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Authors

Armatol, A
Armengaud, E
Armstrong, W
[et al.](#)

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A novel technique for the study of pile-up events in cryogenic bolometers

A. Armatol,¹ E. Armengaud,¹ W. Armstrong,² C. Augier,³ F. T. Avignone III,⁴ O. Azzolini,⁵ A. Barabash,⁶ G. Bari,⁷ A. Barresi,^{8,9} D. Baudin,¹ F. Bellini,^{10,11} G. Benato,¹² M. Beretta,¹³ L. Bergé,¹⁴ M. Biassoni,⁸ J. Billard,³ V. Boldrini,^{15,7} A. Branca,^{8,9} C. Brofferio,^{8,9} C. Bucci,¹² J. Camilleri,¹⁶ S. Capelli,^{8,9} L. Cappelli,¹² L. Cardani,¹⁰ P. Carniti,^{8,9} N. Casali,¹⁰ A. Cazes,³ E. Celi,^{12,17} C. Chang,² M. Chapellier,¹⁴ A. Charrier,¹⁸ D. Chiesa,^{8,9} M. Clemenza,^{8,9} I. Colantoni,^{10,19} F. Collamati,¹⁰ S. Copello,^{20,21} F. Cova,^{8,9} O. Cremonesi,⁸ R. J. Creswick,⁴ A. Cruciani,¹⁰ A. D'Addabbo,^{12,17} G. D'Imperio,¹⁰ I. Dafinei,¹⁰ F. A. Danevich,²² M. de Combarieu,¹⁸ M. De Jesus,³ P. de Marcillac,¹⁴ S. Dell'Oro,^{16,8,9} S. Di Domizio,^{20,21} V. Dompè,^{12,17} A. Drobizhev,²³ L. Dumoulin,¹⁴ G. Fantini,^{10,11} M. Fasoli,^{8,9} M. Faverzani,^{8,9} E. Ferri,^{8,9} F. Ferri,¹ F. Ferroni,^{10,17} E. Figueroa-Feliciano,²⁴ J. Formaggio,²⁵ A. Franceschi,²⁶ C. Fu,²⁷ S. Fu,²⁷ B. K. Fujikawa,²³ J. Gascon,³ A. Giachero,^{8,9} L. Gironi,^{8,9} A. Giuliani,¹⁴ P. Gorla,¹² C. Gotti,⁸ P. Gras,¹ M. Gros,¹ T. D. Gutierrez,²⁸ K. Han,²⁹ E. V. Hnassen,¹³ K. M. Heeger,³⁰ D. L. Helis,¹ H. Z. Huang,^{27,31} R. G. Huang,^{13,23} L. Imbert,¹⁴ J. Johnston,²⁵ A. Juillard,³ G. Karapetrov,³² G. Keppel,⁵ H. Khalife,¹⁴ V. V. Kobychyev,²² Yu. G. Kolomensky,^{13,23} S. Konovalov,⁶ Y. Liu,³³ P. Loaiza,¹⁴ L. Ma,²⁷ M. Madhukuttan,¹⁴ F. Mancarella,^{15,7} R. Mariam,¹⁴ L. Marini,^{13,23,12} S. Marnieros,¹⁴ M. Martinez,^{34,35} R. H. Maruyama,³⁰ B. Mauri,¹ D. Mayer,²⁵ Y. Mei,²³ S. Milana,¹⁰ D. Misiak,³ T. Napolitano,²⁶ M. Nastasi,^{8,9} X. F. Navick,¹ J. Nikkel,³⁰ R. Nipoti,^{15,7} S. Nisi,¹² C. Nones,¹ E. B. Norman,^{13,36} V. Novosad,² I. Nutini,^{8,9} T. O'Donnell,¹⁶ E. Olivieri,¹⁴ C. Oriol,¹⁴ J. L. Ouellet,²⁵ S. Pagan,³⁰ C. Pagliarone,¹² L. Pagnanini,^{12,17} P. Pari,¹⁸ L. Pattavina,^{12,*} B. Paul,¹ M. Pavan,^{8,9} H. Peng,³⁷ G. Pessina,⁸ V. Pettinacci,¹⁰ C. Pira,⁵ S. Pirro,¹² D. V. Poda,¹⁴ T. Polakovic,² O. G. Polischuk,²² S. Pozzi,^{8,9} E. Previtali,^{8,9} A. Puiu,^{12,17} A. Ressa,^{10,11} R. Rizzoli,^{15,7} C. Rosenfeld,⁴ C. Rusconi,¹² V. Sanglard,³ J. Scarpaci,¹⁴ B. Schmidt,^{24,23} V. Sharma,¹⁶ V. Shlegel,³⁸ V. Singh,¹³ M. Sisti,⁸ D. Speller,^{39,30} P. T. Surukuchi,³⁰ L. Taffarello,⁴⁰ O. Tellier,¹ C. Tomei,¹⁰ V. I. Tretyak,²² A. Tsymbaliuk,⁵ A. Vedda,^{8,9} M. Velazquez,⁴¹ K. J. Vetter,¹³ S. L. Wagaarachchi,¹³ G. Wang,² L. Wang,³³ B. Welliver,²³ J. Wilson,⁴ K. Wilson,⁴ L. A. Winslow,²⁵ M. Xue,³⁷ L. Yan,²⁷ J. Yang,³⁷ V. Yefremenko,² V. Yumatov,⁶ M. M. Zarytsky,²² J. Zhang,² A. Zolotarova,¹⁴ and S. Zucchelli^{7,42}

