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Performance of the CUORE bolometers —First CUORE results

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Summary. — The CUORE (Cryogenic Underground Observatory for Rare Events) Experiment is a ton-scale bolometric detector based at the Gran Sasso National Laboratories in central Italy. The goal of the experiment is to investigate the $0\nu\beta\beta$ decay of ^{130}Te. CUORE started pre-operation runs in January 2017. First science runs were carried out in early Spring 2017. Two optimization campaigns followed in order to set the best operating conditions for the $0\nu\beta\beta$ search.

1. – The CUORE experiment and the $0\nu\beta\beta$ search

The discovery of the non-zero neutrino masses by precision measurements of neutrino flavor oscillations has strongly revived the interest into the Dirac or Majorana nature of the neutrino and its absolute mass scale. Indeed, Majorana neutrinos are a common ingredient of a number of extensions of the Standard Model and could play a crucial role in cosmological evolution.

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 simultaneus 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 ($Q_{\beta\beta}$). In fig. 1, the $2\nu\beta\beta$ decay, predicted by the standard model, is compared with the $0\nu\beta\beta$ process.

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 the case of a finite number of observed background counts

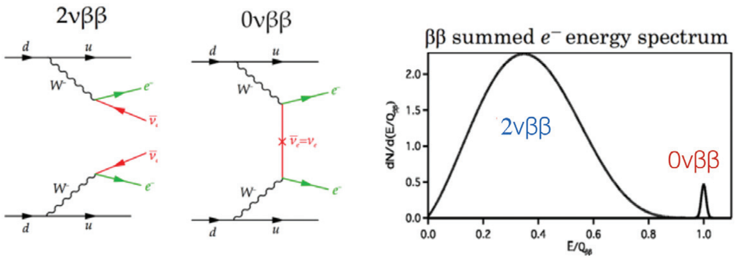

Fig. 1. – $2\nu\beta\beta$ and $0\nu\beta\beta$ decay Feynman diagrams and sum electrons energy spectra.

($N_B = M \cdot T \cdot B \cdot \Delta > 1$), and assuming a Poisson statistics, this is simply given by the square root of the background counts and the sensitivity can be expressed as

$$S^{0\nu}(n_\sigma) = \ln 2 \frac{\epsilon x \eta N_A}{n_\sigma M_A} \sqrt{\frac{MT}{B\Delta}}, \tag{1}$$

where M is total detector mass (kg), T is the measure time (y), B is the background index in counts/(keV $\cdot$ kg $\cdot$ y), Δ is the energy resolution (keV), N_A the Avogadro number, x the stoichiometric multiplicity of the element containing the $\beta\beta$ isotope, η the isotopic abundance of $\beta\beta$ isotope, ϵ the detection efficiency, and M_A the molecular mass of the detector compound.

Despite its simplicity, eq. (1) outlines all the relevant experimental parameters and is an irreplaceable guideline for the design of any $0\nu\beta\beta$ experiment. In particular, in order to maximize the sensitivity any experiment must have a low background rate (B) near $Q_{\beta\beta}$, a good energy resolution (Δ) and a large isotopic mass ($M \cdot \eta$).

When the expected number of background counts along the measurement time is lower than 1, the Poisson statistics can no longer be applied. We enter the improperly called "zero background" regime and the sensitivity becomes

$$S^{0\nu}_{ZB}(n_\sigma) = \ln 2 \frac{\epsilon x \eta N_A M T}{N_\sigma M_A}, \tag{2}$$

where N_σ is a constant value depending only on the selected confidence level. This is a very coveted condition since in this regime the sensitivity scales linearly with time and is independent of the background rate and the energy resolution. Most next generation experiments aim at it.

1˙1. *The CUORE challenge.* – 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 [6].

