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Latest Results from the CUORE Experiment

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Abstract
The Cryogenic Underground Observatory for Rare Events (CUORE) is the first cryogenic experiment searching for $0\nu\beta\beta$ decay that has been able to reach the one-tonne mass scale. The detector, located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, consists of an array of 988 TeO_2 crystals arranged in a compact cylindrical structure of 19 towers. CUORE began its first physics data run in 2017 at a base temperature of about 10 mK and in April 2021 released its 3rd result of the search for $0\nu\beta\beta$, corresponding to a tonne-year of TeO_2 exposure. This is the largest amount of data ever acquired with a solid state detector and the most sensitive measurement of $0\nu\beta\beta$ decay in ^{130}Te ever conducted . We present the current status of CUORE search for $0\nu\beta\beta$ with the updated statistics of one tonne-yr. We finally give an update of the CUORE background model and the measurement of the ^{130}Te $2\nu\beta\beta$ decay half-life and decay to excited states of ^{130}Xe, studies performed using an exposure of 300.7 kg yr.

Keywords Neutrinos · Double-beta decay · Macro-calorimeters · Cryogenics · CUORE

1 The CUORE Experiment

The CUORE (Cryogenic Underground Observatory for Rare Events) is a tonne-scale cryogenic experiment utilising low temperature detectors (LTDs), TeO_2 calorimeters read by NTD thermistors, which is located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy [1].

The main goal of the experiment is to search for rare events and/or for physics beyond the Standard Model [2]. The principal analysis is the search of $0\nu\beta\beta$ decay in ^{130}Te, which would imply a Majorana nature for the neutrino [3–7]. Other studies which are performed are: measurement of $2\nu\beta\beta$ decay of ^{130}Te [8] and study of backgrounds, study of other rare decays ($^{130}Te\beta\beta$ decay to excited states [9], $0\nu/2\nu\beta\beta$

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decay of ^{128}Te [10], $0\nu(\beta^+ + EC)$ ^{120}Te decay [11]), low energy studies (dark matter—WIMPs, axions, supernova neutrinos) and spectral shape studies ($0\nu/2\nu\beta\beta$ decay with Majoron emission, CPT violation in $2\nu\beta\beta$ decay).

1.1 The CUORE Detector

The development of TeO_2 calorimeters for double beta decay searches started in early 1980s with the group of E. Fiorini in Milano [12]. They started with small crystals (few tens of g) operated as LTDs; over time the technology improved and reached the scale of tens of kg (eg. MiDBD, Cuoricino, CUORE-0) [13]. The technology was then mature to approach the tonne-scale with CUORE.

The CUORE detector is an array of closely packed 988 TeO_2 crystals arranged in 19 towers. It consists of a very large mass of TeO_2, 742 kg (206 kg of ^{130}Te). Each tower hosts 52 detectors arranged in 13 floors of 4 crystals each [14]; each detector is composed of a TeO_2 absorber, a Ge-NTD thermistor utilised for measuring the temperature variation due to energy deposition, and a Si-heater [15] utilised to stabilise the detector's response over small thermal drifts. When the detectors are operated at ~10 mK, for 1 MeV energy deposition in the crystal, the temperature rise is $\Delta T_{\mathrm{crystal}} \sim 100$ μK/MeV, corresponding to a voltage variation at the edges of the NTD, $\Delta V_{\mathrm{NTD}} \sim 400$ μV/MeV. For this reason, a dedicated front-end electronics has been designed for CUORE, which handles both the amplification of the NTD signal and its bias polarisation [16].

1.2 The CUORE Technological Challenge

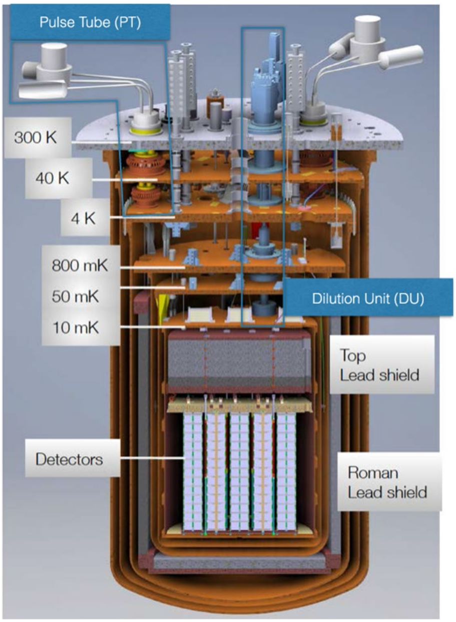
The CUORE experiment is a very unique challenge in terms of cryogenic infrastructure and background requirements.