(CUPID Collaboration)

¹IRFU, CEA, Université Paris-Saclay, Saclay, France

²Argonne National Laboratory, Argonne, IL, USA

³Institut de Physique des 2 Infinis, Lyon, France

⁴University of South Carolina, Columbia, SC, USA

⁵INFN Laboratori Nazionali di Legnaro, Legnaro, Italy

⁶National Research Centre Kurchatov Institute, Institute for Theoretical and Experimental Physics, Moscow, Russia

⁷INFN Sezione di Bologna, Bologna, Italy

⁸INFN Sezione di Milano - Bicocca, Milano, Italy

⁹University of Milano - Bicocca, Milano, Italy

¹⁰INFN Sezione di Roma, Rome, Italy

¹¹Sapienza University of Rome, Rome, Italy

¹²INFN Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy

¹³University of California, Berkeley, CA, USA

¹⁴Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

¹⁵CNR-Institute for Microelectronics and Microsystems, Bologna, Italy

¹⁶Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

¹⁷Gran Sasso Science Institute, L'Aquila, Italy

¹⁸IRAMIS, CEA, Université Paris-Saclay, Saclay, France

¹⁹CNR-Institute of Nanotechnology, Rome, Italy

²⁰INFN Sezione di Genova, Genova, Italy

²¹University of Genova, Genova, Italy

²²Institute for Nuclear Research of NASU, Kyiv, Ukraine

²³Lawrence Berkeley National Laboratory, Berkeley, CA, USA

²⁴Northwestern University, Evanston, IL, USA

²⁵Massachusetts Institute of Technology, Cambridge, MA, USA

²⁶INFN Laboratori Nazionali di Frascati, Frascati, Italy

²⁷Fudan University, Shanghai, China

²⁸California Polytechnic State University, San Luis Obispo, CA, USA

²⁹Shanghai Jiao Tong University, Shanghai, China

³⁰Yale University, New Haven, CT, USA

³¹University of California, Los Angeles, CA, USA

³²Drexel University, Philadelphia, PA, USA

³³Beijing Normal University, Beijing, China

³⁴Centro de Astropartículas y Física de Altas Energías, Universidad de Zaragoza, Zaragoza, Spain

³⁵ARAID Fundación Agencia Aragonesa para la Investigación y el Desarrollo, Zaragoza, Spain

