in $T^{0\nu}_{1/2}$?

- Increase the statistics
  - More active mass (new BEGe detectors)
  - Longer data taking
- Improve energy resolution
  - Use BEGe detectors
  - Improve shaping filter
- Reduce Background
  - Cleaner cables and electronics
  - Lighter detector holders
  - Special care in crystal production
  - Reject residual background radiation
    - Improve PSD (BEGe detectors)
    - Read LAr scintillation light



Production and Characterization of 30 Enriched BEGe Detectors*

- 35 kg of Ge crystal 86% enriched in ^{76}Ge produced ad Canberra Oak Ridge (US)
- Ge crystals stored underground before shipment to Europe
- 30 BEGe detectors produced at Canberra Olen (Be)
- Complete characterization performed with the HEROICA setup in the Hades underground facility at SCK·CEN in Mol (Be)



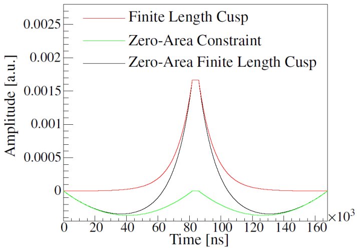
Performed tests

- High Voltage scan with ^{60}Co
- Average top surface dead layer (DL) determination with ^{133}Ba and ^{241}Am
- Active volume (AV) determination with ^{60}Co
- PSD performance with ^{228}Th

*E. Andreotti et al., JINST 8 (2013) P06012

The Zero-Area Cusp (ZAC) filter

- The semi-Gaussian filters does not specifically filter low-frequency noise
- Best noise whitening filter: infinite cusp
- In presence of low-frequency 1/f noise: zero-area filter
- Result: zero-area cusp filter

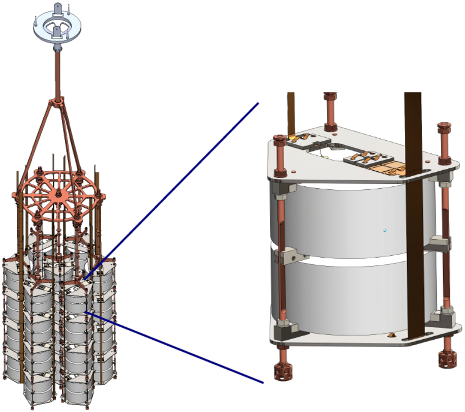


- ZAC successfully tested on Phase I data, and will be used for all Phase II

Detector	FWHM [keV] Semi-Gaussian Shaping	FWHM [keV] ZAC Shaping	Improvement [keV]
ANG2	4.73	4.29	0.44
ANG3	4.62	4.29	0.33
ANG4	4.41	4.11	0.30
ANG5	4.17	3.87	0.30
RG1	4.67	4.19	0.48
RG2	5.06	4.86	0.20
Agamennone	2.86	2.70	0.16
Andromeda	2.88	2.75	0.13
Anubis	2.91	2.79	0.12
Achilles	3.59	2.85	0.74

*G. Benato et al., TAUP 2013, Poster 130

Phase II Detector Assembly*



The Phase II detector array

- Closer detecor $\rightarrow$ better anti-coincidences
- 7 strings, 1 in the middle, 6 outside
- BEGe mounted in pairs, coaxial separately

The detector holder

- Reduce as much as possible the material in vicinity of Ge
- Replace Cu with mono-crystalline Si
- Factor 1.5 reduction in Cu and PTFE for kg of Ge

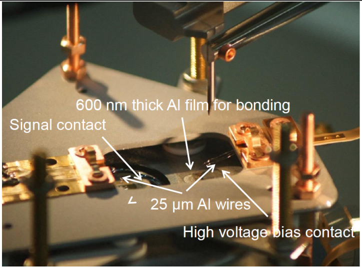
Material and radioactivity budget (^{228}Th)

