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SIGNAL AND BACKGROUND (PULSE SHAPE) MODELLING FOR THE LEGEND EXPERIMENT

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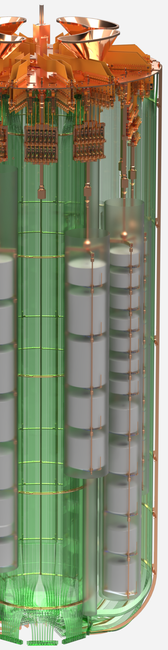
LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

1. The LEGEND experiment



The LEGEND experiment searches for neutrinoless double beta ($0\nu\beta\beta$) decay using active HPGe detectors enriched in ^{76}Ge ($\gtrsim 90\%$) serving both as source of the $\beta\beta$ decaying isotope and as detector of the emitted electrons.

- Observable: sum energy of the two emitted electrons
- $0\nu\beta\beta$ experimental signature: sharp peak at the endpoint of the $2\nu\beta\beta$ spectrum ($Q_{\beta\beta} \simeq 2039$ keV).

$0\nu\beta\beta$ is an extremely rare decay: $T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ yr [1]
⇒ Background suppression is a crucial requirement:

- Experimental setup: underground operation (LNGS), shielding, clean materials.
- Analysis: techniques to discriminate signal-like from background events

LEGEND HPGe detectors are operated as fully depleted diodes: when an interaction takes place within the detector volume, the produced ionization charges drift towards the electrodes. Their motion induces a current on the p^+ readout electrode, which is integrated by a charge-sensitive amplifier. In these charge signals:

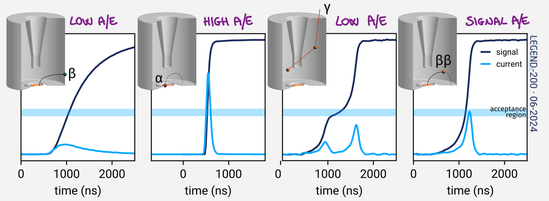
- The amplitude is proportional to the deposited energy
  ↦ excellent energy resolution
- The shape depends on the topology
  ↦ useful PSD properties

2. Pulse shape discrimination (PSD)

In a $0\nu\beta\beta$ event, the two emitted electrons would be absorbed in germanium within ~ 1 mm^3: this defines the topology of signal-like events as highly localized bulk single site events (SSE).

Contrarily, background events can have different topologies:

- multi-site events (MSE) ↦ typically γ events, scattering multiple times
- n^+ surface events ↦ typically external β, penetrating the ~1 mm n^+ layer
- p^+ surface events ↦ typically α from surface contamination, which can penetrate only the thinner p^+ contact



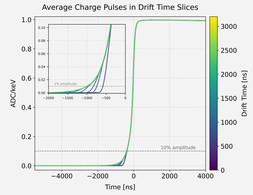
These different topologies originate different charge/current signal shapes, which can be discriminated by PSD parameters, such as A/E:

$$A/E = \frac{\text{amplitude current pulse}}{\text{deposited energy}}$$

3. Pulse shape (discrimination) modelling

The goal of this work is to develop a scalable method for realistic modelling of pulse shape features in simulated (MC) events. This will enable, for the first time in a Ge-based $0\nu\beta\beta$ experiment, the construction of a background model after PSD, built applying the same cuts to data and to simulations. This will result in improved understanding of the residual background and enhanced sensitivity to both $0\nu\beta\beta$ searches and new physics analyses

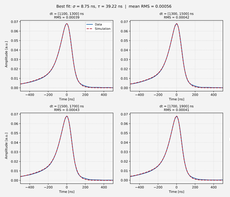
Pulse shapes in data



The time it takes for ionization charge to reach the electrodes (drift time := time max $A - T_0$) depends on the location of the energy deposition.
⇒ drift time slicing of the acquired SSE ↔ virtual scan of the detector volume.

Average pulses are built in drift time slices and the comparison shows that the detector response is highly uniform in the whole bulk, with small deviations only at very low drift time, i.e. for events depositing their energy close to the p^+ contact.

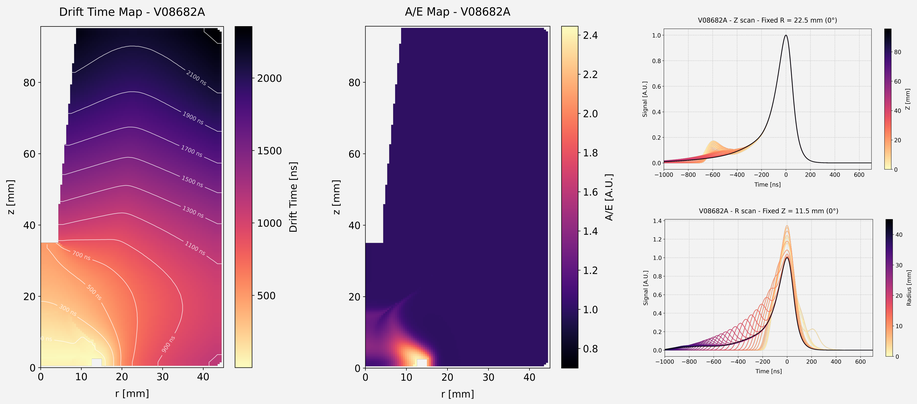
Pulse shape simulation



Realistic HPGe pulse shapes are simulated by combining:

- Full field and charge drift simulation inside the detector, using SSD.jl [2]
- Effective electronics response tuned against real data and applied to ideal pulses by convolution. The tuning of the electronics response is done by minimizing the RMS between the simulated average current pulses and the average current pulses from data in all the suitable drift time slices. At best fit parameters the full pulse shape is correctly modelled.

