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Authors
Alduino, C
Alfonso, K
Avignone, FT
et al.

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The CUORE and CUORE-0 experiments at LNGS

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

[1] Dept of Physics and Astronomy, Univ of South Carolina, Columbia, SC 29208, USA
[2] Dept of Physics and Astronomy, Univ of California, Los Angeles, CA 90095, USA
[3] INFN – Laboratori Nazionali di Legnaro, Legnaro (Padova) I-35020, Italy
[4] INFN – Sezione di Bologna, Bologna I-40127, Italy
[5] Dipartimento di Fisica, Sapienza Università di Roma, Roma I-00185, Italy
[6] INFN – Sezione di Roma, Roma I-00185, Italy
[7] Department of Physics, University of California, Berkeley, CA 94720, USA
[8] INFN – Sezione di Genova, Genova I-16146, Italy
[9] INFN – Sezione di Milano Bicocca, Milano I-20126, Italy
[10] INFN – Sezione di Padova, Padova I-35131, Italy
[11] Dipartimento di Fisica e Astronomia, Università di Padova, I-35131 Padova, Italy
[12] Dipartimento di Fisica, Università di Milano-Bicocca, Milano I-20126, Italy
[13] INFN – Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila) I-67100, Italy
[14] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[15] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[16] Nuclear Science Division, Lawrence Berkeley Nat Lab, Berkeley, CA 94720, USA
[17] Dipartimento di Fisica, Università di Genova, Genova I-16146, Italy

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[18] Wright Laboratory, Department of Physics, Yale University, New Haven, CT 06520, USA
[19] Dipartimento di Ingegneria Civile e Meccanica, Università degli Studi di Cassino e del Lazio Meridionale, Cassino I-03043, Italy
[20] Center for Neutrino Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA
[21] INFN – Gran Sasso Science Institute, L'Aquila I-67100, Italy
[22] Dip di Scienze Fisiche e Chimiche, Università dell'Aquila, L'Aquila I-67100, Italy
[23] INFN – Laboratori Nazionali di Frascati, Frascati (Roma) I-00044, Italy
[24] CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Univ. Paris-Saclay, 91405 Orsay, France
[25] Physics Dept, California Polytechnic State Univ, San Luis Obispo, CA 93407, USA
[26] INPAC and School of Physics and Astronomy, Shanghai Jiao Tong University; Shanghai Laboratory for Particle Physics and Cosmology, Shanghai 200240, China
[27] Lab de Fisica Nuclear y Astroparticulas, Univ de Zaragoza, Zaragoza 50009, Spain
[28] Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna I-40127, Italy
[29] Service de Physique des Particules, CEA / Saclay, 91191 Gif-sur-Yvette, France
[30] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[31] Dept of Nuclear Engineering, University of California, Berkeley, CA 94720, USA
[32] Department of Physics, University of Wisconsin, Madison, WI 53706, USA
[33] Engineering Division, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

[a] Deceased

E-mail: chiara.brofferio@unimib.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, in particular, the installation of all towers in the cryostat was completed in August 2016 and commissioning started in fall 2016. The experiment has completed the pre-operation phase and is currently in data taking. We present here the achievements of CUORE during the commissioning phase and the limit on the ^{130}Te half-life for the neutrinoless double beta decay that has been released after the first 3 weeks of collected data. Physics results from CUORE-0 will also be updated.

1. Introduction

Neutrinoless Double Beta Decay (0νDBD) searches [1][2][3] represent a unique tool to assess the Dirac/Majorana nature of neutrino and to check the Lepton Number Conservation law. The experimental approach is usually based on the observation of a large number of nuclei, stable in normal beta decay but for which a double weak interaction process, changing the nuclear charge by two units, is energetically favorable. The decay involving the simultaneous emission of two electrons and two neutrinos (2νDBD) is allowed by the Standard Model of Electroweak Interactions and has been observed for several nuclides [4]. However, if neutrinos have a Majorana nature (and mass), a process without the emission of any neutrino is possible. A 0νDBD is an unambiguous signal of a Majorana mass and of a violation of the lepton number conservation. Moreover, the study of such decay can put a constraint on the absolute neutrino mass scale, which is at the moment unknown [5].

