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Search for neutrinoless double-beta decay with CUORE

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Summary. — The CUORE (Cryogenic Underground Observatory for Rare Events) experiment, hosted at Gran Sasso National Laboratories in Italy, is a ton-scale cryogenic experiment designed for the search for neutrinoless double beta decay of ^{130}Te. The first results on $0\nu\beta\beta$ decay of ^{130}Te, from the analysis on the two months of CUORE science runs acquired in 2017, will be presented.

1. – Neutrinoless double-beta decay

Neutrinoless double-beta ($0\nu\beta\beta$) decay is a lepton number violating process that can occur only if neutrinos are Majorana fermions [1-4] and is presently the most sensitive probe of the neutrino nature. A worldwide effort is dedicated to the search of this decay, since its discovery would demonstrate that lepton number is violated and that neutrinos are massive Majorana particles. Furthermore, $0\nu\beta\beta$ searches can strongly constrain the absolute neutrino mass scale and hierarchy [5]. $0\nu\beta\beta$ decay consists in the transformation of a nucleus into one of its isobars with the simultaneous emission of two electrons: $(A, Z) \rightarrow (A, Z + 2) + 2e$. The experimental signature of the decay is a peak in the summed energy spectrum of the two emitted electrons at the Q-value of the decay ($Q_{\beta\beta}$).

The experimental sensitivity can be obtained by considering the half-lifetime corresponding to the maximum signal compatible with the background fluctuations at a given confidence level (n_σ). In order to maximize the sensitivity any experiment must have a low background rate near $Q_{\beta\beta}$, a good energy resolution and a large isotopic mass.

2. – The CUORE experiment

The CUORE (Cryogenic Underground Observatory for Rare Events) experiment is a ton-scale bolometric detector based at the Gran Sasso National Laboratories; its goal is to investigate the $0\nu\beta\beta$ decay of ^{130}Te [6].

The use of ^{130}Te isotope for the search of the $0\nu\beta\beta$ process has few advantages. Its large transition energy ($Q_{\beta\beta}(^{130}\text{Te}) = 2527.518\,\text{keV}$) implies a favourable phase space factor and helps to reduce the background contributions from natural radioactivity. The natural isotopic abundance of ^{130}Te, $\eta = 33.8\%$, is the highest among the $\beta\beta$ emitters. Moreover, the use of TeO_2 crystals makes it possibile to have the ^{130}Te source embedded in the detector, increasing the detection efficiency ($\epsilon \sim 90\%$). It is possible to produce a large number of high quality detectors, since the technology for the growth of TeO_2 crystals is well developed. TeO_2 crystals operated as bolometers at very low temperatures [7, 8] can reach excellent energy resolutions ($\Delta \sim 0.1\%$ at $Q_{\beta\beta}$). This limits the effects of background events, in particular the irreducible contribution due to the $2\nu\beta\beta$ decay.

The CUORE detector consists of an array of 988 bolometric TeO_2 crystals ($5 \times 5 \times 5\,\text{cm}^3$ each) arranged into 19 identical structures called "towers". Each tower hosts 52 bolometers arranged in 13 floors, each containing 4 crystals, see fig. 1. Each crystal has a mass of 750 g, resulting in a total mass of 742 kg of TeO_2, or 206 kg of ^{130}Te.

The CUORE goal sensitivity is $\sim 9 \times 10^{25}$ yr (90% C.L.), in 5 years of data taking [9]. This is based on an expected background index of 10^{-2} c/(keV · kg · yr) and an energy resolution of 5 keV FWHM in the Region Of Interest (ROI), around $Q_{\beta\beta}$. In order to reach this goal, CUORE needs to operate in a very quiet environment protected by radioactive [10] and noise contributions. Therefore the experiment is hosted in a deep underground location, to reduce direct and induced backgrounds from cosmic rays. The detectors are also protected by means of heavy passive shields against the environmental and construction materials radioactivity. To reduce the crystals vibrations, the detector is mechanically decoupled from the cryostat structure by means of a dedicated suspension system.

