Title

Results from CUORE and CUORE-0

Authors

Moggi, N
Alduino, C
Alfonso, K
et al.

Peer reviewed

Results from CUORE and CUORE-0

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

[1]Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA
[2]Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
[3]INFN – Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila) I-67100, Italy
[4]INFN – Laboratori Nazionali di Legnaro, Legnaro (Padova) I-35020, Italy
[5]INFN – Sezione di Bologna, Bologna I-40127, Italy
[6]Dipartimento di Fisica, Sapienza Universita` di Roma, Roma I-00185, Italy
[7]INFN – Sezione di Roma, Roma I-00185, Italy
[8]Department of Physics, University of California, Berkeley, CA 94720, USA
[9]INFN – Sezione di Genova, Genova I-16146, Italy
[10]Dipartimento di Fisica, Universita` di Milano-Bicocca, Milano I-20126, Italy
[11]INFN – Sezione di Milano Bicocca, Milano I-20126, Italy
[12]INFN – Sezione di Padova, Padova I-35131, Italy
[13]Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[14]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[15]Dipartimento di Fisica, Universit`a di Genova, Genova I-16146, Italy
[16]Department of Physics, Yale University, New Haven, CT 06520, USA
[17]Dipartimento di Ingegneria Civile e Meccanica, Universita` degli Studi di Cassino e del Lazio Meridionale, Cassino I-03043, Italy
[18]INFN – Gran Sasso Science Institute, L'Aquila I-67100, Italy
[19]Dipartimento di Scienze Fisiche e Chimiche, Universita` dell'Aquila, L'Aquila I-67100, Italy
[20]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[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 Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[25]Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza, Zaragoza 50009, Spain
[26]Dipartimento di Fisica e Astronomia, Alma Mater Studiorum – Universita` di Bologna, Bologna I-40127, Italy
[27]Service de Physique des Particules, CEA / Saclay, 91191 Gif-sur-Yvette, France
[28]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[29]Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA
[30]Center for Neutrino Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA
[31]Department of Physics, University of Wisconsin, Madison, WI 53706, USA
[32]SUPA, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
[33]Engineering Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[34]Deceased

a)niccolo.moggi@bo.infn.it

Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric experiment searching for neutrinoless double beta decay that has been able to reach the 1-ton scale. The detector consists of an array of 988 TeO_2 crystals arranged in a cylindrical compact structure of 19 towers. The construction of the experiment and the installation of all towers in the cryostat was completed in August 2016: the experiment is now in data taking phase. In this talk, beyond updating the physics results from CUORE-0, we will discuss the achievements and technical challenges of the CUORE construction phase, with particular emphasis on the background reduction strategy, the performance of the detector during pre-operation and the projected first results from the full detector run.

INTRODUCTION

Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothesized process never convincingly observed so far due to its extreme rarity. It can be regarded as one of the most sensitive probes to physics beyond the Standard Model (see, for example, [1]). The observation of $0\nu\beta\beta$ relies on the detection of the two emitted electrons. Being the energy of the recoiling nucleus negligible, this result in an experimental signature characterised by a peak in the spectrum of the summed electron energies at the Q-value of the isotope under study. Experimental searches hence require detectors with both very large source mass and very low background. A number of experiments are involved in this search with different isotopes and experimental approaches [2] and new techniques for background suppression are being developed [3].

The CUORE experiment [4], presently taking data at the Gran Sasso National Laboratory (LNGS, Italy), is based on the bolometric technique to search for $0\nu\beta\beta$ decay of the ^{130}Te isotope using an array of 988 bolometers. Each bolometer is composed of a crystal which absorbs the energy released by the two electrons and converts it in lattice vibration inducing a temperature rise of the device, and a thermal sensor which converts the temperature rise in a measurable change in voltage. The sensors are neutron transmutation doped Germanium thermistors glued on the absorber. The absorbers are 5×5×5 cm³ crystals of TeO_2, weighing about 750 g each, made of ^{nat}Te which is 34% ^{130}Te and thus acts as both source and detector of the decay. The Q-value of the reaction is 2527.5 keV. The bolometres are arranged in 19 copper structures ("towers") of 13 floors each, 4 bolometers per floor. The copper structures serve also as heat bath. The active detector mass is 742 kg for ~206 kg of ^{130}Te. This experimental approach yields excellent efficiency and energy resolution and requires low heat capacity materials at low temperature. The detector is held inside a dilution refrigerator: when operated at a temperature of ~10 mK the TeO_2 heat capacity is so low that an energy deposition of 1 MeV produces a temperature rise of ~0.1 mK.