³⁶Lawrence Livermore National Laboratory, Livermore, CA, USA

³⁷University of Science and Technology of China, Hefei, China

³⁸Nikolaev Institute of Inorganic Chemistry, Novosibirsk, Russia

³⁹Johns Hopkins University, Baltimore, MD, USA

⁴⁰INFN Sezione di Padova, Padova, Italy

⁴¹Laboratoire de Science et Ingénierie des Matériaux et Procédés, Grenoble, France

⁴²University of Bologna, Bologna, Italy

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Precise characterization of detector time resolution is of crucial importance for next-generation cryogenic-bolometer experiments searching for neutrinoless double-beta decay, such as CUPID, in order to reject background due to pile-up of two-neutrino double-beta decay events. In this paper, we describe a technique developed to study the pile-up rejection capability of cryogenic bolometers. Our approach, which consists of producing controlled pile-up events with a programmable waveform generator, has the benefit that we can reliably and reproducibly control the time separation and relative energy of the individual components of the generated pile-up events. The resulting data allow us to optimize and benchmark analysis strategies to discriminate between individual and pile-up pulses. We describe a test of this technique performed with a small array of detectors at the Laboratori Nazionali del Gran Sasso, in Italy; we obtain a 90% rejection efficiency against pulser-generated pile-up events with rise time of ~ 15 ms down to time separation between the individual events of 2 ms.

I. INTRODUCTION

Two-neutrino double-beta decay ($2\nu\beta\beta$), despite being a rare process, constitutes a dominant fraction of intrinsic radioactivity in low-background neutrinoless double-beta decay ($0\nu\beta\beta$) [1] detectors. Excellent detector energy resolution is essential to distinguish between $2\nu\beta\beta$ decays and $0\nu\beta\beta$ decay candidates. However, for next-generation $0\nu\beta\beta$ searches, aiming at unprecedented low backgrounds, random pile-up of $2\nu\beta\beta$ events can constitute a non-negligible continuum background in the region of interest (ROI) around the $0\nu\beta\beta$ transition Q-value [2].

Cryogenic bolometers meet the requirements of excellent energy resolution, low background and large mass needed for a high-sensitivity $0\nu\beta\beta$ decay search. These detectors have set some of the most stringent limits on the $0\nu\beta\beta$ decay half-life in multiple isotopes, in particular ^{82}Se [3], ^{100}Mo [4] and ^{130}Te [5, 6]. The CUORE Upgrade with Particle IDentification (CUPID), a proposed upgrade of the CUORE experiment, will search for $0\nu\beta\beta$ decay of ^{100}Mo , aiming at a half-life sensitivity greater than 10^{27} yr [7]. CUPID will consist of a large array of ^{100}Mo -enriched Li_2MoO_4 (LMO) scintillating bolometers instrumented with cryogenic light detectors (LDs). The experiment will exploit the experience acquired by running CUORE, the first tonne-scale cryogenic bolometer array, and will take advantage of its low-background cryogenic infrastructure [8]; CUPID will combine this with the effective background reduction strategies demonstrated by the CUPID-0 [9] and CUPID-Mo [10] detectors to realize

a one-tonne array with a background index of the order of 10^{-4} counts $\text{keV}^{-1} \text{kg}^{-1} \text{yr}^{-1}$ in the ROI.

In order to meet this goal, it is important to assess and mitigate each individual background component in the final technical design. Given the *short* decay half-life of ^{100}Mo , 7.1×10^{18} yr [11], the $2\nu\beta\beta$ pile-up is expected to constitute a non-negligible fraction of the overall CUPID background budget. An estimate for a single CUPID-like crystal (300 g of LMO with 100% enrichment of ^{100}Mo) assuming a 1-ms resolving time for the heat detector puts the expected background rate from pile-up of about 3.5×10^{-4} counts $\text{keV}^{-1} \text{kg}^{-1} \text{yr}^{-1}$ [7]. Characterization of the pile-up induced background requires a thorough understanding of the resolving time CUPID-like bolometers can achieve.