A powerful two-stage cooling system and a dedicated cryostat have been designed in order to maintain stably the detectors at a temperature of ~ 10 mK over very long periods [11]. The cooling of the detector is accomplished by a two-stage cryogen free refrigerator consisting of five Pulse Tube cryocoolers (PTs), and a powerful custom dilution

Fig. 1. – The complete CUORE detector: the 19 towers modules hosting the 988 TeO_2 crystal.

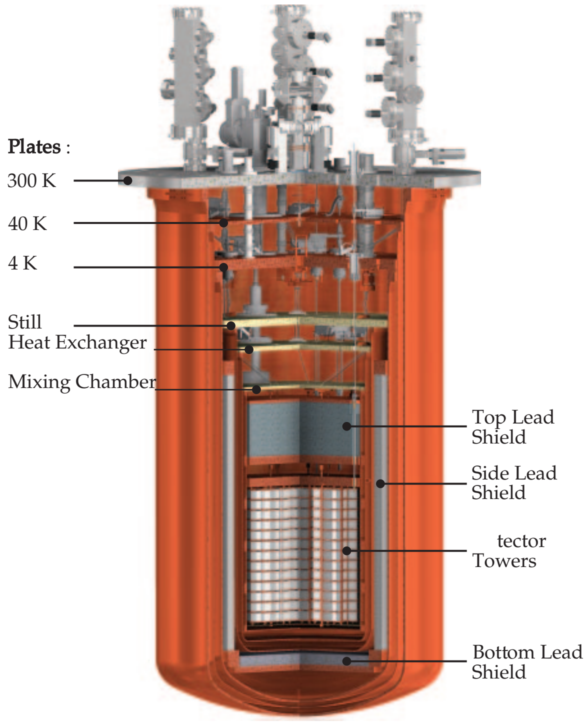

Fig. 2. – Rendering of the the CUORE experiment. The focus is mainly on the cryostat structure: the plates corresponding to the different thermal stages, the shielding lead and the vacuum chambers.

refrigerator (DR). The thermal isolation from the environment is obtained through a multi-stage custom cryostat, consisting of six coaxial nested copper vessels.

The cryostat has been equipped with a custom Detector Calibration System (DCS) to guarantee the access to the innermost layers of the detector. It is composed by 12 ^{232}Th γ-ray sources (thoriated tungsten). The DCS allows to calibrate the detector response over the energy full range up to the region of interest for $0\nu\beta\beta$ [12].

A rendering of the CUORE cryostat and detector is shown in fig. 2.

3. – CUORE operations

The CUORE detector cool-down started at the beginning of December 2016 and by late January 2017 the detector reached a base temperature lower than $\sim 8\,$mK.

The first months of 2017 were devoted to the initial characterization of the detector. A huge effort was devoted in reducing the transmission of vibrations by the cooling system. In order to minimize the impact of the mechanical vibrations induced by the PT cryocoolers, a system to stabilize and control the relative phases of the pressure oscillations inside their transfer lines was developed [13]. At that point the optimal operating temperature, corresponding to the best performance of the detectors, had to be identified and set. The base temperature of the system was therefore allowed to vary over a set of pre-defined values by acting on the parameters of the cryogenic system. The resolution on the baseline and on the heater pulses, and the NTD resistance at

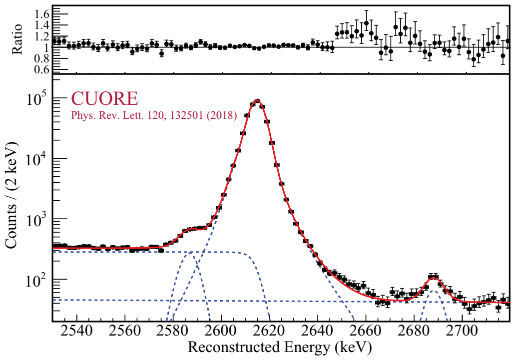

Fig. 3. – Cumulative result from the 19 tower-dependent fit of the Tl peak used to estimate the line shape parameters of each bolometer dataset in calibration data [14].

working point were used as a proxy to identify the temperature which could provide the best signal to noise ratio and ensure a linear and stable behavior of the detectors. The working temperature for the first CUORE physics runs was set to 15 mK.

