Improvement of the Energy Resolution via an Optimized Digital Signal Processing in GERDA Phase I

ISSP 2015

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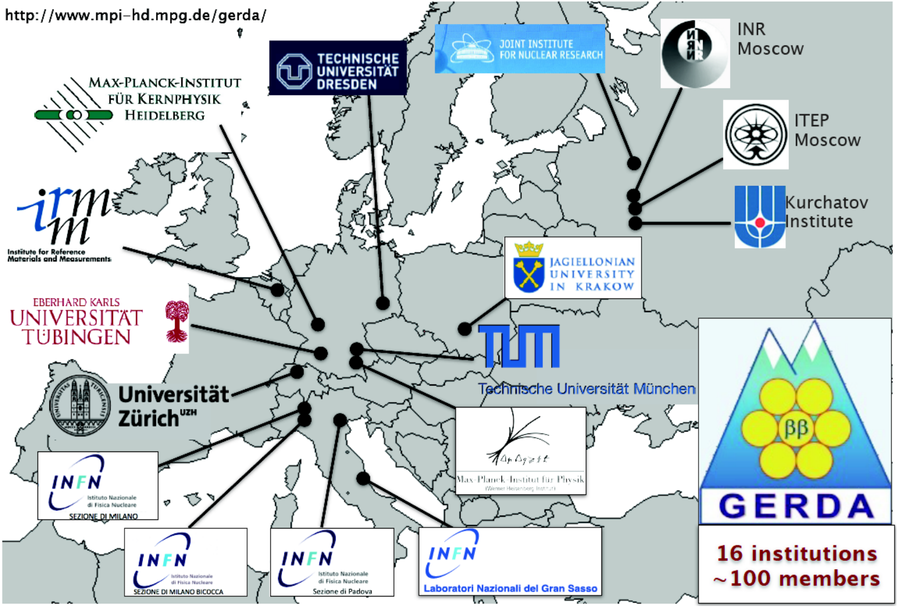
http://www.mpi-hd.mpg.de/gerda/



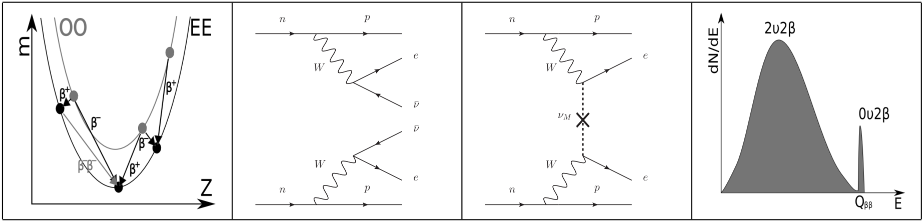
Investigating the Neutrino nature

Open questions

- Is lepton number conservation violated?
- Is the neutrino a Majorana particle?
- What's the absolute neutrino mass scale?
- What's the neutrino mass hierarchy?

Possible answer: double beta decay

- Occurs in even-even isobars
- Measurable if single β decay energetically forbidden
- Rare process $\rightarrow$ ultra-low bkg required!



$2\nu\beta\beta$ decay

- Allowed in the SM, ΔL=0
- Signature: continuum from 0 to $Q_{\beta\beta}$
- Half life: $T^{2\nu}_{1/2} \sim (10^{18}\text{-}10^{24})$ yr
- $T^{2\nu}_{1/2}(^{76}\text{Ge}) = \left(1.926 \pm 0.095\right) \cdot 10^{21}$ yr
  ArXiV:1501.02345

$0\nu\beta\beta$ decay

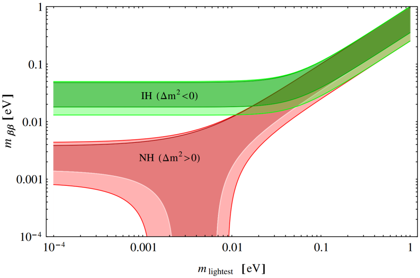
- Non-SM process, ΔL=2
- Possible only if neutrinos have Majorana mass component
- Signature: peak at $Q_{\beta\beta}$(^{76}Ge: 2039 keV)