The large mass of the detector has to be cooled down to ~ 10 mK; therefore it is utilised a multistage cryogen-free cryostat [17, 18], in which the Pulse Tubes (PTs) are cooling down the outer vessels from 300 to 4 K, then a Dilution Unit (DU) cools down the inner volumes from 4 K to the base temperature, 10 mK. A rendering of the CUORE cryostat is reported in Fig. 1. Moreover, CUORE has to be operated in low background conditions being an experiment searching for rare events [19]. Indeed, the experiment is hosted deep underground at the LNGS; strict radio-purity controls were performed on the materials and during the assembly, and there are passive shields from external and cryostat radioactivity. Moreover, the detector itself with its high granularity acts with self-shielding.

2 CUORE Data Taking

The CUORE data taking started in spring 2017. After an initial data taking phase, significant effort was devoted to understanding the system and optimising the data taking conditions [20]. Since March 2019 the data taking is continuing

Fig. 1 Rendering of the CUORE cryostat hosting the detector. (Adapted from [18])



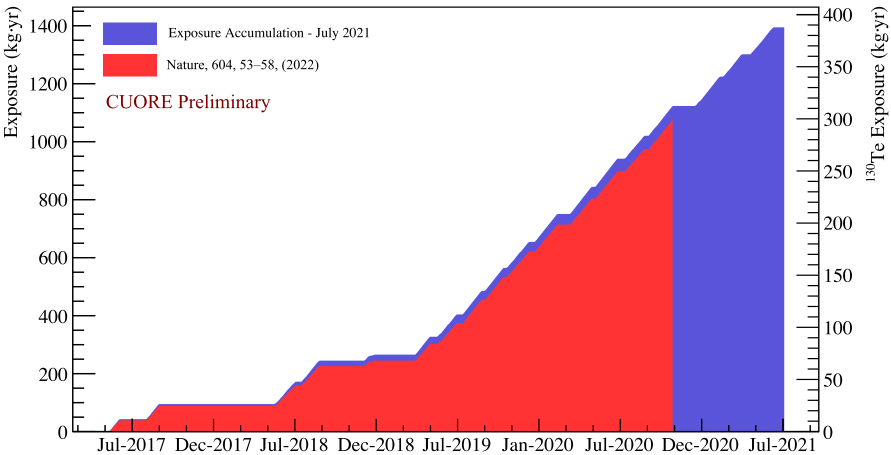


Fig. 2 CUORE exposure up to July 2021

smoothly with > 90% uptime, at an operating temperature 11.8 mK. In July 2021, the CUORE detector temperature was set to 15 mK. The CUORE data taking rate is ∼ 50 kg/month. CUORE reached the important milestone of one tonne-yr TeO_2 accumulated exposure in late 2020, with a continuous data taking and excellent stability of the cryogenics. The CUORE current exposure is ∼ 1400 kg yr (July 2021). See Fig. 2.

The CUORE detector data are grouped in datasets, which consist in almost 1 month of background/physics data bracketed between few days of calibration. A continuous monitoring of detector stability is performed by measuring the working resistance of the NTDs, and of the minimum noise configuration.

2.1 Detector Response

The CUORE pulses are characterised by rise and decay times of the order of 0.1 s and 1 s, respectively. Indeed, the detector response is quite slow, but this is not a huge problem for the CUORE physics searches, dealing with rare events and very low backgrounds. The rise time is limited by the RC coupling between the NTD working resistance (100MΩ–1GΩ) and the parasitic capacitance of the electrical links. The NTD working resistance stability is measured and monitored over time for all the CUORE detectors [21].