First CUORE science runs started in April 2017 and approximately two months of physics data were collected up to September 2017. Further optimization campaigns were performed after each science run, during July and October 2017.

4. – CUORE science runs and first physics results

As mentioned in the previous section, the first CUORE science run was started in April 2017. A first short dataset was acquired in order to test the readiness of the data processing tools and to check the detector working points and trigger thresholds. Two periods of science data were then acquired. Dataset 1:1 month from May to June 2017; Dataset 2:1 month from August to September 2017. Each CUORE dataset is bracketed by an initial and a final calibration run and has an approximate duration of four to six weeks.

The performance of the CUORE detector during the science runs was very promising. In total, 984 over 988 CUORE bolometers are operational. The trigger thresholds spanned a range from $\sim$ 20 keV to few hundreds keV, that we expect to reduce further for future low-energy studies. The total collected $0\nu\beta\beta$ exposure is 86.3 kg $(^{nat}TeO_2)\cdot$ yr, or 24.0 kg$(^{130}Te)\cdot$ yr.

Priority was first given to the search of $0\nu\beta\beta$ decay of TeO_2 [14].

Calibration data from the ^{232}Th source strings deployed in the detector core were used to set the energy scale of the CUORE bolometers. The physics spectra, in which to look for a possible $0\nu\beta\beta$ signal, were obtained after applying a series of selection criteria: single pulse-like events collected during periods of stable operation (basic quality cuts), the shape of each waveform was required to be consistent with that of a proper signal template (PSA selection), signals occurring within 10 ms of an event in a different bolometer were rejected (anti-coincidence selection). The efficiencies for the selection cuts were then evaluated and averaged over all channels for each dataset. Science data were blinded until all the selection and fit procedures had been fixed.

The energy resolution of each detector near $Q_{\beta\beta}$ was evaluated by considering the detector response to the 2615 keV ^{208}Tl γ line in calibration. The peak line shape has

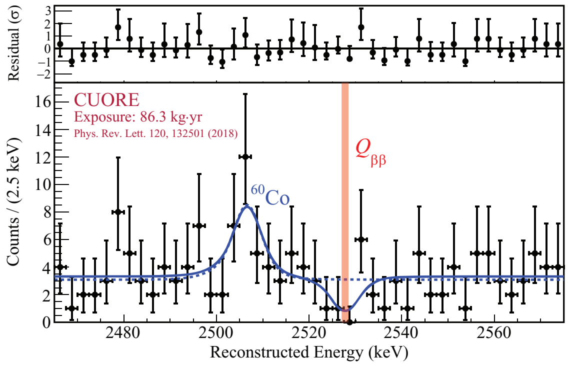

Fig. 4. – Spectrum of $0\nu\beta\beta$ decay candidates observed in CUORE and best-fit model result (solid line) overlaid [14].

been modeled empirically with a primary Gaussian component centered at 2615 keV and two additional Gaussian components, one on the right and one on the left of the main peak. The line shape parameters for each bolometer are estimated with a simultaneous un-binned extended maximum likelihood (UEML) fit on a tower basis. For Dataset 1, the evaluated Tl peak resolution was 9.0 keV FWHM. After the optimization phase carried out during July 2017, the energy resolution observed in Dataset 2 was improved to 7.4 keV FWHM. The cumulative average resolution at 2615 keV, exposure weighted, is 8.0 keV FWHM. The Tl peak line shape observed in calibrations is shown in fig. 3.

