Performances of Germanium Detectors by Optimized Readout and Digital Filtering Techniques in the Framework of the GERDA Experiment.

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1. The Neutrinoless Double Beta Decay

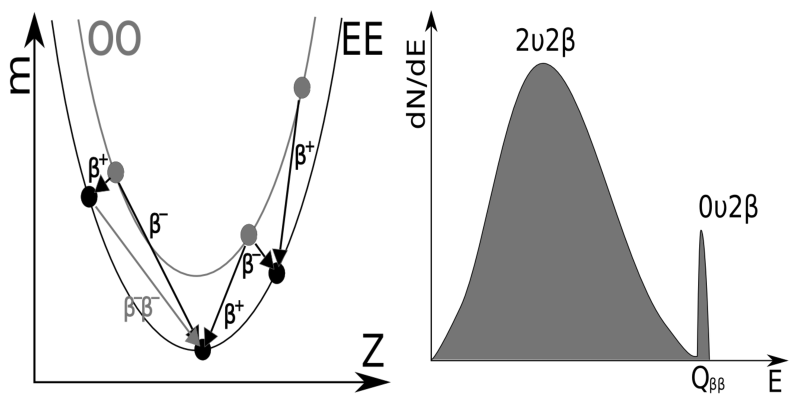
The two neutrino double beta decay ($2\nu 2\beta$) is a second order process, described by the Standard Model (SM), which takes place when the usual beta decay is energetically forbidden. In the neutrinoless decay mode ($0\nu 2\beta$), one neutrino is exchanged between two decaying neutrons: it is not foreseen by the SM but could happen if:

- the neutrino is a Majorana particle ($\nu = \bar{\nu}$) of non-vanishing mass;
- the lepton number conservation is violated (by two units);

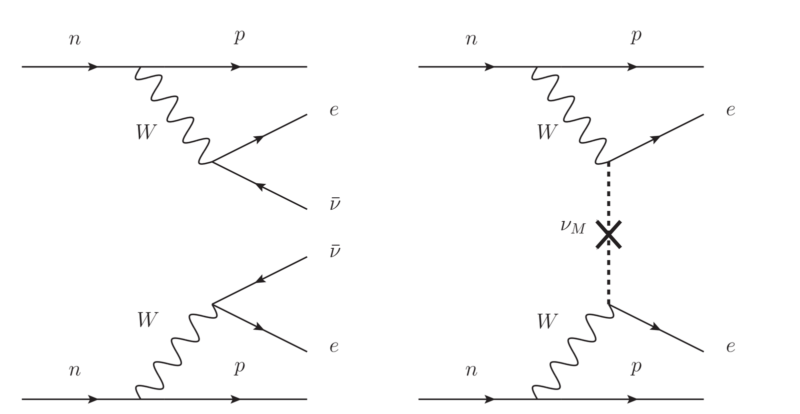
The $0\nu 2\beta$ decay half-life is given by:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = F^{0\nu}|M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Where $F^{0\nu}$ is the phase space, $M^{0\nu}$ the nuclear matrix element, $\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2$ and $Q_{\beta\beta}$ is the Q-value.
The experimental signature is a continuum energy spectrum arising from zero to the Q-value of the reaction for the $2\nu 2\beta$ mode and a peak at the Q-value for the $0\nu 2\beta$.



Left: the $2\nu 2\beta$ decay can take place if the single beta decay is energetically forbidden. Right: expected signature for the $2\nu 2\beta$ and $0\nu 2\beta$ decay (not in scale).



Left: in the $2\nu 2\beta$ decay two independent β decays takes place at the same time. Right: in the $0\nu 2\beta$ decay only two electrons are emitted.

2. The Experimental Sensitivity to $0\nu 2\beta$ Decay

The energy resolution is a crucial parameter for obtaining physics results. It is usually given as the Full Width at Half Maximum (FWHM = 2.35σ) of the spectral peaks, once fitted by a Gaussian and in GERDA is quoted at $Q_{\beta\beta}$.
An improved resolutions involves:

- higher sensitivity to the presence of background-induced gamma peaks;
- more precision in the construction of the background model;
- in case a $0\nu 2\beta$ decay signal is present, more precision in the computation of the number of $0\nu 2\beta$ decay events;
- in case no $0\nu 2\beta$ decay signal is present, a stronger limit for the value of its half-life, $T_{1/2}^{0\nu}$.