For large size calorimeters, the energy resolution is not limited by the intrinsic thermal noise fluctuation. For a CUORE-like ideal TeO_2 crystal, the latter can be estimated to be 50–200 eV at $\sim$ 10 mK, while the measured energy resolution is of the order of few keV. Transmission of vibrations by the cooling system appears to be the dominant noise contribution on the CUORE detectors. Pulse Tube-induced vibrations are responsible for peaks at 1.4 Hz and its harmonics in the detectors noise power spectrum; that is the frequency of the pressure waves generated by the PTs. In order to reduce and stabilise this effect an active noise cancellation technique is applied on the PTs motor-heads drivers; the PT-phases configuration inducing the lower noise on most of the detectors is identified through a phase scan and it is kept stable over time during the data taking [22]. Residual mechanical vibrations and oscillations can induce both low and high frequency peaks in the noise power spectrum. Passive damping systems for decoupling the detector to the main cryogenic infrastructure are installed. Moreover, offline noise cancellation algorithms utilizing auxiliary accelerometers, microphones and seismometers data are being developed [23].

2.2 Data Processing

The voltage output from the CUORE detectors is sampled at 1 kHz and saved into a data-stream. The analysis procedure aims to trigger the signal pulses, measure their amplitude (energy) and reject spurious events [24].

The amplitude of the triggered pulses is calculated via an Optimum Filter, maximising the signal-to-noise ratio; a gain stabilisation, utilising heater pulses, is applied in order to correct for small thermal drifts. The detector response is then calibrated in order to convert the reconstructed amplitudes to energies; an external calibration system (^{232}Th and ^{60}Co gamma sources) allows to calibrate in a wide energy range, from 511 to 2615 keV. The high granularity of the CUORE detector allows to perform coincidence studies, identifying events happening close in time in multiple crystals; these events are assigned with different values of multiplicity. The Principal Component Analysis (PCA) is utilised to reject spurious pulses [25].

3 New Results from CUORE

In April 2021, CUORE released a new result of the search for $0\nu\beta\beta$ decay of ^{130}Te, corresponding to an exposure of 1038.4 kg yr of TeO_2 (288 kg yr of ^{130}Te). The collected data correspond to 15 datasets; the average number of CUORE detectors over the several datasets, utilised for the analysis is ~ 934 over 988. The energy spectrum is built selecting events passing several analysis cuts: pulses with no pile-up and baseline instabilities (Base Cuts), events with energy deposition in a single crystal (anti-coincidence, AC) and clean particle pulses (pulse shape discrimination, PSD); the average selection efficiency of these cuts is 92.4(2)%. The reconstructed energy resolution at $Q_{\beta\beta}$ is 7.8(5) keV FWHM and the background index in the region of interest (ROI) is ~ $1.49(4) \times 10^{-2}$ ct/(keV kg yr). The reconstructed CUORE physics energy spectrum is reported in Fig. 3 (top). No peak-like signature at the $Q_{\beta\beta}$ of ^{130}Te has been found yet. An half-life limit for the $0\nu\beta\beta$ decay of ^{130}Te is extracted