The CUORE choice of using the ^{130}Te isotope to search for the $0\nu\beta\beta$ process has been driven by several factors. 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. ^{130}Te has also the highest natural isotopic abundance, $\eta = 33.8\%$, 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 (actually coinciding with it), increasing the detection efficiency ($\epsilon \sim 90\%$). The technology for the growth of TeO_2

crystals is well developed and makes it possible to produce a large number of high quality detectors, in principle providing no limits to the active mass (M). 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 goal sensitivity is $\sim 9 \times 10^{25}$ y (90% C.L.), in 5 years of data taking [9]. This is based on an expected background index of $10^{-2}c/(\text{keV} \cdot \text{kg} \cdot \text{y})$ 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 (vibrational and electrical) 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. In particular a massive shield cast from ancient lead extracted from a roman ship sunk off the coasts of Oristano (Sardinia, Italy), is maintained at low temperature (4 K), close to the detector. To reduce the crystals vibrations, the detector is mechanically decoupled from the cryostat structure by means of a dedicated suspension system. A specific design for an almost complete decoupling of the cryostat from the transfer lines of the cooling system has also been implemented.

A powerful two-stage cooling system has been designed in order to maintain stably the setup at a temperature of ∼10 mK over very long periods. In order to limit the radioactive contributions from the structure of the cryostat, a strict radio-purity assay has been carried out for all the construction materials (that in many cases has required to renounce the materials most commonly used in cryogenics). A similar care has been devoted also to the assembly and commissioning procedures in order to avoid recontamination.

1·2. *CUORE TeO_2 bolometers.* – 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. 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 TeO_2 crystals act at the same time as source and detectors of $0\nu\beta\beta$ decays, and are held in the tower structure by means of Cu frames and PFTE holders. Each crystal is instrumented with a Neutron Transmutation Doped germanium (NTD-Ge) thermistor (which acts as a voltage transducer) and a silicon heater to monitor the response stability [11]. The NTDs and the heaters are glued on each crystal by means of a fixed number of epossidic glue spots. The signal readout is accomplished through Cu-PEN cables which run along the tower structures (figs. 2 and 3) and are connected to the NTD and heaters by 25 μm ball bonded gold wires. Each NTD is separately biased by means of a dedicated circuit maintained at room temperature and characterized by a differential low noise read-out and two large load resistors. Calibration pulses from high precision pulser boards are sent periodically to the heaters to correct for possible thermal instabilities of the system [12].

Each TeO_2 absorber acts as an independent bolometer where any deposited energy is converted into thermal phonons. This induces a slight temperature variation of the crystal and a corresponding voltage pulse at the thermistor ends. The amplitude of each pulse is then proportional to the energy deposit ($\Delta T_{crystal} \sim 100\,\mu\text{K/MeV}$, ΔV_{NTD} $\sim 300\,\mu\text{V/MeV}$).

The simplest thermal model of the CUORE bolometer [13] considers just the thermal

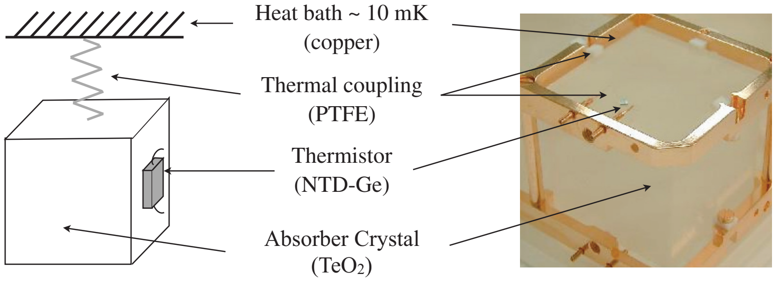

Fig. 2. – A representation of a CUORE-like single bolometer: TeO_2 crystal, thermistor and link to the heat bath [13].

Fig. 3. – The complete CUORE detector: the 19 towers modules hosting the 988 TeO_2 crystals.

capacity of the absorber (TeO_2 crystal lattice specific heat $C(T) \propto T^3$) and a single thermal link G between the crystal and the heat bath. The pulses are characterized by an amplitude proportional to the temperature variation ($\Delta T \propto \frac{E_{dep}}{C}$) and a main exponential tail component, with $\tau \propto \frac{C}{G} \approx 1\,\mathrm{s}$.

The NTD-Ge thermistor resistance varies with temperature with an exponential law ($R(T) = R_0 \exp^{(\frac{T_0}{T})^{1/2}}$). Therefore the operating temperature and the NTD bias voltage have to be carefully chosen in order to match the read-out circuit and electronics design.