CUPID will use neutron transmutation doped (NTD) thermistors [12] as temperature (phonon) sensors. NTD-based macro-calorimeters have a relatively slow time response; for crystals of a few hundreds grams, the typical rise time of a thermal pulse is of the order of few tens of ms and the pulse decay is typically in the range of (0.1–1) s. In an ideal detector, the rise time is generally a function of the temperature-dependent NTD working resistance, while the decay time is proportional to the ratio of the absorber crystal heat capacity and the conductance to the thermal sink. Given the relatively slow response to an energy deposition, multiple particle interactions close in time will produce overlapping thermal pulses, resulting in a cumulative pulse, whose rising edge will be affected by the pile-up of the underlying events. Therefore, characterizing the rising edge of thermal pulses is crucial to discrimination of pile-up events.

In this work, we describe a new technique we developed to study the time resolution of CUPID-like detectors, and produce a controlled sample of pile-up events

* Also at: Physik-Department, Technische Universität München, Garching, Germany

to determine the pile-up rejection efficiency of a pulse shape analysis. We tested this technique in a dedicated measurement carried out at the Laboratori Nazionali del Gran Sasso (LNGS), in Italy.

II. MEASUREMENT

An array of LMO crystals was deployed to study the performance of CUPID-like detectors, with crystals of similar dimension and shape to those that are intended to be used in the actual experiment [13]. This deployment is one of a series of bolometric tests planned to optimize the final technical design for CUPID. The array was operated at the Hall C cryogenic facility at LNGS between the summer of 2019 and the spring of 2020. The final runs of this measurement were devoted to generating a controlled sample of pile-up events to study the pile-up rejection efficiency.

The array consisted of 8 LMO cubic crystals ($45 \times 45 \times 45 \text{ mm}^3$) arranged in two 4-crystal floors. The crystals on the bottom floor were covered on the side with a reflecting aluminum foil, while those on the top floor were not. A total of 12 Ge disks (diameter 44-mm, thickness 0.175 mm) acting as LDs were placed below, in between, and above the crystal-floors, so that each LMO crystal faced two LDs. Each LMO crystal and LD was instrumented with a NTD sensor for the signal readout. For the pile-up study we focused on three LMO detectors which were instrumented with a functioning silicon heater, since pulsing the heater is crucial to generating the controlled sample of pile-up events.

The detector was operated at about 18 mK and the measured NTD working resistances were in the range of (10 – 50) M Ω . The observed rise time values for thermal pulses in the LMO crystals were approximately 15 ms.

Detector signals were conditioned by custom front-end electronics boards, which include a programmable amplifier and anti-aliasing (Bessel-Thomson) filter [14]. The filter cut-off frequency was set to 63 Hz, slightly higher than the expected signal bandwidth, to reduce the high frequency noise while not affecting the signal shape. The boards also provided independent programmable biases for the NTDs. The detector waveforms were acquired continuously with a sampling frequency of 2 kHz. The data stream was then triggered by means of an online derivative trigger [15]. Each triggered pulse (i.e. an event) consists of a 5-s window opened around the trigger sample, which by construction is fixed to 1 s from the start of the time window (pre-trigger).

The runs dedicated to the study of pile-up background aimed at producing a controlled set of pile-up events on which to benchmark the rejection efficiency of our analysis algorithms. To do this, we continuously injected signal-like pulses in the detector, scanning a range of values for both the pulse amplitudes and the time separation between consecutive pulses. The pulses were induced by injecting a calibrated amount of energy (via Joule heat-

ing) into the crystals heaters using a programmable waveform generator (Tektronix AFG1062).

