IL NUOVO CIMENTO **45 C** (2022) 145
DOI 10.1393/ncc/i2022-22145-1

COMMUNICATIONS: SIF Congress 2021

Synthetic data for the CUORE experiment

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received 31 January 2022

Summary. — CUORE (Cryogenic Underground Observatory for Rare Events) is a ton-scale experiment located at LNGS (Laboratori Nazionali del Gran Sasso), Italy, whose goal is to search for neutrino-less double beta decay ($0\nu\beta\beta$) in ^{130}Te. The proposed research deals with the generation of synthetic (mock) data for the study of the CUORE detector response function. The production of synthetic data is a new tool we designed to consider all the missing information from a Monte Carlo simulation: the detector non-idealities, as well as noise and pulse shape.

1. – The CUORE experiment

The Cryogenic Underground Observatory for Rare Events (CUORE) [1] is a ton-scale experiment based at the INFN Laboratori Nazionali del Gran Sasso (LNGS), in Assergi (AQ), Italy. The goal of the experiment is to investigate the $0\nu\beta\beta$ decay of ^{130}Te. It is instrumented with an array of 988 TeO_2 crystals housed in a custom-designed cryostat [2] operated at a stable temperature of $\sim$10 mK, since 2017. The total TeO_2 mass is 742 kg, corresponding to 206 kg of ^{130}Te. Each crystal acts as an independent low-temperature detector (figs. 1(a) and (b)).

2. – CUORE data acquisition and processing

The data acquisition and processing consist of a series of steps designed to obtain the energy spectrum. First, data are acquired and digitized in a continuous stream mode at a sampling rate of 1 kHz. A trigger algorithm setting a threshold on the derivative of the continuous stream is used to identify particle signals. The triggered data are divided into windows of 10 seconds each. We also randomly acquire noise windows to build the optimum filter [3] that we use to evaluate the amplitude of the signals:

$$V_{OF} \propto \frac{S(\omega)^*}{|N(\omega)|^2} e^{i\omega\tau_{max}}\ V(\omega), \tag{1}$$

where $S(\omega)^*$ is the complex conjugate of the Fourier transform of the ideal detector response $s(t)$, $|N(\omega)|^2$ is the Noise Power Spectrum (NPS), $V(\omega)$ is the signal, and τ_{max} the time at which the signal reaches its maximum. We choose the ideal detector response to be the Average Pulse (AP) computed on trigger data, and $|N(\omega)|^2$ to be the Average Noise Power Spectrum (ANPS) computed on noise windows.

Fig. 1. – (a) CUORE towers. (b) CUORE detectors.

3. – The CUORE "mock" software

The CUORE "mock" software exploits noise time series simulations to create a stream of synthetic data. It mimics the acquisition of experimental data, starting from the particle interaction simulation to the storage of triggered and continuous data. The software inputs are an NPS and a pulse shape. The NPS is needed for the generation of the noise time series, and the pulse shape to construct pulses: they are added directly to the continuous stream (fig. 2) with amplitude and time obtained with a Monte Carlo simulation of the radiation interaction with the crystals. After being generated, data are ready to be processed with the CUORE official analysis software. The heart of synthetic data production is the noise time series generation which can be a difficult task when a precise model of the noise sources is missing. We build the noise time series according to the algorithm proposed in [4, 5]. It is based on Carson's theorem: the superposition of randomly delayed pulses of a definite shape $f(t)$ with arbitrary coefficient A gives rise to a pulse train $n(t)$:

$$n(t) = A \sum_k f(t - t_k). \tag{2}$$

The delays t_k are distributed according to Poisson statistics. The goal of the algorithm is to find a suitable $f(t)$ from an NPS to build a complete buffer of noise $n(t)$. Figure 3 (blue) shows the final result of the algorithm ($n(t)$) starting from the noise template ($f(t)$) computed with an Average NPS (ANPS) from CUORE data (fig. 3 (orange)).

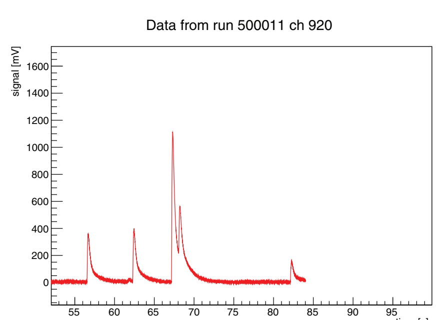

Fig. 2. – Simulated detector stream of data.

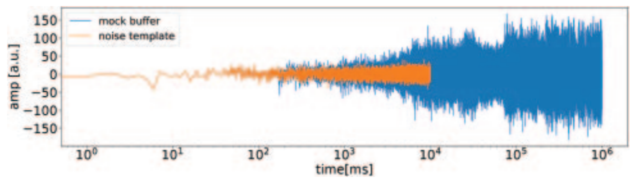

Fig. 3. – Superposition of starting noise window (orange). Simulated noise time series (blue).