1˙3. *CUORE cryogenic infrastructure and auxiliary systems*. – The CUORE cryostat has been designed to house the ton-scale detector described above and to maintain it stably at a temperature around 10 mK for at least 5 years [14].

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 refrigerator (DR).

The PTs (PT415-RM by Cryomech [15]) are characterized by two stages at 40 K and 4 K and provide the basic cooling power. They bring and maintaing the corresponding

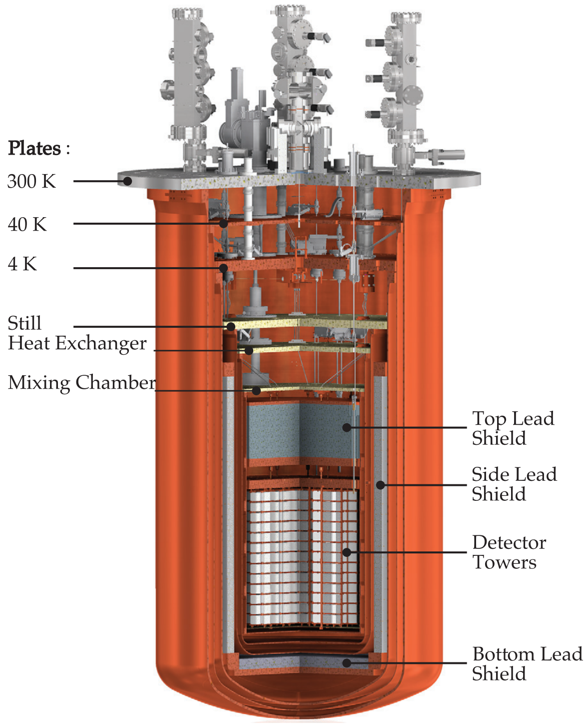

Fig. 4. – Rendering of the the CUORE experiment. The focus is mainly on the cryostat structure: the plates corresponding to the different thermal stages, the shielding lead and the vacuum chambers.

stages of the cryostat at their design temperature.

The cooldown to a base temperature below 10 mK is then provided by the continuous-cycle ^{3}He-^{4}He Dilution Refrigerator (DR), designed and built by Leiden Cryogenics [16].

A fast cooling system (FCS) has also been designed and realized to boost the initial cooling phase. This is used to help bring the system from room temperature to less than 30–40 K, and is based on a flow of cold helium gas through the cryostat chambers to speed up the cooling process.

The thermal isolation from the environment (crucial to maintain the very low temperature over long periods of time) is obtained through a multi-stage custom cryostat, consisting of six coaxial nested copper vessels, each with a corresponding top plate and flange which defines six nested independent volumes. Only electron beam welding has been used for the construction of the cryostat vessels in order to avoid any possible contamination from carry-over of the welding electrodes.

The six vessels act mainly as thermal shields. They are maintained at temperatures of 300 K, 40 K, 4 K, 600 mK, 50 mK and 10 mK, respectively. The 300 K and the 4 K vessels are vacuum tight and define two separated volumes: Outer and Inner Vacuum Chamber (OVC and IVC). Super-insulations layers are applied on the external surfaces of the 40 K and 4 K vessels.

In order to minimize the transmission of vibrations from the supporting structure, the cryostat is anchored from above to a structure called Main Support Plate (MSP), while the detectors array is suspended, inside the 10 mK vessel, by means of independent damping suspensions [17].

The detector is shielded from environmental radioactivity and radioactive contaminations of the cryostat elements by means of several radiation shields:

- a massive shield maintained at room temperature and characterized by 30 cm of modern lead against environmental gamma radioactivity, and 10 cm of polyethylene and a layer of CB_4 to get rid of environmental neutrons. The shield is mounted on a movable platform which brings the structure around the cryostat during operation;
- a thick (30 cm) modern lead disc suspended on top of the detector and maintained at 50 mK to shield from the radioactivity of the cryostat elements and the environment;
- a 6 cm layer of ancient (roman) lead on the side and bottom of the detector and maintained at a temperature of 4 K.

