Lowering the CUORE energy threshold

S. Copello[1,2], C. Alduino[3], K. Alfonso[4], D. R. Artusa[3,5], F. T. Avignone III[3], O. Azzolini[6], T. I. Banks[7,8], G. Bari[9], J.W. Beeman[10], F. Bellini[11,12], A. Bersani[2], M. Biassoni[13,14], A. Branca[15], C. Brofferio[13,14], C. Bucci[5], A. Camacho[6], A. Caminata[2], L. Canonica[16,5], X. G. Cao[18], S. Capelli[13,14], L. Cappelli[2], L. Carbone[14], L. Cardani[11,12], P. Carniti[13,14], N. Casali[11,12], L. Cassina[13,14], D. Chiesa[13,14], N. Chott[3], M. Clemenza[13,14], C. Cosmelli[11,12], O. Cremonesi[14], R. J. Creswick[3], J. S. Cushman[18], A. D'Addabbo[5], I. Dafinei[12], C. J. Davis[18], S. Dell'Oro[5,19], M. M. Deninno[9], S. Di Domizio[1,2], M. L. Di Vacri[5,20], A. Drobizhev[7,8], D. Q. Fang[17], M. Faverzani[13,14], G. Fernandes[1,2], E. Ferri[14], F. Ferroni[11,12], E. Fiorini[14,13], M. A. Franceschi[21], S. J. Freedman[8,7], B. K. Fujikawa[8], A. Giachero[14], L. Gironi[13,14], A. Giuliani[22], L. Gladstone[16], P. Gorla[5], C. Gotti[13,14], T. D. Gutierrez[23], E. E. Haller[10,24], K. Han[25], E. Hansen[16,4], K. M. Heeger[18], R. Hennings-Yeomans[6,8], K. P. Hickerson[4], H. Z. Huang[4], R. Kadel[26], G. Keppel[6], Yu. G. Kolomensky[7,26,8], A. Leder[16], C. Ligi[21], K. E. Lim[18], X. Liu[4], Y. G. Ma[17], M. Maino[13,14], L. Marini[1,2], M. Martinez[11,12,27], R. H. Maruyama[18], Y. Mei[8], N. Moggi[28,9], S. Morganti[12], P. J. Mosteiro[12], T. Napolitano[21], C. Nones[29], E. B. Norman[30,31], A. Nucciotti[13,14], T. O'Donnell[32,7,8], F. Orio[12], J. L. Ouellet[16], C. E. Pagliarone[5,33], M. Pallavicini[1,2], V. Palmieri[6], L. Pattavina[5], M. Pavan[13,14], G. Pessina[14], V. Pettinacci[12], G. Piperno[11,12,c], C. Pira[6], S. Pirro[5], S. Pozzi[13,14], E. Previtali[14], C. Rosenfeld[3], C. Rusconi[14], S. Sangiorgio[30], D. Santone[5,20], N. D. Scielzo[30], V. Singh[7], M. Sisti[13,14], A. R. Smith[8], L. Taffarello[15], M. Tenconi[22], F. Terranova[13,14], C. Tomei[12], S. Trentalange[4], M. Vignati[12], S. L. Wagaarachchi[7,8], B. S. Wang[30,31], H. W. Wang[17], J. Wilson[3], L. A. Winslow[16], T. Wise[18,34], A. Woodcraft[35], L. Zanotti[13,14], G. Q. Zhang[17], B. X. Zhu[4], S. Zimmermann[36] and S. Zucchelli[37,9].

[1] Dipartimento di Fisica, Universita' di Genova, Genova I-16146, Italy
[2] INFN Sezione di Genova, Genova I-16146, Italy
[3] Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA
[4] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
[5] INFN Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila) I-67010, Italy
[6] INFN Laboratori Nazionali di Legnaro, Legnaro (Padova) I-35020, Italy
[7] Department of Physics, University of California, Berkeley, CA 94720, USA
[8] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[9] INFN Sezione di Bologna, Bologna I-40127, Italy
[10] Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720,