A slighly better performance was observed in science runs with respect to calibrations. Values of (8.3 ± 0.4) and (7.4 ± 0.7) keV FWHM were observed in Dataset 1 and 2, respectively. A scaling factor was therefore applied to the energy resolution evaluated in calibration runs to get the correct energy resolution at $Q_{\beta\beta}$ in science runs. The exposure weighted average energy resolution at $Q_{\beta\beta}$ in the science runs is (7.7 ± 0.5) keV FWHM.

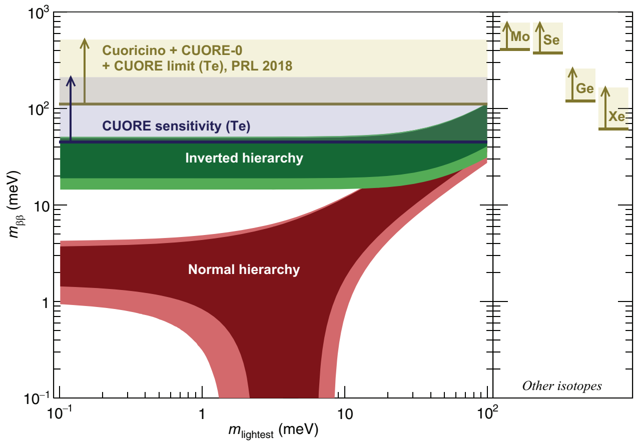

Fig. 5. – Experimental limits on $m_{\beta\beta}$. The regions of $m_{\beta\beta}$ allowed by oscillations are shown both for inverted and normal hierarchies of neutrino mass. The horizontal bands with arrows indicate the most stringent upper limits on $m_{\beta\beta}$ coming from the experimental searches of $0\nu\beta\beta$ with several isotopes and with the new results for ^{130}Te from CUORE combined with CUORE-0 and Cuoricino; moreover the CUORE sensitivity on $m_{\beta\beta}$ for 5 years of data taking is shown.

A UEML fit was performed in the region of interest around $Q_{\beta\beta}$ (2465–2575 keV) to evaluate the TeO_2 decay rate (fig. 4). The fit model consists in a flat background (dataset-dependent), a sum peak for ^{60}Co coincident γ rays (1173 and 1332 keV) and a posited peak at $Q_{\beta\beta}$. Each peak is modeled using the calibration line shape discussed above. The $0\nu\beta\beta$ decay rate, $\Gamma_{0\nu}$, is constrained to be the same for all the detectors and is let vary freely in the fit. The position of the $0\nu\beta\beta$ peak was fixed to the reconstructed $Q_{\beta\beta}$ energy.

The best fit signal decay rate $\Gamma_{0\nu}$ is $(-1.0^{+0.4}_{-0.3}(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-25}\text{yr}^{-1}$. The background index in the ROI averaged over both datasets was obtained after removing the $0\nu\beta\beta$ component from the model:(0.014 ± 0.002)counts/(keV·kg·yr).

This analysis lead to the conclusion that there is no evidence for $0\nu\beta\beta$ decay. An upper limit of $T^{0\nu}_{1/2}(^{130}\text{Te}) > 1.3 \times 10^{25}$yr (90% C.L. including syst.) on the half-life $T^{0\nu}_{1/2}$ was extracted by integrating the profile likelihood for $\Gamma_{0\nu} \geq 0$.

By combinining the CUORE result (24.0 kg · yr exposure) with the CUORE-0 (9.8 kg · yr exposure) [15, 16] and Cuoricino (19.75 kg · yr exposure) [17] results we obtain a 90% C.L. Bayesian half-life limit of $T^{0\nu}_{1/2}(^{130}\text{Te}) > 1.5 \times 10^{25}$yr.