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 of 12 ^{232}Th γ-ray sources (thoriated tungsten), which are preliminarly cooled at 4 K before the final deployment to base temperature into the detector volume. The DCS allows to calibrate the detector response over the energy full range up to the region of interest for $0\nu\beta\beta$ [18].

A rendering of the CUORE cryostat and detector is shown in fig. 4.

2. – CUORE operations

The commissioning of the CUORE cryogenic system was completed in February 2016 with a final cooldown of the system at full load. Preparations for the detector installation immediately started. By the end of August 2016 the CUORE detector was hanging from the cryostat plate surrounded by protection bags. Fixing the interfaces with the cryostat required for an additional couple of months. By the end of November 2016 the system was eventually ready for the initial cool-down.

2˙1. *CUORE cool-down.* – The CUORE detector cool-down started at the beginning of December 2016. During the initial phase (down to ∼35 K) the 5 PTs were assisted by the FCS. The cool-down progressed regularly and, after ∼ 20 days, the system reached a temperature of ∼3.4 K. The exchange gas was then pumped for about 3 weeks in order to reach the right vacuum condition for turning on the DR unit. By January 27, 2017 the detector reached a base temperature lower than ∼8 mK (fig. 5). The first CUORE pulse appeared few hours later, when a number of detectors were biased to check their behavior. The commissioning of the detector immediately followed.

2˙2. *Detector characterization and optimization.* – The first months were devoted to the initial characterization of the detector. A huge effort was devoted to reduce the transmission of vibrations by the cooling system, which immediately appeared to be the dominant noise contribution. The suspension system, designed to mechanically decouple the detector structure from the structure of the cryostat, was characterized in order to find the optimal parameters providing the requested cut-off frequency of about 0.5 Hz in both the vertical and horizontal directions. Then, in order to minimize the impact of the mechanical vibrations induced by the PT cryocoolers, a system to stabilize and

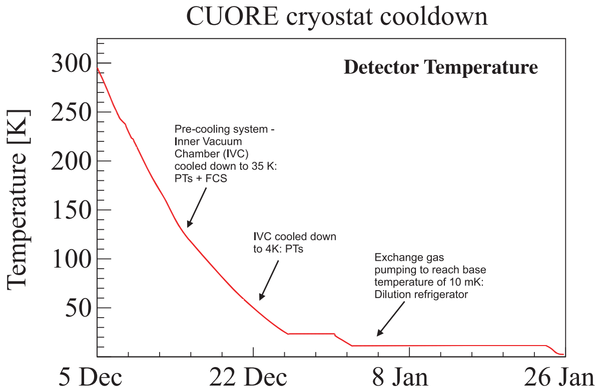

Fig. 5. – CUORE detector cool-down: plot of the detector temperature decrease while each element of the multi-stage cryostat was turned on.

control the relative phases of the pressure oscillations inside their transfer lines was developed [19]. Indeed pressure oscillations induce vibrations of the transfer lines which are transmitted to the structure of the cryostat and eventually to the detectors.

At this point the system was ready for choosing the optimal operating temperature, corresponding to the best performance of the detectors. The base temperature of the system was therefore let to vary over a set of pre-defined values by acting on the parameters of the cryogenic system. Then, for each temperature and for a selected number of representative detectors (3 towers characterized by a different NTD production set), the polarization voltages providing the best signal-to-noise ratio and ensuring a linear and stable behavior were determined.

To this end, a I-V "load curve" (a set of increasing voltages at the detector ends) was first built for each detector, in order to identify the best bias voltage. Then, a small number of fixed amplitude heater pulses were fired on each detector in order to evaluate the bias corresponding to the maximum detector response. A finite number of periodograms was eventually collected in order to evaluate the detector noise power spectra and compute the signal-to-noise ratio. In particular, the resolution on the baseline and on the heater pulses, and the NTD resistance at working point (R_{wp}) were used as a proxy to choose the working temperature, which was set to 15 mK.