This technique is commonly used for the thermal gain stabilization of bolometers [16, 17]. Our experience has shown that the heater can be used to correct the (temperature-dependent) detector gain against small temperature drifts because the pulse amplitude to temperature ratio behaves in the same way for heater pulses and particle pulses. However, in this work, for the first time we tried to emulate the shape of physics pulses with heater pulses, paying special attention to the rising edge. The underlying idea, now tested with a commercial module, is to include this feature in our pulser, thus being constantly able to monitor the pile-up discrimination of our detectors. The pulse shape of physics pulses and heater-induced pulses can be different due to the mechanisms of phonon generation and propagation. A possible reason is that the heater should mainly inject acoustic phonons into the crystal, while particle interactions would produce optical phonons directly inside the absorber, which immediately begin to degrade [18]. The shape and amplitude of heater pulses is also affected by the heater-wire conductance, which appears as an additional component of the detector.

Using the heater allows the detector to be thermally excited with precise control of the time separation and energy of the underlying excitation pulses. Given the goals of the study, this approach is more effective than using an intense radioactive source which has several disadvantages, including that the activity has to be tuned to a suitable rate and the arrival time and energy of particles exciting the detector cannot be controlled on the event-by-event level.

The waveform generator was configured to deliver a particular class of pulses for a fixed amount of time. For each configuration, we set the number of pulses to be injected, the pulse amplitudes and the time interval between successive pulses. The shape of the input waveform was chosen so that the rising edge of the heater-induced pulses matched as closely as possible the rising edge observed for particle-induced pulses. Figure 1 shows the rising edge observed for thermal pulses from particle events and heater events excited with rectangular, exponential and sawtooth waveforms. We found that the thermal pulses excited by sawtooth waveforms (right triangle with vertical rise and slow negative ramp) best reproduced the rising edge observed in particle induced pulses.

To generate reference individual pulses, the proxy for a well isolated particle events, we set the waveform-tooth width and amplitude to 50 ms and 170 mV, respectively, which produced pulses in the detectors with equivalent particle energies of (1.5 – 2.5) MeV on the different channels. The time interval between two successive individual waveforms was set to 15 s, so that the detectors had returned to baseline before the start of a new pulse. For the pile-up sample, we generated pairs of excitations with the second beginning before the detector had recovered from the first excitation in the pair. We set the waveform-

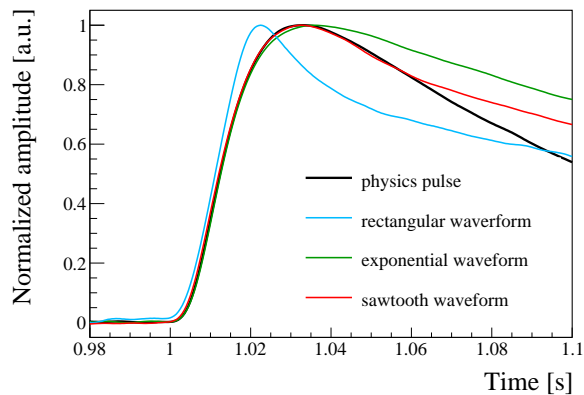


FIG. 1. Overlay of the rising edge and initial part of the decay for a particle pulse (black) and heater pulses excited by rectangular (blue), exponential (green) and sawtooth (red) waveforms.

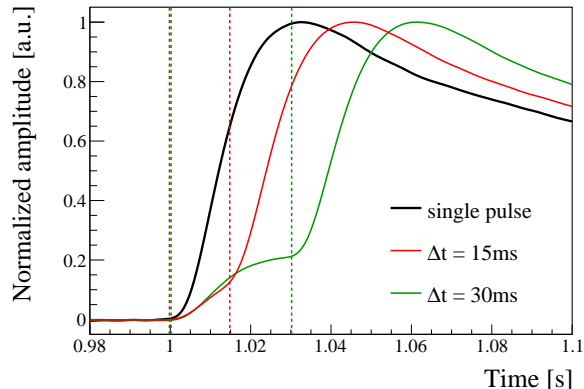


FIG. 2. Examples of heater-induced pile-up pulses excited by two sawtooth waveforms with amplitude ratio $\alpha = 1.4$ close in time. It can be seen that the time separations between the two pulses (the begin of the rise is taken as a reference) reflects that of the original waveforms (Δt). A time-isolated reference pulse is shown for comparison.