The half-life limits can be used to extract a limit on the effective Majorana neutrino mass ($m_{\beta\beta}$) in $0\nu\beta\beta$ decay models mediated by a light Majorana neutrino exchange. To this end we used the phase-space factor $G(Q_{\beta\beta}, Z)$ and the nuclear matrix elements M_{nucl}, from a broad range of recent calculations [18-23]. The corresponding limit is $m_{\beta\beta} <$ 110–520 meV at 90% C.L., depending on the nuclear matrix element estimates utilized (fig. 5).

5. – Conclusions

CUORE is the first tonne-scale operating bolometric $0\nu\beta\beta$ detector.

The first physics results on $0\nu\beta\beta$ of ^{130}Te after ~ 2 months of data taking are released: $T^{0\nu}_{1/2}$ (^{130}Te) $> 1.3 \times 10^{25}$ yr (90% C.L. including systematics). The cryostat performed exceptionally well and important information on the detectors performance, noise, resolutions and background levels have been collected. The detector optimization campaign focused on energy resolution improvement was followed by a period of maintenance of cryogenics and calibration systems in early 2018. CUORE started taking data again in spring 2018.

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REFERENCES

[1] Racah G., *Nuovo Cimento*, **14** (1937) 322.
[2] Furry W. H., *Phys. Rev.*, **56** (1939) 1184.
[3] Pontecorvo B., *Sov. Phys. JETP*, **26** (1968) 984.
[4] Schechter J. and Valle J., *Phys. Rev. D*, **25** (1982) 2951.
[5] Dell'Oro S., Marcocci S., Viel M. and Vissani F., *Adv. High Energy Phys.*, **2016** (2016) 2162659.

[6] Artusa D. R. *et al.*, *Adv. High Energy Phys.*, **2015** (2015) 879871.
[7] Fiorini E. and Niinikoski T., *Nucl. Instrum. Methods*, **224** (1984) 83.
[8] Enss C. and McCammon D., *J. Low Temp. Phys.*, **151** (2008) 5.
[9] CUORE Collaboration (Alduino C. *et al.*), *Eur. Phys. J. C*, **77** (2017) 532.
[10] CUORE Collaboration (Alduino C. *et al.*), *Eur. Phys. J. C*, **77** (2017) 543.
[11] Alessandria F. *et al.*, *The CUORE cryostat: A 10 mK infrastructure for large bolometric arrays*, in preparation.
[12] Cushman J. S. *et al.*, *Nucl. Instrum. Methods A*, **844** (2017) 32.
[13] D'Addabbo A., Bucci C., Canonica L., Di Domizio S., Gorla P., Marini L., Nucciotti A., Nutini I., Rusconi C. and Welliver B., *Cryogenics*, **93** (2018) 56.
[14] CUORE Collaboration (Alduino C. *et al.*), *Phys. Rev. Lett.*, **120** (2018) 132501.
[15] CUORE Collaboration (Alfonso K. *et al.*), *Phys. Rev. Lett.*, **115** (2015) 102502.
[16] CUORE Collaboration (Alduino C. *et al.*), *Phys. Rev. C*, **93** (2016) 045503.
[17] Andreotti E. *et al.*, *Astropart. Phys.*, **34** (2011) 822.
[18] Kotila J. and Iachello F., *Phys. Rev. C*, **85** (2012) 034316.
[19] Barea J., Kotila J. and Iachello F., *Phys. Rev. C*, **91** (2015) 034304.
[20] Simkovic F., Rodin V., Faessler A. and Vogel P., *Phys. Rev. C*, **87** (2013) 045501.
[21] Hyvarinen J. and Suhonen J., *Phys. Rev. C*, **91** (2015) 024613.
[22] Menendez J., Poves A., Caurier E. and Nowacki F., *Nucl. Phys. A*, **818** (2009) 139.
[23] Rodriguez T. R. and Martinez-Pinedo G., *Phys. Rev. Lett.*, **105** (2010) 252503.