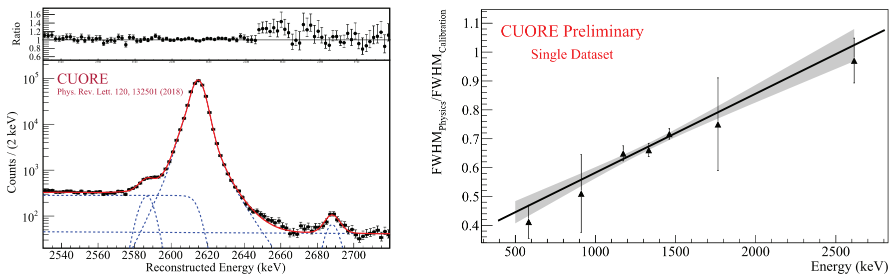

Fig. 4. – (a) CUORE detector response function. (b) Resolution *vs.* energy.

The A in eq. (2) is a proper coefficient needed for the noise RMS rescaling of the final buffer (fig. 3 (blue)).

4. – Detector response function and energy resolution

In CUORE [6], we model the detector response to the mono-energetic $0\nu\beta\beta$ decay signal based on the measured response to the ^{208}Tl γ-peak (2615 keV) in calibration measurements. We call the profile of the detector response function at ^{208}Tl the *lineshape*: a superposition of three slightly shifted Gaussian distributions with the same width (fig. 4(a)). Aside from the non-ideal detector response function, we also observe a relation between resolution and energy (fig. 4(b)). The extrapolated resolution (FWHM) at the Q-value is $\approx$7.8 keV to be compared with $\approx$3 keV noise width. In order to investigate the origin of the *lineshape* and energy resolution trend as a function of energy, we produced different sets of synthetic data. We found deviations from a Gaussian response of the

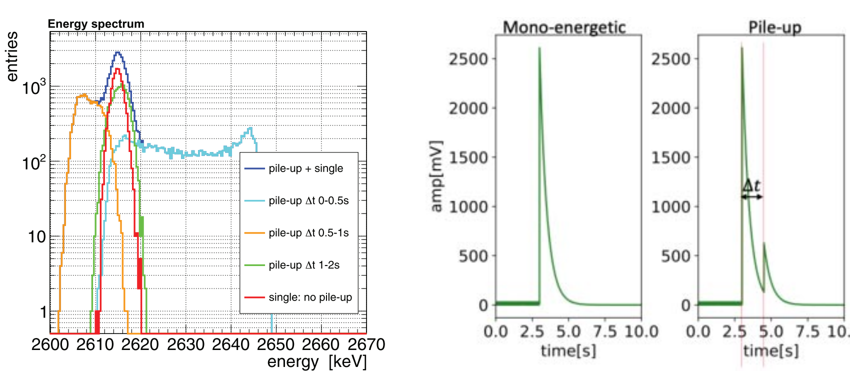

Fig. 5. – (a) Energy spectrum (Δt = time between pulses). (b) Events in pile-up tests.

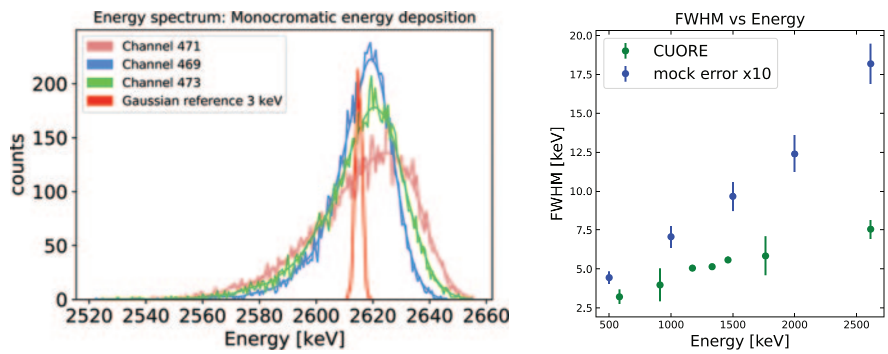

Fig. 6. – (a) Detector response to 2615 keV deposition. (b) Energy resolution *vs.* energy.

detector when simulating extremely high pile-up conditions. Figure 5(a) shows the result of the test: the energy spectrum produced applying the optimum filter to the simulated data. In the pile-up test, the continuous stream of data was half composed by mono-energetic deposition (2615 keV), and half by pile-up, fig. 5(b). We were also able to obtain an energy resolution trend as a function of energy by implementing an accurate phenomenological model to construct the pulses in the continuous stream. The model is based on the fit of the CUORE pulses [7,8]. We built a simulation with pulse shape from our model, taking into account fluctuations and correlations of the fit parameters, and fixed pulse amplitude (2615 keV). Figure 6(a) shows the energy spectrum: the peak shape deviates from a Gaussian profile and the resolution has the same order of magnitude as the CUORE one. We also simulated increasing energy depositions and found a resolution trend compatible with the CUORE experimental one, fig. 6(b).

5. – Conclusions

The proposed study demonstrates how synthetic data are efficient in approaching the study of the CUORE detector response function. In fact, we found contributions to the peak shape due to pile-up and obtained an energy resolution trend as a function of energy by injecting pulses in the continuous stream with an accurate theoretical model. The study, even if preliminary, is giving promising results, paving the way for the understanding of the CUORE detector response function.

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