2˙3. *Science runs and first physics results.* – Although the detector optimization phase was still far from being completed, by the beginning of April 2017 a first CUORE science run was started. First CUORE operations started on April 14, 2017. Following the CUORE-0 experience, CUORE data were grouped in datasets. Each dataset is bracketed by an initial and a final calibration run and has an approximate duration of four to 6 weeks. 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.

Further optimization campaigns were performed after each science run, during July and October 2017.

The performance of the CUORE detector during the science runs was excellent. Only 4 channels over 988 were non-operational. The trigger thresholds spanned a range from ∼20 keV to few hundreds keV, that we expect to reduce further for future low-energy studies. A stable average trigger rate per bolometer of ∼50 mHz was observed in calibrations and ∼6 mHz during science runs. The total collected $0\nu\beta\beta$ exposure is 86.3 kg($^{\mathrm{nat}}$TeO$_2$) · y, or 24.0 kg(^{130}Te)· y.

Priority was first given to the search of $0\nu\beta\beta$ decay of TeO$_2$ [20]. Calibration data from the ^{232}Th source strings deployed in the detector core were used to set the energy scale of the CUORE bolometers. Six gamma lines ranging from 239 keV to 2615 keV were used to create a calibration function for each bolometer and each dataset. The physics spectra, in which to look for a possible $0\nu\beta\beta$ signal, were obtained after applying a series of selection criteria. Basic quality cuts were applied in order to select single pulse-like events collected during periods of stable operation. Moreover the shape of each waveform was required to be consistent with that of a proper signal template (PSA selection). In order to reduce background contributions from decays depositing energy in multiple crystals, signals occurring within 10 ms of an event in a different bolometer were rejected (anti-coincidence selection). The efficiencies for these 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. As already observed in CUORE-0, the peak line shape is slightly non-Gaussian. We model it 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. 6.

We also observed a slighly better performance 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

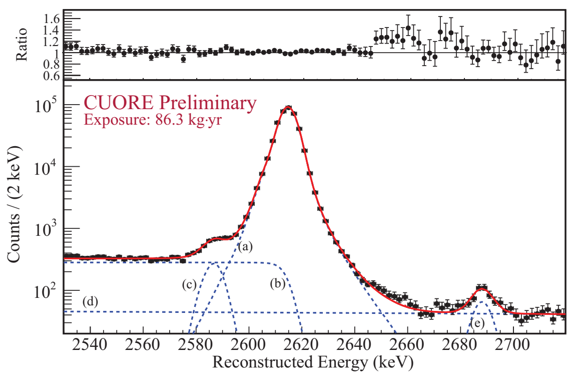

Fig. 6. – Cumulative result from the 19 tower-dependent fit of the Tl peak used to estimate the line shape parameters of each bolometer-dataset in calibration data [20].

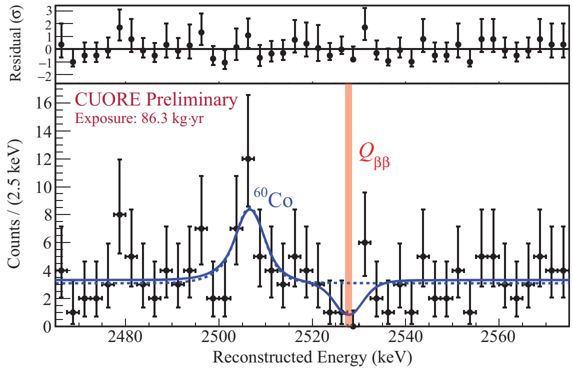

Fig. 7. – Spectrum of $0\nu\beta\beta$ decay candidates observed in CUORE and best-fit model result (solid line) overlaid [20].

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.

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. 7). 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 let to 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 $(-1.0^{+0.4}_{-0.3}(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-25}\text{y}^{-1}$. 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·y).