THE CUORE CHALLENGE AND BACKGROUND MITIGATION STARTEGY

The sensitivity to $0\nu\beta\beta$ may be estimated [5] in terms of some key experimental parameters: $S_{T_{1/2}} \propto \eta \cdot \varepsilon \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$ where η is the isotopic abundance of the isotope, ε the efficiency, M the mass, t the exposure time, B the number of background events and ΔE the energy resolution[1]. Hence one of the primary goals was to minimize the radioactive background in the region of interest (ROI) around the Q-value.

The Cuoricino and CUORE-0 experiences

The CUORE design profited of the experience gained with its precursors Cuoricino [6] and CUORE-0 [7]. CUORE-0 was a single CUORE tower, operated from 2013 to 2015 inside the Cuoricino cryostat, built to test the low-background cleaning and assembly techniques developed for CUORE. As an independent experiment CUORE-0 found no evidence of $0\nu\beta\beta$ and reported a lower limit on its half-life [8] which, combined with Cuoricino, is the most stringent limit in ^{130}Te to date ($T_{1/2} > 4.0 \times 10^{24}$ y at 90% C.L.) corresponding to an effective Majorana neutrino mass in the range 270-760 meV depending on the nuclear matrix element (NME) used for calculations.

As a step toward a larger experiment, CUORE-0 has confirmed that the background in the ROI is dominated by radioactive contaminants. Namely two sources were identified: 1) γ rays from contaminants in the cryostat and 2) "degraded" α particles from contaminants on the surface of the crystals and of the copper facing the crystals. These αs release part of their energy on the surface of emission and part on the surface of the detector component that absorbs them. Though an anti-coincidence analysis may reject crystal-crystal events, all other cases give rise to a continuous background in the ROI. CUORE-0 has proven a ~6.8 fold reduction of this background with respect to Cuoricino (0.11±0.001 to 0.016±0.001 between 2700 and 3900 keV) thanks to *a)* a strict material selection and dedicated Cu cleaning procedure [9] that combines tumbling, electropolishing, chemical etching and magnetic plasma etching, *b)* a rigid protocol adopted for crystal production and careful selection of the materials used to grow the crystals, *c)* assembly and temporary storage of the towers inside glove-boxes in N_2 atmosphere inside a class 1000 clean room, *d)* storage of all detector parts inside dedicated cabinets under constant N_2 flux in LNGS hall A to avoid recontamination. On the other hand, the γ component of the background observed is consistent with that of Cuoricino.

The strongest calibration line (2615 keV from ^{208}Tl, only 87 keV above ROI) was used in order to estimate the energy resolution in the ROI. The physics-exposure-weighted mean of the resolution values for all the bolometers was 4.9 keV (FWHM) which, projected to the Q-value, gives 5.1±0.3 keV (FWHM). This result demonstrates the feasibility of the CUORE goal of 5 keV energy resolution.