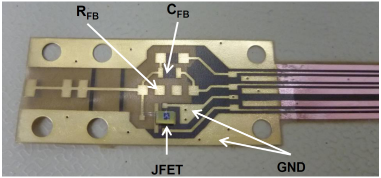
- Phase I: 1μBq per kg of detector mass
- Phase II: 0.4(0.3)μBq per kg of BEGe (coaxial)

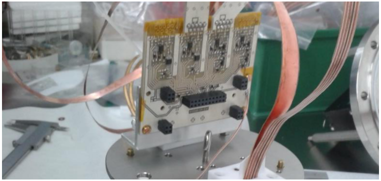
* V. Wagner, DPG 2014, HK 15.5
T. Bode, DPG 2014, T 105.1

Contacting

- HV and signal contacts realized with ultrasonic bonding at LNGS
- Thin Al film deposite on Ge to allow bonding
- Bonds made of 25 μm thick Al wires
- Low mass, reliable contacts





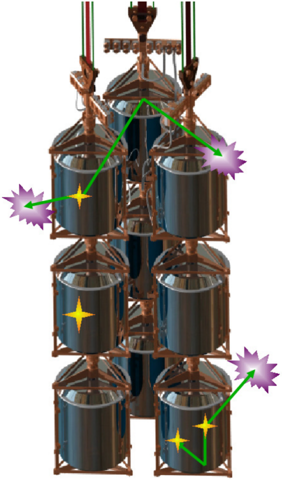


Front-end electronics

- Separate very front-end (VFE) JFET and FE charge sensitive amplifier (CC3)
- Minimize mass in vicinity of Ge
- More radioactive and complex parts (CC3) at $\sim$ 50 cm from Ge detectors
- BEGe have low capacitance: cables between diode and JFET increase the input capacitance C_{in} $\rightarrow$ shorter cables = less noise

*V. Wagner, DPG 2014, HK 15.5; T. Bode, DPG 2014, T 105.1

LAr Scintillation Veto for Background Suppression*



Possible events are:

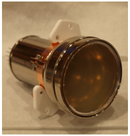
- $\beta\beta$ events, releasing energy "only" in Ge
- γ's can do multiple scattering and release energy both in Ge and Lar $\rightarrow$ veto!
- Surface α and β events
  - Different pulse shape due to energy release in dead layer: PSD
  - Might release energy in LAr, too $\rightarrow$ veto!

How does the LAr veto work?

- Energy released in LAr induces scintillation light
- $\lambda = 128$ nm, $\sim 4 \cdot 10^5$ pe/MeV
- Solution: install light detectors in LAr in "vicinity" of the Ge diodes!

*A. Wegmann, DPG 2014, HK 15.1

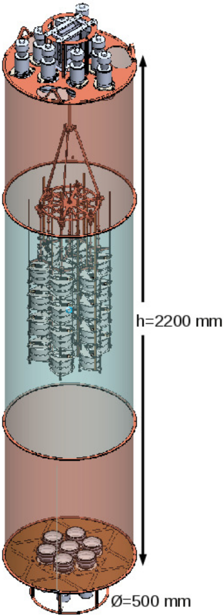
Photomultipliers



- 3" R11065-20 MOD
- 9 on top, 7 at bottom

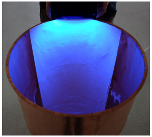
Scintillating fibers

- BCF-91A, TPB coated
- Light readout at both ends by SiPM on top



Top/bottom Cu shroud with reflective foil

- Tetratex coated with TPB as wavelength shifter (WLS)
- Installed on inner side of Cu shroud



Nylon mini-shrouds

- transparent → compatible with LAr instrumentation
- Coated with WLS
- One for each Ge string

Summary

- Phase I data taking successfully completed
- $T^{2\nu}_{1/2} = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{21}$ yr (90% CL)

Outlook

- Upgrade for Phase II is ongoing
- Aimed sensitivity: $2 \cdot 10^{26}$ yr
- Expected start of Phase II: late 2014 - early 2015