Most sensitive experiments are presently based on the homogeneous approach in which the nuclei under observation are part of the detector itself. The sensitivity of such experiments scales with the square root of the exposure (the live time times the detector mass) and the inverse of the observed background rate, since it is supposed that this also scales with the detector mass.

Low temperature detectors (LTD) are naturally suitable for this approach. These detectors are simply based on the possibility to register a temperature increase in a crystal, acting as absorber, when a particle interacts with it. In fact, the heat capacity of any cold diamagnetic and dielectric crystal is proportional to the cube of the ratio between the operating and Debye temperatures and can therefore become so small that even the tiny energy released by a particle in form of heat can be revealed by the temperature increase of the crystal by means of a suitable thermal sensor. Many interesting compounds have already been studied as candidates for this approach [6] with excellent results both on intrinsic radio-purity and on energy resolution, which is fundamental to reduce the number of counts due to 2νDBD at the Q-value of the decay in the 2-electrons energy sum spectrum, where the events from 0νDBD are expected. This background is in fact the only unavoidable one that will always be present.

2. The TeO_2 choice and CUORE-0

^{130}Te is an optimal candidate to search for 0νDBD [7] due to its high transition energy (2527.5 keV), and large isotopic abundance (34.2 %), which allows performing a sensitive experiment with natural tellurium. TeO_2 has demonstrated to be an optimal choice for LTD crystals to be used in 0νDBD searches, thanks to its high enough Debye temperature [8], good crystal properties, very low intrinsic radioactivity [9] and favorable Te mass percentage in the compound (27%). TeO_2 LTDs have been pioneered by the Milano group in a series of constantly increasing mass (from 6 g to 6.8 kg) experiments carried out at Laboratori Nazionali del Gran Sasso (LNGS) [10], which opened the way to CUORE [11], a 1-ton LTD experiment for ^{130}Te 0νDBD.

Suggested by Ettore Fiorini in 1998, CUORE physics potential attracted many international collaborators, that convinced the community (and the funding agencies) of the feasibility of the project with a smaller (41 kg) experiment, CUORICINO [12]. This experiment was in fact able to show not only the technical possibility of scaling in mass by using arrays of LTD towers, but also that the technique was mature to compete in background reduction (0.169 c/keV kg y) and 0νDBD half-life limits (2.8×10^{24} y at 90% C.L.) [13]. Once funded, CUORE detector was designed and optimized under all the possible aspects [14][15], to push the sensitivity as far as possible [16]. The demonstrator of all these efforts has been the single tower CUORE prototype, CUORE-0.

CUORE-0 consisted of 52 5×5×5 cm^3 TeO_2 crystals assembled in a tower of 13 floors for a total TeO_2 mass of 39 kg. All the technical details of the detector and its performance can be found in the literature [17]. CUORE-0 was not only the first prototype of a CUORE tower, but a small scale competing experiment, that after a 9.8 kg y exposure was able to improve the background (0.058 c/keV kg y) and 0νDBD half-life limits (2.7×10^{24} y at 90% C.L.) with respect to CUORICINO [18] and to measure with the highest precision ever obtained the half-life of ^{130}Te 2νDBD ($T_{2\nu} = (8.2 \pm 0.2_{stat} \pm 0.6_{syst}) \times 10^{20}$ y) [19]. Many other searches are still under study, like the decays of ^{120}Te and of ^{130}Te on the first 0^+ excited state, and will be published soon.

A detailed Monte Carlo simulation that exploits the information about the contaminations of materials obtained through radio-assay screening campaigns and bolometric measurements was built and fine-tuned on CUORE-0 data with excellent results [19]. The information extracted from CUORE-0 background model were then used to tune the general CUORE Monte Carlo simulation [20], that confirmed that the goal of a Background Index (BI) in the Region Of Interest (ROI) of 10^{-2} c/keV kg y was within reach. With CUORE-0 the 5 keV FWHM energy resolution goal was also achieved, on the full 9.8 kg y exposure.