Measurement of $2\nu\beta\beta$ with CUORE-0

CUORE-0 data was used to build a background model that allows to disentangle and quantify all sources that contribute to the overall energy spectrum. A total of 56 sources were identified and ascribed to parts of the detector. The energy of the lines in the M_1 (single bolometer) and $\sum_2$ (two bolometers summed energy) spectra, the time variation of their counting rates, the observation of coincidences in the detector, were all used to select the final source list. The source activities were estimated, when possible, by external screening measurements, previous bolometric experiments results [10] and cosmogenic activation calculations, and were used as a priori information of a Bayesian fit to the experimental spectra made with a linear combination of all the identified sources. A Geant4-based MC was used to simulate the sources and the particle interactions in the detector so that the final fit takes into account the detector response function and other read-out features. In order to properly reconstruct the experimental data, the energy spectrum of the electrons from $2\nu\beta\beta$ decay must be added to the source list (Figure 1). $2\nu\beta\beta$ decay of 130Te accounts for ~10% of the events in the M_1 region from 118 to 2700 keV. Removing the $2\nu\beta\beta$ component results in a dramatically poorer fit. A direct outcome of this analysis [11] is the measure of the half-life of ^{130}Te $2\nu\beta\beta$ decay: $T_{1/2}^{2\nu} = [8.2 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})] \times 10^2$ y which is the most accurate to date.
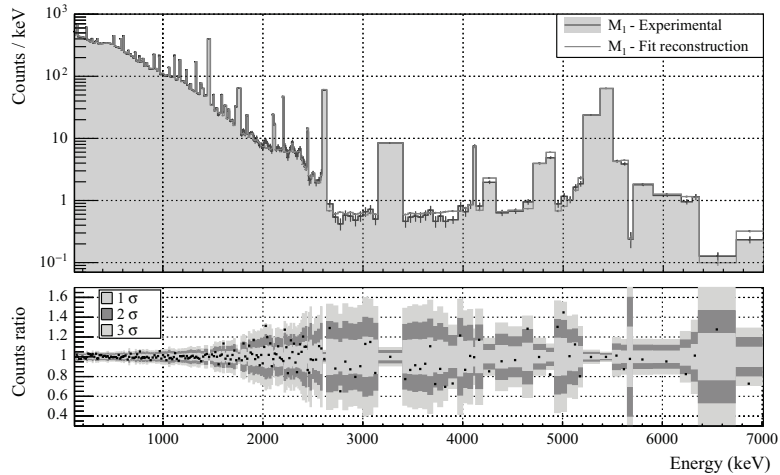
FIGURE 1. Comparison of the simulated and experimental energy spectrum when also the $2\nu\beta\beta$ process is taken into account.

CUORE background reconstruction

A new custom made cryostat was built to host and cool the CUORE detector. To satisfy the cryogenics and low radioactivity requirements the cryostat is cryogen-free: the first cooling stage to 4 mK is provided by five pulse tubes and the base temperature of 10 mK is reached with a dilution refrigerator. The six stages of the cryostat with their thermal shields are made of oxygen-free high thermal conductivity copper. In CUORE more low-activity roman lead shields were added inside the cryostat to shield the detector from γ rays originated in the cryostat, and an additional neutron and γ shield surrounds the whole cryostat. Additionally a better self-shielding and an improvement in the efficiency of rejection is expected through coincidence multi-hit analysis thanks to the larger number of bolometers. In the reconstruction of the CUORE background a sensitivity on contaminant concentration better than that achieved with standard techniques was obtained for many sources together with a more efficient disentanglement of the species in the detector parts, especially for surface contaminations. This allowed to group the sources of background used in the fit into classes: crystals and Cu holders that do not change in CUORE w.r.t. CUORE-0 (are just replicated 19 times); the cryogenic and radioactive shield system that is new in CUORE. The contribution from these elements to the M_1 spectrum is shown in Figure 2. The largest contribution (in CUORE-0) comes from the shield system.
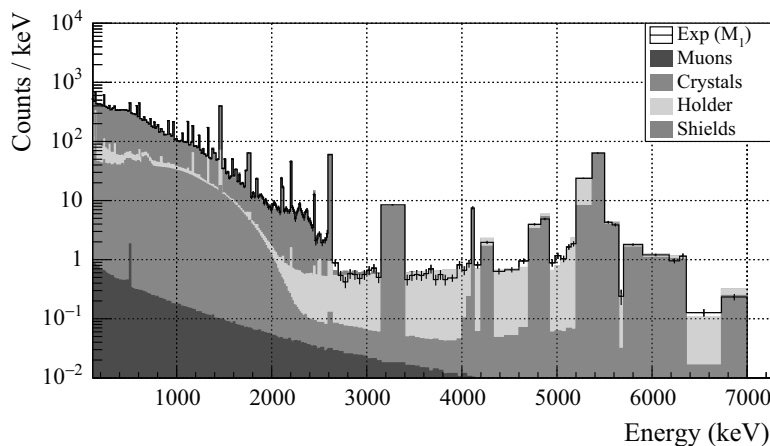
Component	Fraction [%]
Shields	74.4±1.3
Holder	21.4±0.7
Crystals	2.64±0.14
Muons	1.51±0.06