The achievable limit on $T_{1/2}^{0\nu}$ is:

$$T_{1/2}^{0\nu} \propto a\varepsilon\sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

a = enrichment fraction
ε = efficiency
M = detector mass
t = exposure
BI = Background Index
ΔE = energy resolution

Advantages of Ge
Disadvantages of Ge

3. Digital Signal Processing in the GERDA Experiment

The GERmanium Detector Array (GERDA) experiment at the Gran Sasso National Laboratory is designed to study the $0\nu 2\beta$ decay by using enriched germanium diodes deployed naked in Liquid Argon (LAr). The detectors are protected from the external radiation by a multi-layered shielding made of:

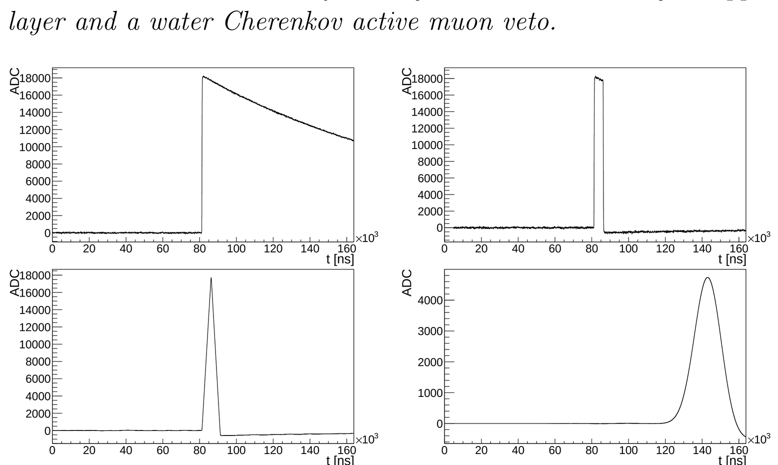
- a water Cherenkov active muon veto;
- copper to absorb gammas;
- LAr to cool down the detectors and further absorb gammas and neutrons.

The energy reconstruction is performed via an offline pseudo-Gaussian shaping applied to the digital waveforms[1]. This procedure consists of 2 steps:

- a differentiation of the sampled signal $x_0[t]$ with time delay $L = 5\ \mu s$:
$$x_0[t] \rightarrow x_1[t] = x_0[t] - x_0[t-L]$$
- a Moving Average (MA) with the same width, repeated 25 times:
$$x_i[t] \rightarrow x_{i+1}[t] = \frac{1}{L}\sum_{t'=t-L}^{t} x_i[t'] \quad i = 1 \ldots 25$$

The energy is then given by the height of the pseudo-Gaussian. This algorithm is stable and relatively fast, but does not take into consideration the different characteristics of the signals in each single detector.

A string with three germanium detectors as they are used in GERDA (left) and a mock-up of the whole experiment (right): the detectors are in a LAr filled cryostat and shielded by a copper layer and a water Cherenkov active muon veto.



The GERDA signal reconstruction: a digitized waveform (top left), the same after the differentiation (top right) and after applying the MA once (bottom left) and 25 time (bottom right).

4. Digital Signal Processing with Germanium Detectors

The energy resolution in a germanium detector depends on two factors:

$$\mathrm{FWHM}^2 = \mathrm{FWHM}_{\mathrm{det}}^2 + \mathrm{FWHM}_{\mathrm{noise}}^2$$

where

- $\mathrm{FWHM}_{\mathrm{det}} = 2.35\sqrt{\varepsilon \cdot F \cdot E}$ represents statistical charge fluctuation ($F = 0.13$ is the Fano factor and $\varepsilon = 2.96$ eV energy to create electron-hole pair);
- $\mathrm{FWHM}_{\mathrm{noise}}$ is the electronic noise of the read-out.