The mass mechanism

- For light Majorana ν exchange:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

- $G^{0\nu}(Q,Z)$ = Phase Space integral
- $\left|M^{0\nu}\right|^2$ = nuclear matrix element
- $\langle m_{\beta\beta}\rangle^2 = \sum_i U_{ei}^2 m_i$ = effective ν mass
- U_{ei} = PMNS mixing matrix elements



Phys. Rev. D90 (2014) 033005

Experimental sensitivity:

- Number of signal events:

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

- Number of background events:

$$n_B = BI \cdot \Delta E \cdot M \cdot t$$

where:

f = enrichment fraction

N_A = Avogadro number

m_A = atomic mass

ε = total efficiency

M = detector mass

t = live time

$M \cdot t$ = exposure

BI = Background Index

ΔE = Region Of Interest (ROI)

Why using germanium?

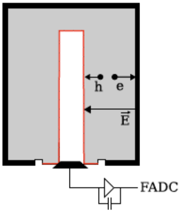
- High total efficiency: $\varepsilon \sim 0.75$
- Best energy resolution on the market: $\sim 1.5‰$ Full Width at Half Maximum (FWHM) at $Q_{\beta\beta}$
- Can be enriched to 86% in ^{76}Ge

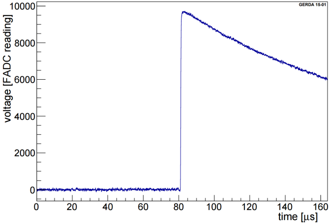
How to reduce the background?

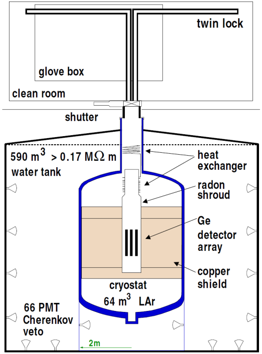
- Operate the experiment underground
- Use active veto for cosmic muons and external radiation
- Minimize radioactive contamination in the materials close to the detectors
- Current pulse is different for single site events (like $0\nu\beta\beta$ signal) versus multi-site events (like Compton scattered γ) or surface events
  $\rightarrow$ Pulse Shape Discrimination (PSD)

Ge detector readout

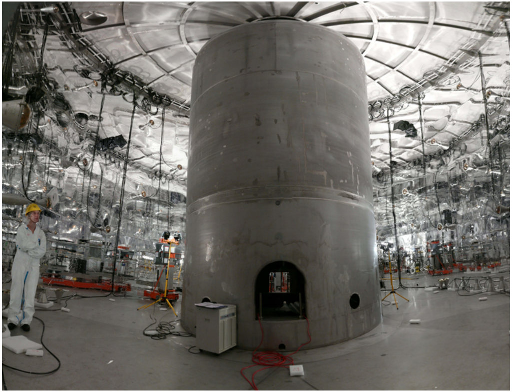
- Ge diode in reverse bias
  $\rightarrow$ measurement of ionization energy
- FADC allows offline analysis of recorded signals (energy, rise time, PSD parameters, ...)







- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden (μ flux ~ 1 m^{-2}h^{-1}))
- Array of bare Ge detectors 86% enriched in ^{76}Ge directly inserted in liquid argon (LAr)



Why Liquid Argon + Water?