USA
[11] Dipartimento di Fisica, Sapienza Universita' di Roma, Roma I-00185, Italy
[12] INFN Sezione di Roma, Roma I-00185, Italy
[13] Dipartimento di Fisica, Universita' di Milano-Bicocca, Milano I-20126, Italy
[14] INFN Sezione di Milano Bicocca, Milano I-20126, Italy
[15] INFN Sezione di Padova, Padova I-35131, Italy
[16] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[17] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[18] Department of Physics, Yale University, New Haven, CT 06520, USA
[19] INFN Gran Sasso Science Institute, L'Aquila I-67100, Italy
[20] Dipartimento di Scienze Fisiche e Chimiche, Universita' dell'Aquila, L'Aquila I-67100, Italy
[21] INFN Laboratori Nazionali di Frascati, Frascati (Roma) I-00044, Italy
[22] CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Universit Paris-Saclay, 91405 Orsay, France
[23] Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA
[24] Department of Materials Science and Engineering, University of California, Berkeley, CA 94720, USA
[25] Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[26] Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[27] Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza, Zaragoza 50009, Spain
[28] Dipartimento di Scienze per la Qualita' della Vita, Alma Mater Studiorum Universita' di Bologna, Bologna I-47921, Italy
[29] Service de Physique des Particules, CEA / Saclay, 91191 Gif-sur-Yvette, France
[30] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[31] Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA
[32] Center for Neutrino Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA
[33] Dipartimento di Ingegneria Civile e Meccanica, Universita' degli Studi di Cassino e del Lazio Meridionale, Cassino I-03043, Italy
[34] Department of Physics, University of Wisconsin, Madison, WI 53706, USA
[35] SUPA, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
[36] Engineering Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[37] Dipartimento di Fisica e Astronomia, Alma Mater Studiorum Universita' di Bologna, Bologna I-40127, Italy

E-mail: `simone.copello@ge.infn.it`

Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) is a ton-scale double beta decay experiment based on TeO_2 cryogenic bolometers and is currently in the last construction stage at the Gran Sasso National Laboratory (LNGS). Its primary goal is to observe neutrino-less double beta decay of ^{130}Te, however thanks to the ultra-low background and large projected exposure it could also be suitable for other rare event searches, as the detection of solar axions, neutrinos from type II supernovae or direct detection of dark matter. The sensitivity for these searches will depend on the performance achieved at the low energy threshold. For this reason a trigger algorithm based on continuous data filtering has been developed which will allow lowering the threshold down to the few keV region. The new trigger has been tested in CUORE-0, a single-tower CUORE prototype consisting of 52 TeO_2 bolometers and recently concluded, and here we present the results in terms of trigger efficiency, data selection and low-energy calibration.

IOP Conf. Series: Journal of Physics: Conf. Series **888** (2017) 012047 doi:10.1088/1742-6596/888/1/012047

1. The CUORE experiment

CUORE (Cryogenic Underground Observatory for Rare Events) is a ton-scale double beta decay experiment based on tellurium dioxide (TeO2) cryogenic bolometers and is currently in the last construction stage at the Gran Sasso National Laboratory (LNGS, Italy). Its primary goal is the observation of the neutrino-less double beta decay of ^{130}Te using an array of 988 detectors, with a total sensitive mass of 741 kg. Every detector is a 750 g crystal of TeO_2, held by a copper structure and the array is divided in 19 towers. CUORE data taking will start in few months by the beginning of 2017 and it will last five years. Its expected background (10^{-2} counts/keV/kg/year around the $Q_{0\nu\beta\beta}$=2528 keV) and big exposure make CUORE suitable also for other rare event searches such as the detection of solar axions, neutrinos from type II supernovae or direct detection of dark matter. Another fundamental requirement for these searches is the low energy threshold: for this reason we developed a new trigger algorithm, called optimum trigger, able to reach the few keV region.

CUORE-0 was a single CUORE-like tower that took data from 2013 to 2015, here used to test the trigger technique. Its primary goal was to demonstrate CUORE targets in terms of background and energy resolution and its total sensitive mass was 39 kg [1]. Each detector ($5\times5\times5$ cm^3 TeO_2 crystal) was cooled down to about 10 mK in order to operated as a bolometer. In a bolometer the particle energy deposition causes a heating, of the order of 100 μK/MeV, that can be measured by a thermistor (a neutron transmutation doped germanium semiconductor or NTD-Ge) glued on the detector itself. The signal, induced by the resistance variation of each NTD, is amplified, filtered and continuously acquired with a sampling frequency of 125-1000 Hz. In the neutrinoless double-beta decay analysis a real-time derivative trigger was applied. In the same time the samples were disk saved in order to apply the off-line optimum trigger.

2. The Optimum Trigger

The optimum trigger is an off-line trigger based on the optimum filter [2], that is the filter that maximizes the signal-to-noise ratio. Its transfer function is:

$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{-j\omega_k i_M} \tag{1}$$

where $s(\omega_k)$ is the Discrete Fourier Transform (DFT) of the average discrete pulse shape s_i, i_M is the position of the maximum of s_i, and h is a normalization constant that leaves unmodified the amplitude of the signal.