3. CUORE construction and commissioning

The CUORE detector is composed by a closely packed array of 19 towers CUORE-0-like, for a total of 988 TeO_2 bolometers operated at a temperature of ~ 10 mK in a custom-made cryostat installed at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Each bolometer is equipped with a neutron transmutation doped (NTD) thermal sensor and a silicon heater, for gain stabilization [21][22]. With a total detector mass around 740 kg of TeO_2 (206 kg of ^{130}Te), CUORE is the first ton-scale cryogenic detector ever put into operation.

To cope with the strong requirements for surface (re)contamination, the detector components were produced, handled and cleaned according to specific protocols, the towers were assembled by use of specific glove-boxes always flushed with nitrogen to avoid ^{222}Rn or ^{210}Pb [23], and their installation in the cryostat was performed using a radon free modular clean room [24]. To shield the detector from gamma and neutron environmental background different layers of copper, lead (70 ton aprox, of which 8 ton inside the cryostat, at low temperature), borated polyethylene and boric acid are used.

The installation of the 19 towers was successfully completed in Summer 2016, obtaining 984 functioning bolometers out of 988. The cryostat interfaces and radiation shields were assembled in the following months. Cool down started in Dec. 2016. The custom-made dilution refrigerator system works without LHe and the cooling at intermediate temperatures (~ 40 K and ~ 4 K) is based on five pulse tube cryo-coolers. The dimensions, experimental volume (~ 1 m^3), mass (~17 t), and cooling power (3 μW at 10 mK) make it the largest and most powerful cryogen-free dilution refrigerator system in operation. Nonetheless, it took almost 1 month to cool to base temperature. A stable temperature of ~ 7 mK was reached on January 27, 2017. We then started the detector pre-operation phase, to optimize the signal readout, the mechanical and electrical noise reduction and the working points of the bolometers. In April 2017 the optimization was not yet completed but the Collaboration decided to start a preliminary science run to extract the very first hints on energy resolution and BI in the ROI.

4. First data-set results

In May 2017, we collected three weeks of physics data bracketed by two calibration periods. During calibration 12 "sausage-like" strings containing ^{232}Th sources are temporarily deployed inside the detector region in order to guarantee an approximately uniform γ-ray illumination of the detectors [25]. Six γ-lines (from 239 keV to 2615 keV) are then used to perform the energy calibration of the 984 bolometers. During the physics run we acquired an exposure of 38.1 kg y of TeO_2 (10.6 kg y of ^{130}Te), already greater than the total exposure collected by CUORE-0.

For this initial analysis 889 detectors (~90 %) were used, discarding those that would have required more efforts on stability and noise reduction. In our analysis approach, once the calibration is successfully applied, the physics data are blinded. This is obtained by introducing an artificial peak at the Q-value. The model and fitting strategy are then optimized and fixed before unblinding. A detailed description of the full procedure, that was developed for CUORE-0 and then used on this first dataset, is available in the literature [26]. The physics spectrum, see figure 1, is built after applying a series of selection criteria aimed at improving the experimental sensitivity. We therefore remove periods of low quality data (caused by noisy laboratory conditions) and reject pile-up events. Then we select only signals consistent with a proper template waveform (pulse shape analysis) in order to identify real particle events and finally we exclude events that simultaneously trigger more than one crystal, to reduce the background due to events depositing energy in multiple crystals.

For this first run we evaluated an overall detection efficiency of (55.3 ± 3.0)%, which includes a (88.35 ± 0.09)% probability that a 0νDBD is fully contained in a single crystal and a (62.6 ± 3.4)% probability that a physics event is not discarded when the selection criteria are applied.

We evaluate the detector energy resolution near the ROI by fitting the 2615 keV line in the physics spectrum. The harmonic mean of the detector FWHM resolutions for this preliminary run has been found to be 7.9 ± 0.6 keV.