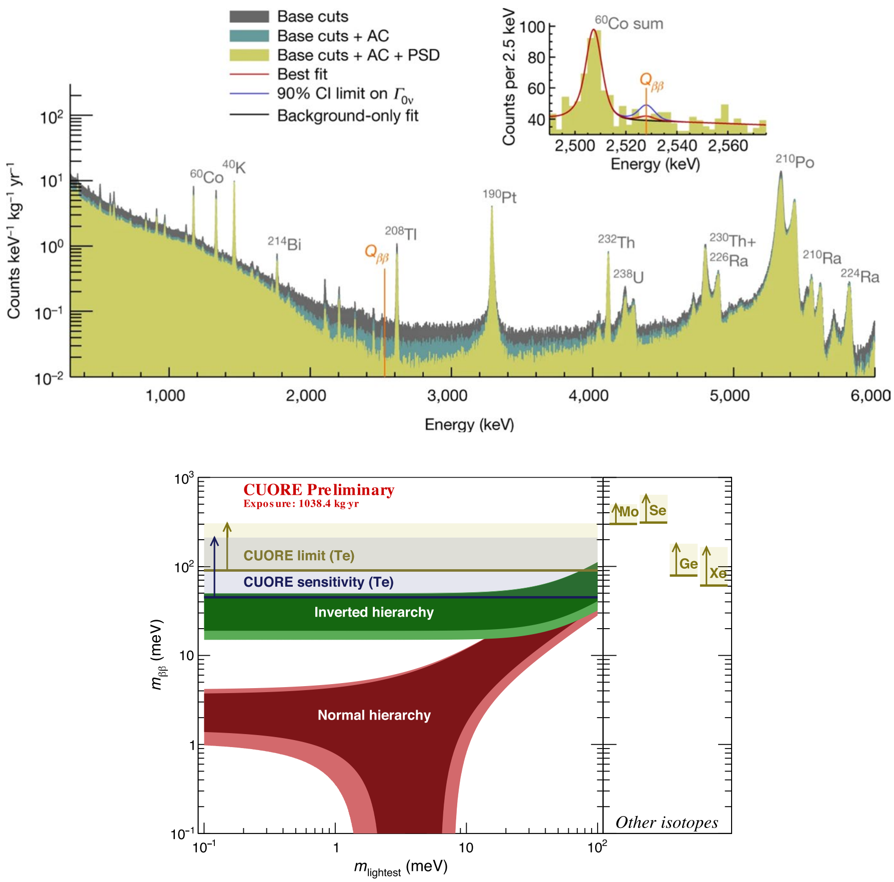


Fig. 3 CUORE one tonne-year data release: physics spectrum after the several analysis cuts (Figure taken from [7]) (top) and limit on the effective neutrino mass (bottom)

with a Bayesian analysis approach: $T^{1/2}_{0\nu} > 2.2 \times 10^{25}$ yr at a 90% credibility interval, with a median exclusion sensitivity of 2.8×10^{25} yr [7]. Compared to the sensitivity, the probability of getting a stronger limit was 72%. The half-life limit is converted into an estimate of the effective neutrino mass from the double-beta decay process, in case of the exchange of a light Majorana neutrino: $m_{\beta\beta} < 90$–305 meV (see Fig. 3 (bottom)).

Recently CUORE reported a new measurement of the ^{130}Te $2\nu\beta\beta$ decay half-life, with 300.7 kg yr TeO_2 exposure: $T^{1/2}_{2\nu} = 7.71\ ^{+0.08(\mathrm{stat})+0.12(\mathrm{syst})}_{-0.06(\mathrm{stat})-0.15(\mathrm{syst})} \times 10^{20}$ yr [8]. That is the most precise measurement of ^{130}Te $2\nu\beta\beta$ decay half-life up to now. CUORE was able to reach such precision due to the high statistics acquired and the good reconstruction of the physics spectrum via a Monte Carlo simulation, which profits from the segmented detector for locating the background sources.

In addition to the previously reported decays to the ground state, CUORE performs the search of $\beta\beta$ decays to the excited states of ^{130}Xe. The ^{130}Te $\beta\beta$ decay to the first 0^+ excited state of ^{130}Xe experimental signature is a cascade of de-excitation gammas in coincidence with the emitted electrons; therefore multi-detector signature are expected in CUORE, which allow a background reduction with respect to the corresponding transitions to the ground state. No evidence of signatures for both $0\nu\beta\beta$ and $2\nu\beta\beta$ mentioned decays have been observed yet; limits on the half-life for these two decay channels can be extracted: $T^{1/2}_{0\nu,0+} > 5.9 \times 10^{24}$ yr and $T^{1/2}_{2\nu,0+} > 1.3 \times 10^{24}$ yr at a 90% credibility interval [9].

4 Conclusion

CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic calorimeters to search for the $0\nu\beta\beta$ decay. CUORE released physics results of ^{130}Te $0\nu\beta\beta$ decay (one tonne-yr exposure) and $2\nu\beta\beta$ decays to ground and excited states with the physics data collected in 2017–2020. A raw exposure of more than one tonne-yr has been achieved and the data taking is proceeding. The CUORE data taking is currently underway to collect 5 years of run time (up to 3 tonne-yr exposure). The CUORE experience is giving an important feedback for the future CUPID project (CUORE Upgrade with Particle IDentification) [26].

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