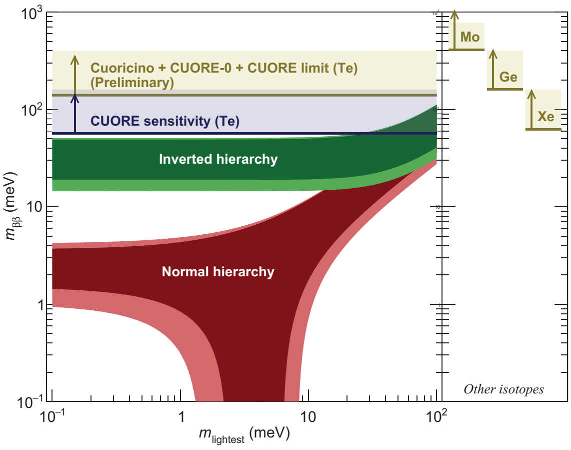

Fig. 8. – Experimental limits on $m_{\beta\beta}$. The regions of $m_{\beta\beta}$ allowed by oscillations are shown both for inverted and normal hierarchies of neutrino mass. The horizontal bands with arrows indicate the most stringent upper limits on $m_{\beta\beta}$ coming from the experimental searches 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.

This analysis lead to the conclusion that there is no evidence for $0\nu\beta\beta$ decay. An upper limit of $T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 1.3 \times 10^{25}$ y (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 · y exposure) with the CUORE-0 (9.8 kg · y exposure) [21, 22] and Cuoricino (19.75 kg · y exposure) [23] results, we obtain a 90% C.L. bayesian half-life limit of $T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 1.5 \times 10^{25}$ y.

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, via eq. (3). 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 [24-29]. The corresponding limit is $m_{\beta\beta} < 110$–520 meV at 90% C.L., depending on the nuclear matrix element estimates utilized (fig. 8).

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2. \tag{3}$$

3. – Conclusions

CUORE is the first ton-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: $T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 1.3 \times 10^{25}$ y (90% C.L. including systematics). An improved limit of $T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 1.5 \times 10^{25}$ y (90% C.L. including systematics) is obtained when combining the results of the precursor experiments Cuoricino and CUORE-0. The cryostat is performing exceptionally well and important information on the detectors performance, noise, resolutions and background levels have been collected. The ongoing detector optimization is focused on improving the resolution through further noise reduction.

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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] CUORE Collaboration (Alduino C. *et al.*), *J. Inst.*, **11** (2016) P07009.

[12] Carniti P., Cassina L., Giachero A., Gotti C. and Pessina G., *J. Instrum.*, **13** (2018) P02029.
[13] Vignati M., *Model of the Response Function of CUORE Bolometers* (2010) (Ph. D. thesis, University of Rome - La Sapienza).
[14] D'Addabbo A. *et al.*, *J. Low Temp. Phys.*, **193** (2018) 589.
[15] Cryomech PT415-RM.
[16] Leiden Cryogenics DRS-CF3000 continuous-cycle.
[17] Bersani A. *et al.*, *The detector suspension system of the CUORE experiment* (in preparation).
[18] Cushman J. S. *et al.*, *Nucl. Instrum. Methods A*, **844** (2017) 32.
[19] D'Addabbo A. *et al.*, *Cryogenics*, **93** (2018) 56.
[20] CUORE Collaboration (Alduino C. *et al.*), *Phys. Rev. Lett.*, **120** (2018) 132501.
[21] CUORE Collaboration (Alduino K. *et al.*), *Phys. Rev. Lett.*, **115** (2015) 102502.
[22] CUORE Collaboration (Alduino C. *et al.*), *Phys. Rev. C*, **93** (2016) 045503.
[23] Andreotti E., *Astropart. Phys.*, **34** (2011) 822.
[24] Kotila J. and Iachello F., *Phys. Rev. C*, **85** (2012) 034316.
[25] Barea J., Kotila J. and Iachello F., *Phys. Rev. C*, **91** (2015) 034304.
[26] Simkovic F., Rodin V., Faessler A. and Vogel P., *Phys. Rev. C*, **87** (2013) 045501.
[27] Hyvarinen J. and Suhonen J., *Phys. Rev. C*, **91** (2015) 024613.
[28] Menendez J., Poves A., Caurier E. and Nowacki F., *Nucl. Phys. A*, **818** (2009) 139.
[29] Rodriguez T. R. and Martinez-Pinedo G., *Phys. Rev. Lett.*, **105** (2010) 252503.