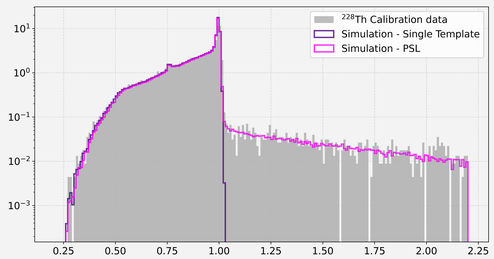
The described PSS method produces high fidelity simulated pulses, but it is not possible to run the full PSS for every MC event (performance)
⇒ need a method to extract the PSD parameters directly at the MC level, bypassing the full PSS for each event
Solution: template-based A/E semi-heuristic estimation ↦ the topology information, coming directly from the MC steps, is merged with the expected pulse shape response of the detector in the locations of the energy deposits
⇒ position-dependent template needed: provided as simulated realistic pulse shape library (PSL).

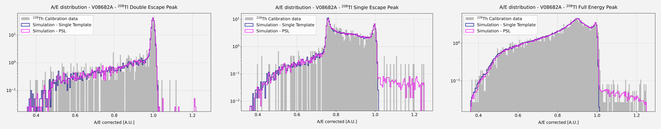


The PSL is built by simulating realistic pulses (SSD.jl charge drift + tuned electronics) for point-like 2039 keV energy depositions on a 0.5 mm [R,Z] grid on the two main crystal axes [0°,45°], yielding a fine scan of the full detector.
⇒ realistic templates available both for bulk events (negligible position-dependence) and for p^+ events (strong position-dependence).
⇒ using pulses in PSL we can build a simulated A/E map of the HPGe detector: as expected the response is extremely uniform in the whole bulk, while it shows large deviations close to the p^+ contact.

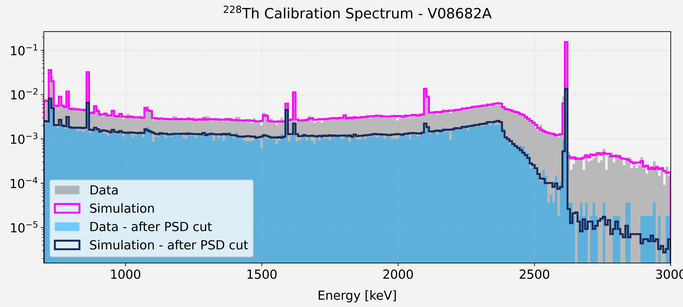
4. Results

The A/E distribution for a simulated ^{228}Th calibration (peak) reproduces all the features of the corresponding distribution in data (gray): the SSE peak at A/E = 1, the MSE distribution at A/E < 1 and the p^+ events tail at A/E > 1. In particular, the latter was missed entirely by previous methods (violet) based on a single pulse shape template (no position dependent).





With the full A/E distribution correctly modelled, it is now possible to apply the same A/E cuts in simulations and data.
To test the method, we simulate the ^{228}Th LEGEND calibration spectrum:



The simulated spectrum reproduces correctly the data both before (gray/magenta) and after (light/dark blue) the PSD cuts.

The obtained results show that the developed method successfully models both bulk and p^+ events in LEGEND HPGe detectors: this provides the tools to build, for the first time in Ge-based $0\nu\beta\beta$ experiments, a background model of the physics data after PSD cuts. This will enable a more accurate characterization of background around $Q_{\beta\beta}$, eventually enhancing the $0\nu\beta\beta$ discovery sensitivity. And the sensitivity to many beyond standard model physics searches, such as exotic $\beta\beta$ decay modes appearing as $2\nu\beta\beta$ spectral distortions.

LEGEND Institutions

Centre for Energy, Environmental and Technological Research
Comenius Univ.
Czech Technical Univ. in Prague and IEAP
Daresbury Laboratory
Duke Univ. and Triangle Universities Nuclear Laboratory
Gran Sasso Science Institute
Hochschule Rhein-Main
Indiana Univ. Bloomington
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Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and Center for Experimental Nuclear Physics and Astrophysics
Univ. of Zurich

References:

1. LEGEND Collaboration, First results on the search for lepton number violating neutrinoless double beta decay with the LEGEND-200 experiment
2. J. Abt et al., Simulation of semiconductor detectors in 3D with SolidStateDetectors.jl

Check out our software:

LEGEND-SimFlow
REBOOST
RHAGE