To reduce the contribution of the noise, the signal has to be shaped with a proper filter function. The equivalent noise charge (ENC) for a generic filter has three components: series, 1/f and parallel noise:

$$\mathrm{ENC}^2 = C_T^2\left(\alpha\frac{v^2}{\tau_f} + \gamma A_f\right) + \beta\tau_f i^2$$

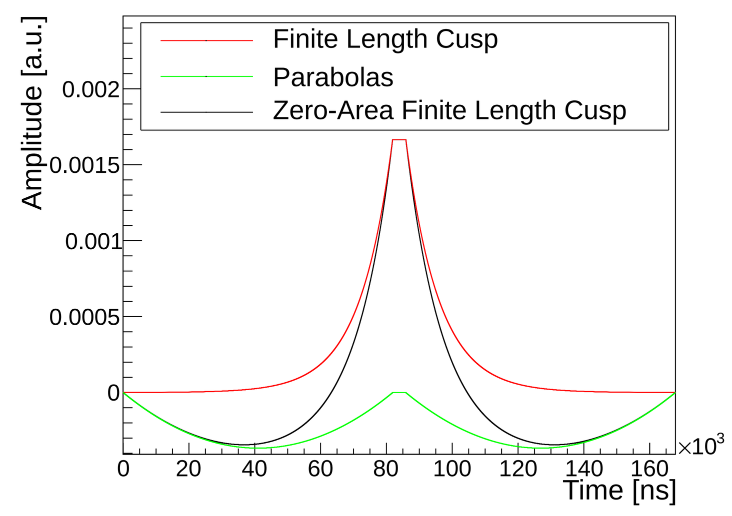
where C_T is the total capacity, α, β, γ are parameters that depends on the filter type, v^2 and i^2 are the root mean values of the series and parallel noise and A_f is the coefficient of 1/f noise. The optimization of τ_f allows to filter out peculiar noise frequencies.

5. Development of a New Filter Algorithm for the Energy Evaluation in GERDA

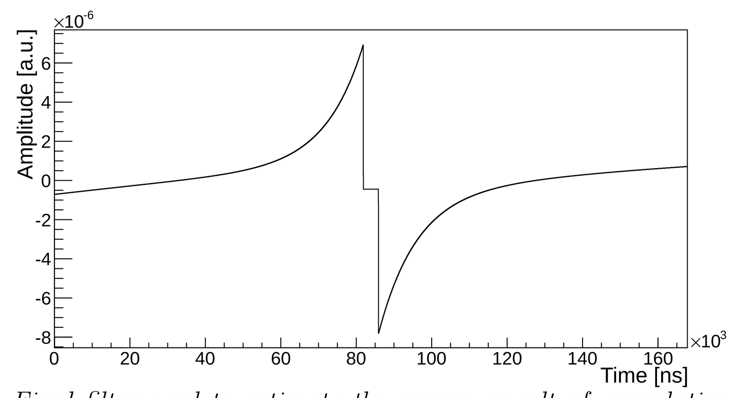
The current energy reconstruction used to process the GERDA data is limited by several factors:

- the same shaping is applied to all the detectors, although the signal formation properties and the noise conditions are different for each of them;
- the pseudo-Gaussian shaping works as a simple low-pass filter, not specifically reducing the 1/f and current low frequency noise;
- the energy computation is composed of 25 operations, which could be substituted by a unique equivalent convolution.

While the theoretical studies show that the best noise whitening filter is the infinite cusp filter[2], in reality, given the finite length of the recorded waveforms, the best resolution is obtained using a **finite cusp-like filter** with the highest length possible. The condition of having **zero area** is introduced in the filter construction in order to remove the low frequency noise. This condition is achieved by subtracting two parabolas to the two parts of the cusp, so that the total area of the final filter is zero. A flat top is then introduced to integrate all the charge released in the diode.
This shaping filter is applied to the current pulse, obtained via a deconvolution of the preamplifier's response function.



Construction of the zero-area finite length cusp filter (black) as the sum of a finite length cusp filter (red) and two negative parabolas (green).



Final filter used to estimate the energy, result of convolution of zero-area finite length cusp filter with the deconvolution filter.