FIGURE 2. The CUORE-0 background sources grouped by their origin in the detector. "Shields" stands for the sum of the cryostat internal and external shields, the external modern lead shield and the internal roman lead shield.
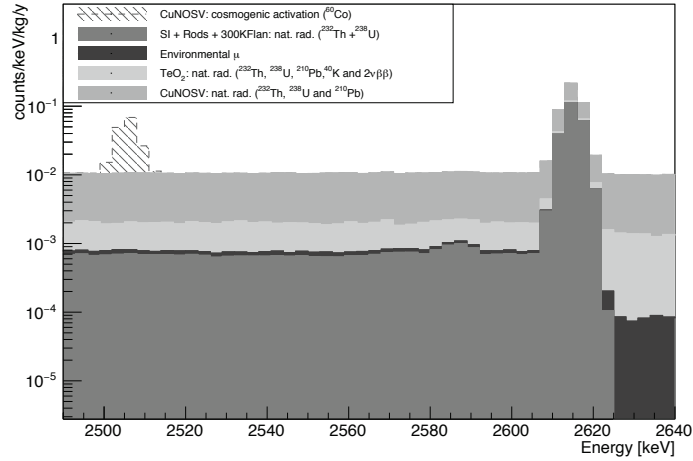
FIGURE 3. Left: the projected CUORE background spectrum in the ROI resulting from the sources identified in CUORE-0, after anticoincidence analysis. The peaks are due to the ^{60}Co line at 2505 keV and the [208]Tl line at 2615 keV. Right: the assembled 19 towers before the closing of the cryostat.

Based on these results and on a campaign of material screening, radioassays and bolometric measurements, the expected background in the ROI was estimated using a MC simulation of the full detector [12]. The total projected event rate for CUORE is $[1.02\pm 0.03(\text{stat.})^{+0.23}_{-0.10}(\text{syst.})]\times10^{-2}$ counts $kg^{-1}keV^{-1}y^{-1}$ dominated by the contribution of the copper holders ascribed to degraded αs from surface contamination. Figure 3 shows the predicted energy spectrum of the 988 bolometer array in the ROI. With this result we can estimate the sensibility of CUORE to $0\nu\beta\beta$ decay. For 5 years data taking, and assuming an energy resolution of 5 keV, the sensitivity [5] will be 9×10^{25} y at 90% C.L. to the half life of [130]Te, and in the range 50-130 meV, depending on the NME (see [13] and references therein), to the effective neutrino Majorana mass. At the same time the sensitivity to an eventual discovery is estimated to be 4×10^{25} y at 90% C.L. under the same assumptions.

CUORE ASSEMBLY, COMMISSIONING and START

The cryostat commissioning was completed in March 2016. It consisted in a series of runs with the full system installed but the detector, except for an 8 TeO$_2$ bolometer array. The system reached a base temperature of 6.3 mK stable on months scale, and encouraging tests of electronics, DAQ, temperature stabilization system and calibration
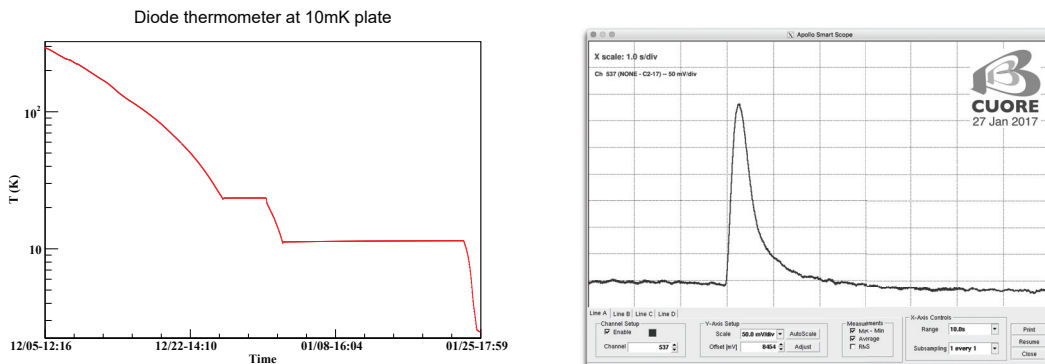

FIGURE 4. Left: cooldown of the full experimental setup measured by one of the diodes on the 10 mK plate. The flat regions are due to technical stops dedicated to optimization of the cryostat and electronic system. Right: the first pulse observed on January 27, 2017.

system were performed. The energy resolution, with no dedicated noise optimization performed, was found to be 10 keV.