$N(\omega_k)$ and s_i must be known in order to build the transfer function. s_i is obtained averaging different pulse shapes while $N(\omega_k)$ is made by averaging the power spectrum of a large set of data windows not containing signals. In Fig. 1 the average pulse, on the left, and the average noise power spectrum, on the right, are visible (unfiltered in black and filtered in dashed red). The filtered baseline is analyzed with a simple threshold trigger: when the samples exceed a certain value, the trigger fires. An exception is made since the filtered pulse presents lobes at both sides and, if the pulse energy is high enough, they can exceed the threshold and produce fake signals. To avoid this, the regions of the two lobes are vetoed.

3. CUORE-0 results

CUORE-0 ran for about two years and we used its data to test the optimum trigger in terms of trigger efficiency, data selection and energy calibration. Trigger efficiency can be evaluated in two ways. Since every crystal was equipped with a resistor, we could use it to inject a certain amount of energy, and verify if the trigger actually fired. This behavior can be predicted by modeling the noise energy distribution as a Gauss function, and this makes the energy dependence of the trigger efficiency to follow the error function. If we define the trigger threshold as the energy at which the efficiency reaches the 99.9%, 20% of CUORE-0 channels show an optimum trigger

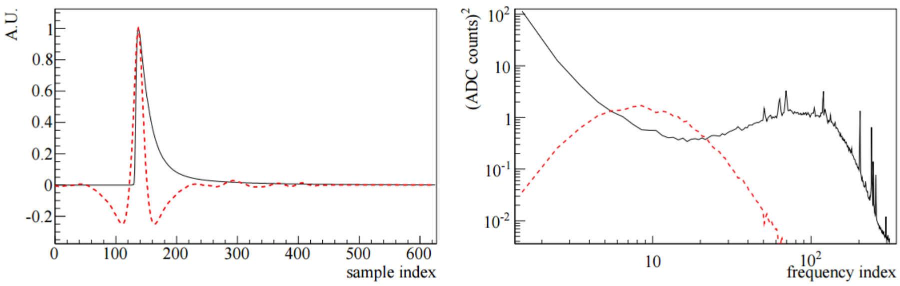

Figure 1. An example of pulse (left) and average noise power spectrum (right) before the filter (solid black line) and after the filter (dashed red line).

threshold in the 6-8 keV range compared to a standard trigger threshold of 20-30 keV range. By fitting every filtered event with the filtered average pulse, it is possible to use the χ^2/ndf as a pulse shape discriminator. The scatter plot χ^2/ndf vs. energy is shown in Fig. 2. A first population, with an almost flat energy trend, is composed by particle events while a second band represents spikes, electronics noise and detector vibrations. This shape indicator determines an analysis threshold, being the energy at which the two populations are well separated, of 10 keV for 11 over 50 channels.

The calibration function is evaluated using a ^{232}Th source during dedicated runs, while the calibration stability of every channel is periodically checked by injecting a fixed amount of energy on the crystals. The calibration uncertainty is evaluated by fitting eight X-rays from Th-excited tellurium, between 26 and 32 keV. These peaks can be seen only in the spectrum obtained by summing all the 22 channels that have a threshold low enough (because of the low statistics). These channels present a calibration uncertainty of 0.15 keV at 28 keV.

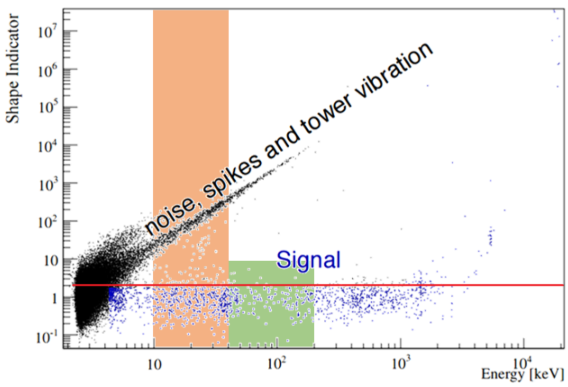

Figure 2. An example of χ^2/ndf shape indicator (S.I.) as a function of energy. The horizontal band represents the particle pulses while the upper one is made of fake signals induced by spikes, electronic noise and mechanical vibration. Here the low energy region of interest between 10 and 40 keV (in orange), and the region between 40 and 200 keV (in green), in which we evaluate the cut value of S.I. for a certain efficiency, are highlighted. In this region only the events with S.I. smaller than 10 are considered particle events. The red horizontal line represents the value of S.I. for 90% selection efficiency.

[1] CUORE collaboration 2016 *CUORE-0 detector: design, construction and operation*, *JINST* **11** P07009
[2] Di Domizio S, Orio F and Vignati M 2011, *Lowering the energy threshold of large-mass bolometric detectors*, *JINST* **6** P02007