Material	^{208}Tl Activity [μBq/Kg]
Rock, concrete	3000000
Stainless steel	~ 5000
Cu (NOSV), Pb	< 20
Purified water	< 1
LN_2, LAr	~ 0

The two phases of GERDA

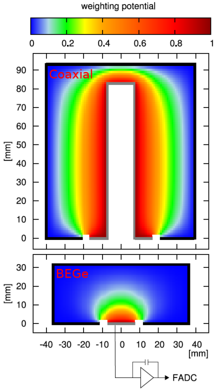
	Mass [kg]	Expected BI [counts/(keV·kg·yr)]	Live time [yr]	Expected $T_{1/2}^{0\nu}$ Sensitivity [yr]
Phase I	15	10^{-2}	1	$2.4 \cdot 10^{25}$
Phase II	35	10^{-3}	3	$1.4 \cdot 10^{26}$

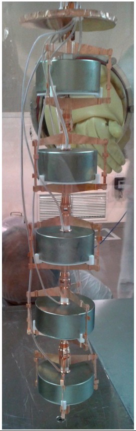
Coaxial detectors

- Inherited from HdM and IGEX experiments
- 2.4‰ FWHM at $Q_{\beta\beta}$ (1.7‰ reachable with better cables & improved signal shaping)
- Total enriched mass: 17.7 kg (analysis on 14.6 kg)

BEGe detectors (design for Phase II)

- BEGe = Broad Energy Germanium
- 1.6‰ FWHM at $Q_{\beta\beta}$ (1.2‰ reachable)
- Enhanced PSD
- $\sim$ 20 kg of BEGe's produced and tested in 2012
- 5 BEGe's inserted in GERDA in July 2012





Sensitivity and energy resolution

$n_B \propto \Delta E \propto FWHM_{Q_{\beta\beta}} \rightarrow$ Need to minimize FWHM for a lower background

$$FWHM(E) = 2.355 \cdot \sqrt{ENC^2 + \eta\, F\, E + c^2\, E^2}$$

where: $ENC =$ Electronic Noise Charge

$\eta =$ average electron-hole pair creation energy (2.96 eV in Ge)

$F =$ Fano factor (~ 0.11 in Ge)

$c =$ charge collection and integration term

Shaping filters and ENC

$$ENC^2 = \alpha \frac{2kT}{g_m \tau_s} C_T^2 + \beta C_T^2 + \gamma \left(e(I_G + I_L) + \frac{2kT}{R_f} \right) \tau_s$$

where: $C_T =$ total capacitance (detector, feedback, preamplifier input)

$\tau_s =$ filter shaping time

$I_G =$ gate current

$I_L =$ leakage current

$R_F =$ feedback resistance

$g_m =$ JFET trasconductance

$\alpha, \beta, \sigma =$ normalization constants related to filter's shape

GERDA energy reconstruction

- Full traces digitized with FADC
- Digital pseudo-Gaussian filter ($25 \times 5\ \mu$s moving average)
- Same filter parameters for all detectors and all Phase I data

Possible improvements

- Stability of energy scale
- "Intrinsic" energy resolution of calibration data
- "Effective" energy resolution of physics data at $Q_{\beta\beta}$

Strategy

- Develop a new digital shaping filter tuned on the experimental noise figure
  $\rightarrow$ Enhanced noise whitening, less sensitive to 1/f noise
- Correct preamplifier response function
- Tune the filter separately for each detector
- Split the Phase I data in different data sets, according to the detector configurations and the noise conditions

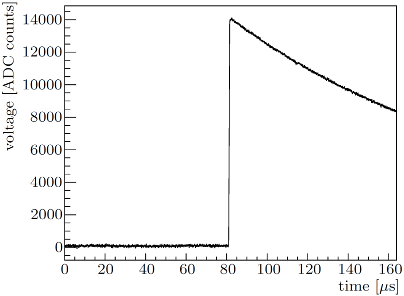
The ZAC filter

- Sinh-like cusp $\rightarrow$ optimal shaping filter for δ-like traces of finite length
- Central flat top (FT) $\rightarrow$ maximize charge integration
- Total zero-area $\rightarrow$ filter out 1/f noise
- Baseline subtraction best performed with parabolic filters