The installation of the towers in the cryostat was performed in a dedicated clean room with radon abatement system procedures and was completed in August 2016 followed by cable routing, closure of the cryostat and DAQ tests. The cool-down started on December and by the end of January 2017 the base temperature was reached and the
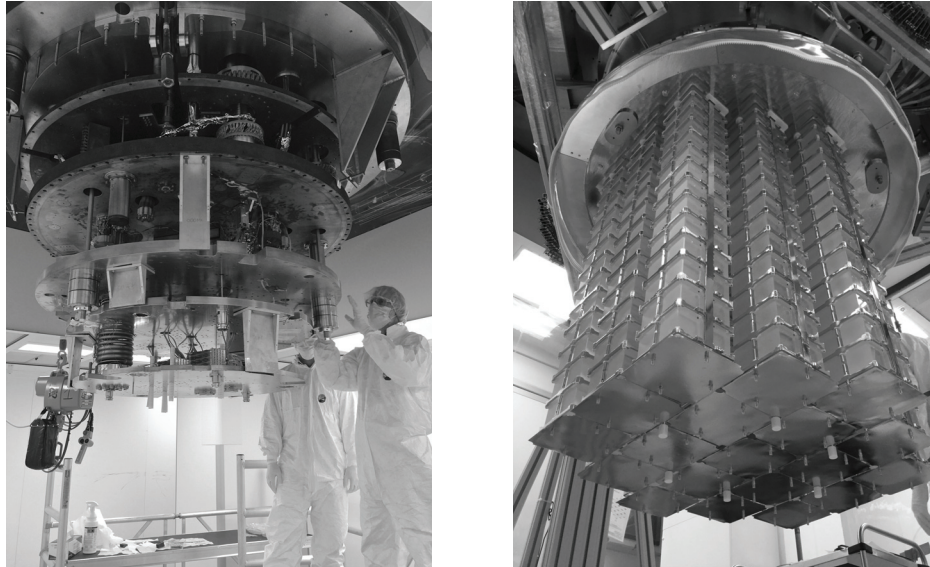

FIGURE 5. Left: the cryostat top plates. Right: the assembled 19 towers before the closing of the cryostat.

first pulse was observed (see Figure 4), followed by an intense period dedicated to noise reduction and improvement of the working point of each bolometer. In April data taking started. At the time of writing we are taking data and working on the calibration and optimization of the detector.

REFERENCES

[1] J.D.Vergados, H. Ejiri and F. Simkovic, arXiv:1205.0649 (2012)
[2] J. J. Gomez-Cadenas *et al.*, arXiv:1109.5515 (2012)
[3] D.R.Artusa *et al.* (CUORE Collaboration), Physical Journal C**74**, 3096 (2014)
[4] C. Arnaboldi *et al.* (CUORE Collaboration), Nucl. Inst. Meth. A**518**, 775 (2004)
     D.R. Artusa *et al.*, Adv. in High Energy Phys. 2015, 879871 (2015)
[5] C. Alduino *et al.* (CUORE Collaboration), arXiv:1705.10816 (2017), submitted to Eur. Phys. J. C
[6] C. Arnaboldi *et al.* (Cuoricino Collaboration), Phys. Rev. C**78**, 035502 (2008)
[7] C. Alduino *et al.* (CUORE Collaboration), JINST **11**, P07009 (2016)
[8] K. Alfonso *et al.* (CUORE Collaboration), Phys. Rev. Lett. **115**, 102502 (2015)
[9] F. Alessandria *et al.* (CUORE Collaboration), Astropart. Phys. **45**, 13-22 (2013)
[10] F. Alessandria *et al.* (CUORE Collaboration), Astropart. Phys. **35**, 839-849 (2012)
[11] C. Alduino *et al.* (CUORE Collaboration), Eur. Phys. J. C**77**, 13 (2017)
[12] C. Alduino *et al.* (CUORE Collaboration), arXiv:1704.08970 (2017), submitted to Eur. Phys. J. C
[13] C. Alduino *et al.* (CUORE Collaboration), Phys. Rev. C**93**, 045503 (2016)