To estimate the background in the ROI and the 0νDBD rate ($\Gamma_{0\nu}$) we perform an Unbinned Extended Maximum Likelihood fit in the [2465-2575] keV range (the ROI) with the same procedure used for CUORE-0 [26]. The best-fit values are $0.98^{+0.17}_{-0.15}\times10^{-2}$ counts/(keV kg y) for the background rate, and $(-0.03^{+0.07}_{-0.04}\ \text{(stat)} \pm 0.01\text{(syst)})\times10^{-24}\ \text{y}^{-1}$ for $\Gamma_{0\nu}$. We find no evidence for the 0νDBD of ^{130}Te and we can only calculate an upper limit of $\Gamma_{0\nu}$ by integrating the profile likelihood in the physical region ($\Gamma_{0\nu} \geq 0$). This corresponds to a half-life lower limit of $T_{1/2}^{0\nu} > 4.5 \times 10^{24}$ y (90% C.L.).

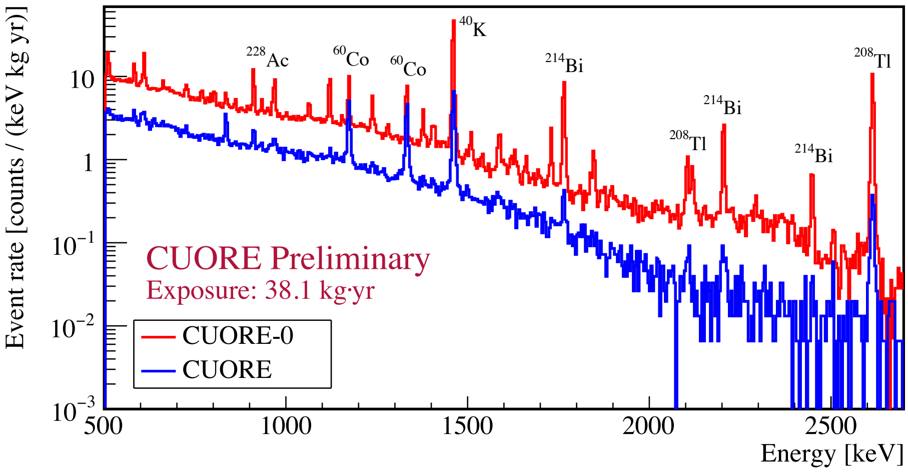

Figure 1: Comparison of physics spectra in the gamma region measured with CUORE and CUORE-0, with prominent γ-lines labeled.

Finally, we combine the first results from CUORE with those obtained from CUORE-0 [18] and Cuoricino [13] with 9.8 kg y and 19.8 kg y exposure of ^{130}Te, respectively. The half-life lower limit obtained by combining the profile negative-log-likelihood curves of the three experiments is $T_{1/2}^{0\nu} > 6.6 \times 10^{24}$ y (90% C.L.).

The combined half-life limit can be then interpreted as a limit on the effective Majorana neutrino mass ($m_{\beta\beta}$) in the framework of models of 0vDBD mediated by light Majorana neutrino exchange. When using the phase-space factors from [27] and nuclear matrix elements from a broad range of recent calculation models [28][29][30][31][32], with the nucleon axial coupling constant $g_A = 1.27$ we get $m_{\beta\beta}$ < (210-590) meV at 90% C.L., depending on the nuclear matrix element estimates employed. We do not consider other g_A values since there is still quite a lack of certainties on what to expect to be the correct number to be used for 0vDBD. See for instance the discussions in [33] and [34].

5. Another optimization campaign and a new science run

After this preliminary science run another optimization campaign of the detector operating conditions was started. We implemented an active noise cancellation system on the pulse tube cryo-coolers using micro-step motor linear drives to control the relative phases of the pulse tube pressure oscillations and fixing the configuration that maximizes the noise cancellation, leveraging the interference between the noise sources [35]. We improved the electrical grounding of the experiment and we performed a temperature scan of the base temperature of the detectors, choosing to work at 15 mK. We optimized the software bandwidth for the pulse amplitude analysis and extended the software trigger window from 5 s to 10 s.

A new science run was then carried out during August 2017. The corresponding dataset as well as the one described in this paper were completely re-processed with a slightly improved analysis procedure and results were presented after the CNNP conference, during CUORE inauguration at LNGS on October, 23rd and will be published on PRL [36].

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