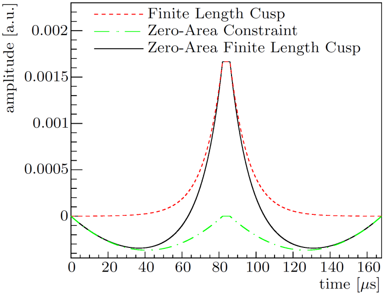
$$ZAC(t) = \begin{cases} \sinh\left(\frac{t}{\tau_s}\right) + A\left[\left(t - \frac{L}{2}\right)^2 - \frac{L}{2}^2\right] & 0 < t < L \\ \sinh\left(\frac{L}{\tau_s}\right) & L < t < L + FT \\ \sinh\left(\frac{2L+FT-t}{\tau_s}\right) + A\left[\left(\frac{3}{2}L + FT - t\right)^2 - \left(\frac{L}{2}\right)^2\right] & L + FT < t < 2L + FT \end{cases}$$

Final filter

- Deconvolution of the preamplifier response function: $f_\tau = \{1, -\exp\left(-\Delta t/\tau\right)\}$
- Final filter through convolution of ZAC with f_τ: $FF(t) = ZAC(t) * f_\tau(t)$

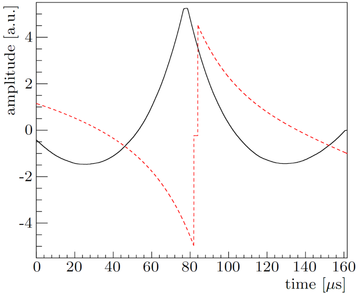


Original waveform

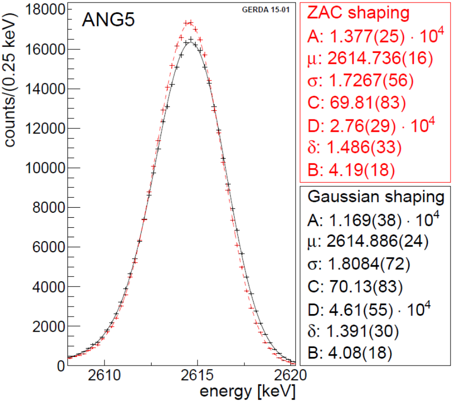


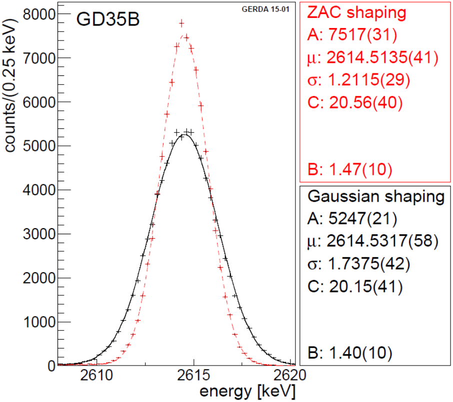
ZAC filter

Final filter FF (dashed red) and filtered waveform (black)