tooth width to 50 ms for both excitations, fixed one amplitude to 170 mV and varied the other from 40 mV to 240 mV in steps of 50 mV. We denote the ratio of the two amplitudes in the pair by α , and so this parameter varied between 0.24 and 1.4. We explored values of the time separation (Δt) between the pulse pairs in the pile-up sample ranging from 40 ms down to 1 ms (the Nyquist limit for the ADC sampling frequency). Figure 2 shows some of the observed thermal pulses; it can be seen that the distortion of the rising edge of pile-up pulses follows the time separation between the excitation pulses.

III. DATA ANALYSIS

The data analysis follows two main steps, a low-level processing and then a high-level analysis, i.e. the actual pile-up study. The low-level processing involves applying

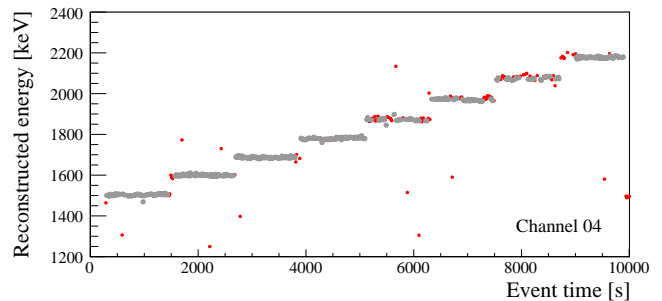


FIG. 3. Time distribution of the events in one of the pile-up runs. Each interval corresponds to a different $\alpha/\Delta t$ configuration. In this sequence, α is fixed to 0.24 while Δt goes from 1 ms to 11 ms (from left to right). The gray dots represent the events selected as heater pulses, the red dots the discarded ones; we keep only clean events with a single trigger fired in the 5-s window.

a software filter to optimize the signal-to-noise ratio and calculating a set of summary variables for each event such as pulse rise time, decay time and energy. These steps are analogous to the standard CUORE workflow [19], which has also been adopted as the starting point for the main analysis of the LMO detectors [13]. These analysis tools are well established and have been applied over the years on multiple detectors [20, 21]. The software filter uses the Optimum Filter (OF) technique [22], which reduces the impact of noise on the reconstructed pulse amplitude and pulse shape parameters. In order to define the OF transfer function, we use the average of the time-isolated reference pulses as the signal response of the system, while we build the noise power spectrum from signal-less event windows acquired in the reference run.

The first step of the high-level analysis is to associate each event with the corresponding waveform generator configuration. This is done based on the event timestamp since, as shown in Fig. 3, each waveform generator configuration corresponds to a specific time window.

We keep only clean events with a single trigger fired in the 5-s window. As pulser events dominate the event rate – the random coincidence of pulser events and events due to natural radioactivity proved to be negligible during the measurement – we apply a ± 5 keV-cut around the median energy of the pulses for each configuration to suppress non-pulser events.

Once the events are selected for each configuration, we study how each of the pulse shape variables calculated in the low-level analysis are distributed for these events. We fit each distribution, one per channel, with a Gaussian function and take the resulting mean $M_{x,i}$ and standard deviation $\sigma_{x,i}$, where x indexes the pulse shape variable studied (rise time, decay time, etc.) and i indexes the waveform generator configuration or time interval. To quantify the utility of a variable to discriminate between individual isolated pulses and pile-up pulses, we define the *discrimination power* as the distance between the two

corresponding distributions, namely

$$D \equiv \frac{|M_{x,i} - M_{x,R}|}{\sqrt{\sigma_{x,i}^2 + \sigma_{x,R}^2}}, \quad (1)$$

where R labels the (channel-dependent) reference quantities for individual isolated heater pulses.