6. Results of the New Filter

The new filter was successfully tested on several GERDA datasets. The first positive results were obtained in the tests of the new preamplifiers for GERDA Phase II. The tests were performed in the Germanium Detector Laboratory (GDL), a GERDA test facility at LNGS. Some GERDA Phase II BEGe detectors were operated in two facilities: the GDL test bench and the Liquid Argon Germanium (LArGe[3]) setup. In the latter, the Phase I front end readout and the detector-to-front-end connections were still present.
In all cases, the evaluation is performed with ^{228}Th calibration data and comparing the FWHM at the 2614.5 keV ^{208}Tl Full Energy Peak (FEP). The best values obtained are:

- FWHM = 2.59 ± 0.01 keV for the GDL data, with an improvement of 1.9 % with respect to the trapezoidal zero-area shaping. The FWHM achieved with an analog spectroscopic amplifier was 2.6 keV.
- FWHM = 3.06 ± 0.01 keV for the LArGe data, with an improvement of 4.3 % with respect to the pseudo-Gaussian shaping

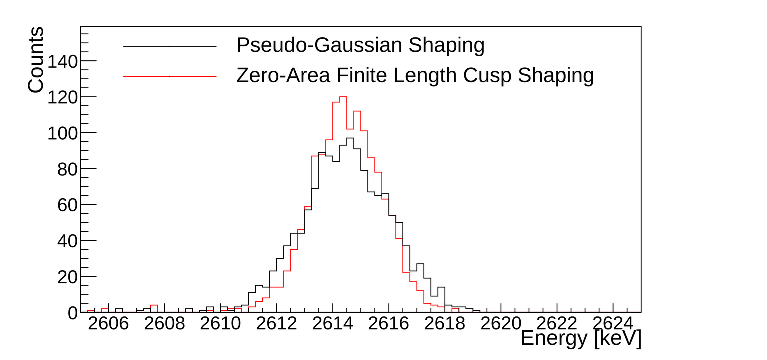
The filter was also tested on GERDA Phase I calibration datasets and optimized for each detector separately, with an overall improvement of the order of 10%. This can be explained by the different noise condition present in GERDA, with the presence of a strong 1/f contribution.
Given the very promising results obtained, all the GERDA Phase I data are currently being reprocessed with the zero-area cusp-like finite length filter.

Detector	FWHM [keV] Pseudo Gaussian	FWHM [keV] Finite Cusp	Improv. [%]	Phase I Exposure [kg·yr]
ANG2	4.74	4.26	10.1	3.81
ANG3	4.67	4.27	8.6	3.21
ANG4	4.35	4.07	6.4	3.19
ANG5	4.21	3.84	8.8	3.69
RG1	4.44	4.17	6.1	2.84
RG2	5.12	4.74	7.4	2.47
GTF112	4.22	3.87	8.3	-
Agamennone	2.88	2.67	7.3	0.55
Andromeda	2.86	2.65	7.3	0.62
Anubis	2.97	2.73	8.1	0.56
Achilles	3.62	2.80	22.7	0.67
Aristoteles	3.10	2.92	5.8	-

Results of the application of new filter on a calibration dataset of GERDA Phase I compared with the pseudo-Gaussian shaping. The values are computed at the 2614.5 keV FEP of ^{228}Tl. The exposure is not reported for two detectors, because they were not used for the analysis of Phase I data.

Shaping Algorithm	FWHM [keV] (Exposure-weighted)
Pseudo-Gaussian	4.41
Finite-Length Zero Area Cusp	4.03

Exposure-weighted FWHM at 2614.5 keV, giving an overall improvement of 8.6%.



^{208}Tl FEP reconstructed with the pseudo-Gaussian shaping and the zero-area finite-length cusp filter for the Achilles detector.

7. Conclusions and Outlook

In this work, new digital filters (Zero Area Cusp-like Finite Impulse Response Filters) have been worked out to improve the energy resolution achieved so far in the GERDA Phase I data analysis. The new filtering algorithms have been applied to several ^{228}Th calibration runs, achieving $\sim 10\%$ improvement on the FWHM, thanks to

- Rejection of fundamental noise: series (voltage) and parallel (current) contributions
- Rejection of pulse tail
- Rejection of detector ballistic deficit: weighting function with flat-top
- Rejection of detector micro-phonics: symmetric and zero-area weighting function

Further improvements are expected by applying specific bandwidth filters to reject disturbances picked-up by the long Phase I detectors-to-front-end unshielded connections. The GERDA sensitivity to $T_{1/2}^{0\nu}$ will take advantage of the improved energy resolution.

References

[1] M. Agostini et al., JINST 6 (2011) P08013
[2] M. O. Deighton, IEEE Trans. Nucl. Sci. 16 (1969) 68-75
[3] M. Heisel, *LArGe: A liquid argon scintillation veto for GERDA*, PhD Thesis, Universität Heidelberg, April 2011