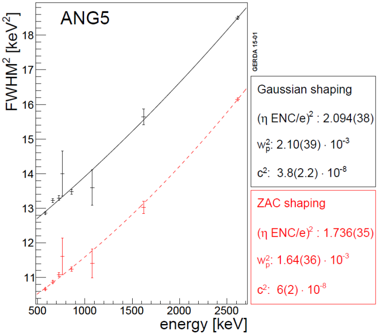


Comparison of the 2614.5 keV Peak



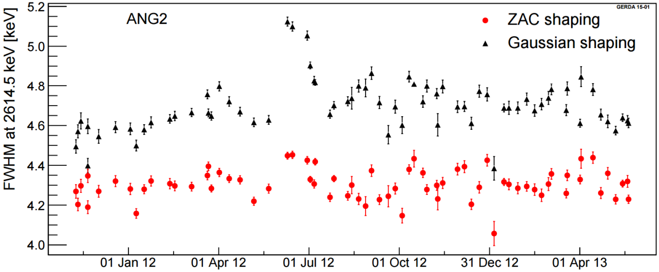


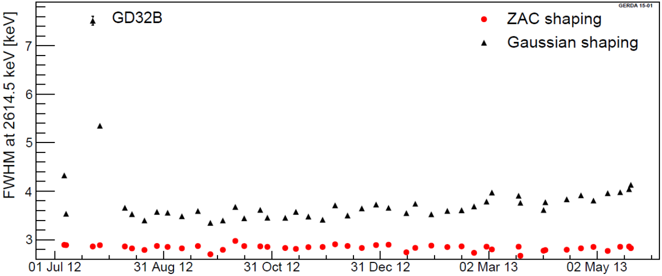
- All Phase I calibration spectra summed-up, same events considered in both cases
- Energy resolution improved in all cases
- Low-energy tail reduced thanks to better charge integration



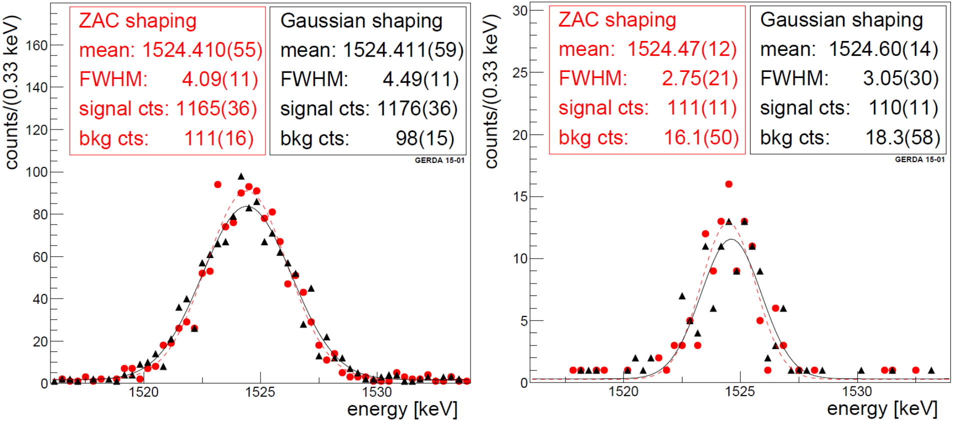
Detector	FWHM at 2614.5 keV Gaussian	ZAC	Improvement [keV]
ANG2	4.712(3)	4.314(3)	0.398(4)
ANG3	4.658(3)	4.390(3)	0.268(4)
ANG4	4.458(3)	4.151(3)	0.307(4)
ANG5	4.323(3)	4.022(3)	0.301(4)
RG1	4.595(4)	4.365(4)	0.230(6)
RG2	5.036(5)	4.707(4)	0.329(6)
GD32B	2.816(4)	2.699(3)	0.117(5)
GD32C	2.833(3)	2.702(3)	0.131(4)
GD32D	2.959(4)	2.807(3)	0.152(5)
GD35B	3.700(5)	2.836(3)	0.864(6)

- Greatest improvement obtained on ENC^2
- Average improvement in FWHM at 2614.5 keV on all Phase I calibration data is 0.30 keV for coaxial and 0.13 keV for BEGes (GD35B excluded)
- Higher improvement for GD35B due to better treatment of low-frequency disturbance by the ZAC filter