The pulse rise time and decay time are natural choices for the variables on which to discriminate since we expect the shape of the pulse to be different in case of isolated and pile-up pulses. However, we use a related combined variable based on the so-called *Test Value Left* (TVL) and *Test Value Right* (TVR). These are χ^2 -like parameters which quantify how well the shape of each filtered pulse matches the shape of the filtered average reference pulse on the left (i.e. rise) and right (i.e. decay) side of the pulse maximum. We find that the combination $\text{TVL}^2 + \text{TVR}^2$ leads to an effective separation ($D > 3$) already at values of Δt of the order of a ms. Recalling Fig. 1, we note that this analysis is comparing heater-induced pile-up pulses to heater-induced isolated pulses and although we constructed the pulses to have similar rise times to particle induced pulses, the decay times are dissimilar. However, we expect the TVR variable will continue to provide some benefit when comparing isolated particle pulses to pile-up particle pulses as the decay time profile of a pile-up pulse is expected to be distorted compared to an isolated pulse. This will be tested in future studies.

In addition to $\text{TVL}^2 + \text{TVR}^2$, we consider another variable, the time separation between the start of the pulse window and the moment in which the filtered pulse reaches its maximum, which we call *delay*. The delay is sensitive to the noise and proved to be a good discriminator for some configurations of α and Δt (Fig. 4). Its complementarity to $\text{TVL}^2 + \text{TVR}^2$ is due to the way we implement the OF. In order to calculate TVL and TVR, the maximum of the filtered pulse is aligned to that of the average pulse; the quality of the alignment depends on the residual noise of the filtered pulse. The more precisely the maxima are superimposed, the more the test values will be sensitive to the pulse distortions due to pile-up. On the other hand, if the alignment is not optimal, the $\text{TVL}^2 + \text{TVR}^2$ might be misled by an overall matching of the pulses, but the delay variable would hint towards a different pulse shape due to possible pile-up.

We analyze all the pulser events in the pile-up runs and define a *rejection efficiency*, ε_{rej} , as the fraction of events that lie outside the $(M_{x,R} \pm 3\sigma_{x,R})$ range for at least one of the two considered variables, $\text{TVL}^2 + \text{TVR}^2$ and delay. This interval is chosen so that the cut applied to the time-isolated reference pulses would select essentially all the events. For each α we fit the distribution of ε_{rej} as a function of Δt with an error function constrained to pass through the origin and extract the Δt threshold corresponding to $\varepsilon_{\text{rej}} = 90\%$ (Fig. 5).

The combined results of this analysis are summarized in Fig. 6, which shows the Δt thresholds obtained for each α for each detector. The two outliers (correspond-

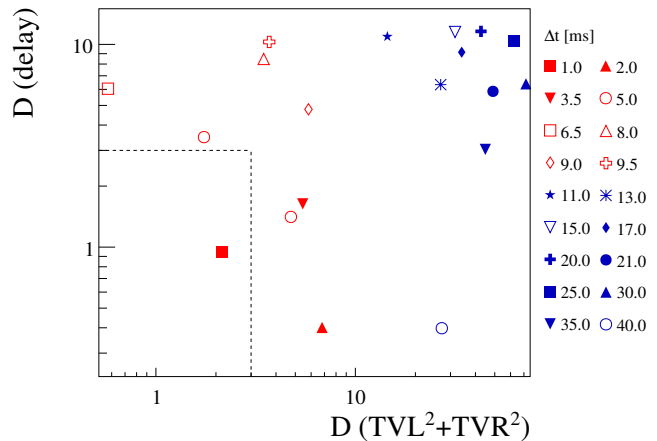


FIG. 4. Comparison between the discrimination power (D) obtained with the $\text{TVL}^2 + \text{TVR}^2$ and delay variables for the configuration $\alpha = 0.24$ of Channel03. The value $D = 3$ for both variables is indicated with a dashed line. The configuration with $\Delta t = 5$ ms has been tested in two different runs; the different values of discrimination power are likely due to the different detector noise (see the discussion in the text).