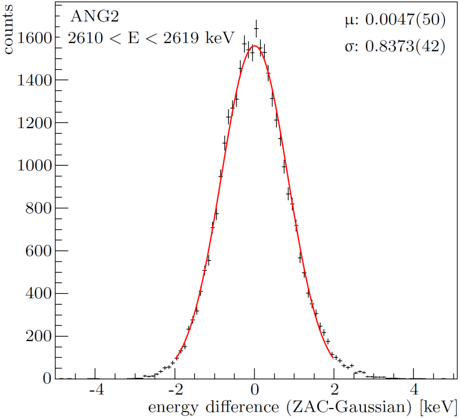


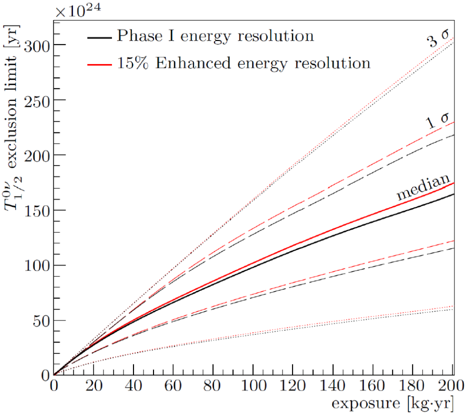
- ZAC filter insensitive to microphonic disturbance of ANG2 (June 2012)
- FWHM brought to nominal for GD35B for all Phase I duration



- ^{42}K peak at 1524.6 keV is the only spectral line in the physics spectrum
- Improvement of $\sim$ 0.4 keV, about 0.1 keV larger than expected for calibration data due to higher precision in the estimation of the calibration curves and lower sensitivity to time evolution of microphonics during physics run
- FWHM improvement at $Q_{\beta\beta}$ estimated to be $\sim$ 0.5 keV for both coaxial and BEGe detectors

Cross-Checks and Outlook





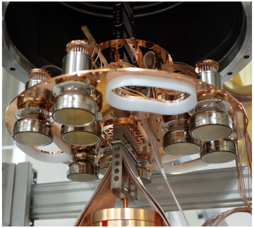
- No surprise in the event-by-event energy difference (verified on physics data, too)
- Phase II $0\nu\beta\beta$ median sensitivity increased by $\sim$ 5%
- Same recipe for filter optimization will be used in Phase II
- Reprocessed Phase I data will be combined with Phase II data for $0\nu\beta\beta$ decay analysis
- GERDA Collaboration, Eur. Phys. J. C (2015) 255.

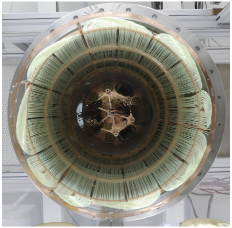
Results with GERDA Phase I data

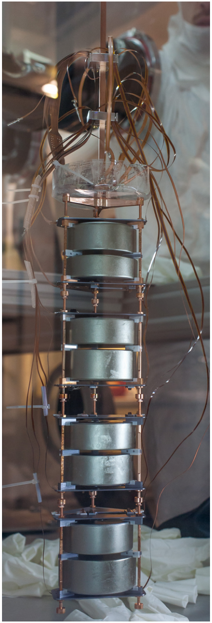
- Energy resolution improved by $\sim$ 15% at $Q_{\beta\beta}$
- Low-frequency noise problem solved by the use of ZAC filter

GERDA Phase II

- Using same filter optimization approach, $\sim$ 5% improvement is expected
- Start of Phase II in 2015, commissioning ongoing. Stay tuned!







Optimization of the ZAC filter

- Phase I data divided in 5 periods according to detector configuration
- Filter optimization performed for 2-3 calibration runs of each period
- Scan parameter space, fit ^{208}Tl peak at 2614.5 keV, compute FWHM

$$f(E) = A\exp\left(-\frac{(E-\mu)^2}{2\sigma^2}\right) + B + \frac{C}{2}\mathrm{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma}\right) + \frac{D}{2}\exp\left(\frac{E-\mu}{\delta}\right)\mathrm{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma} + \frac{\sigma}{\sqrt{2}\delta}\right)$$

- The optimal parameters are stable within each period

Reprocessing of calibration and physics Phase I data

- Create tier2 (uncalibrated spectra) of calibration data using optimized ZAC filter
  $\rightarrow$ Extract calibration curves, produce stability plots (e.g. FWHM vs time)
- Create tier3 (calibrated spectra) of calibration data
  $\rightarrow$ Further stability plots (deviations from literature, ...)
- Produce tier2 and tier3 of physics data using optimized ZAC filter