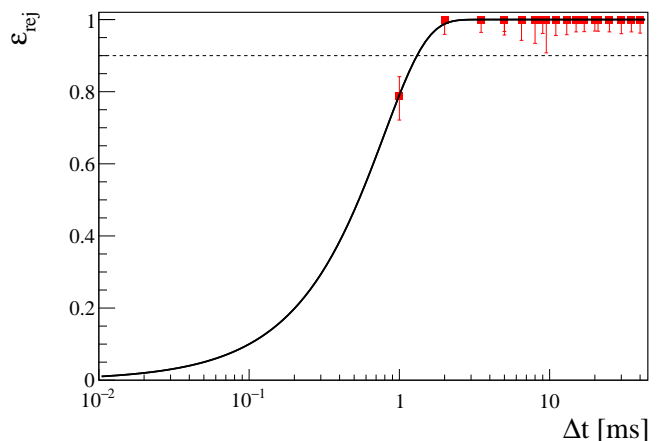


FIG. 5. Pile-up rejection efficiency (ε_{rej}) as a function of Δt for the configuration $\alpha = 0.24$ of Channel03. The solid line is the best-fit error function described in the text. The dashed horizontal line marks $\varepsilon_{\text{rej}} = 90\%$.

ing to $\alpha = 1.12$ for Channel04 and $\alpha = 1.41$ for Channel03) are thought to be due to the sub-optimal detector operating conditions which we experienced while collecting the corresponding data. These points will be further investigated in future measurements.

IV. SUMMARY AND OUTLOOK

We developed a new technique to investigate the ability of cryogenic bolometers to reject pile-up events. Using a controlled sample of pile-up signal events generated by injecting known excitations from a programmable wave-form generator into the crystal heaters we identified a set

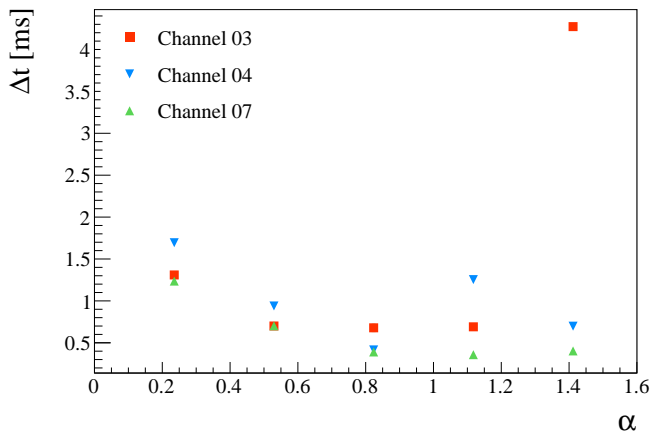


FIG. 6. Δt thresholds corresponding to $\varepsilon_{\text{rej}} = 90\%$ for each configuration of α obtained for the three channels. The two outliers at $\alpha = 1.12$ for Channel04 and $\alpha = 1.41$ for Channel03 are likely due to sub-optimal detector conditions while collecting data for $\Delta t = 1$ ms.

of pulse shape parameters that allow for effective discrimination between individual and pile-up pulses, obtaining a 90% rejection-efficiency for Δt down to 2 ms for pulses with rise time of about 15 ms.

This work is part of a campaign of measurements planned to optimize the technical design of the CUPID detector and develop the analysis chain. In future measurements related to pile-up studies we plan to improve noise conditions and cryogenic stability, explore higher sampling frequencies to probe $\Delta t < 1$ ms and optimize the input excitation functions to better reproduce both the rising and falling edge of physics pulses. These data will be used to benchmark detector response simulations

in development to assess the impact of pile-up on CUPID.

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